Climate-Smart Agriculture

Enhancing Resilient Agricultural Systems, Landscapes, and Livelihoods in Ethiopia and Beyond

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Mekelle University
JIRCAS
World Agroforestry
WeForest Making Earth Cooler
Oregon State University

Editors: *

Kiros Meles Hadgu (PhD), World Agroforestry (ICRAF) - Ethiopia, c/o ILRI Ethiopia,
P. O. Box 5689, Addis Ababa, Ethiopia
Email: K.Hadgu@cgiar.org / kirhadgu@gmail.com

Badege Bishaw (PhD), Department of Forest Ecosystems & Society, 208 Richardson
Hall, Oregon State University, Corvallis, Oregon 97331 USA
Email: badege.bishaw@oregonstate.edu

Miyuki Iiyama (PhD), Japan International Research Center for Agricultural Sciences
(JIRCAS), Ohwashi, Tsukuba, Ibaraki 305-8686, Japan
Email: miiyama@affrc.go.jp

Emiru Birhane (PhD), Mekelle University, College of Dryland Agriculture and Natural
Resources, Department of Land Resource Management and Environmental Protection
(LaRMEP), P. O. Box 231, Mekelle, Ethiopia
Email: emiru.birhane@mu.edu.et

Aklilu Negussie (PhD), WeForest, Ogentroostlaan 15, B-3090 0verijse, Belgium
Email: aklilumekuria@weforest.org / aklilumekuria@gmail.com

Caryn M. Davis, Cascadia Editing, 701 McCall Way, Philomath, Oregon 97370 USA
Email: cascadia.editing@gmail.com / carynmdavis@gmail.com

Bryan Bernart, Cascadia Editing, Los Angeles, California USA
Email: bryan@bernart.net

*** Note:** All editors contributed equally to this volume.

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Tel: +254 (0) 20 7224000, via USA +1 650 833 6645
Fax: +254 (0) 20 7224001, via USA +1 650 833 6646
Email: icraf@cgiar.org
Internet: http://worldagroforestry.org/

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Executive Summary

In Sub-Saharan Africa, the majority of the population depends on subsistence farming in a system characterized by high forest landscape degradation, low soil fertility, erratic rainfall, small farm sizes, and a high population. Over 936.1 million people live in this region, and over 60% of the population depends on farming, according to 2015 data from the World Bank. To meet the increasing food demand (both in quantity and quality) of the increasing population, the agricultural practices in the region have been expanding to forests and biodiversity hotspot areas. At the same time, climate change is posing severe challenges resulting in low agricultural production and low resilience capacities of smallholder communities in this region. To address the challenges, evidence-based and eco-friendly technologies and approaches are crucial for improving food security and livelihoods in the region. Enhancing the production of food on less land in more sustainable ways will improve the capacities of smallholder communities to cope with climate shocks and improve the resiliency of communities and ecosystems. Integrated and climate-smart approaches, for example, on land, water and forest management practices can sustainably increase agricultural productivity, and ecosystem and societal resilience while reducing greenhouse gases (GHG) emissions for enhancing to achieve national, regional, and global developments including food security and livelihoods improvement.

With the aim of compiling climate-smart technologies and practices which combine both food security and climate change issues, the World Agroforestry (ICRAF) in Ethiopia took an initiative to prepare a book with information organized based on scientific knowledge and case studies gathered from different parts of Ethiopia and other Sub-Saharan Africa countries. To this end, ICRAF invited professionals from several institutions and organizations to document and exchange all available evidence based knowledge and local agro-ecological practices with contributions from a range of topics including agriculture, water management, agroforests, soil, ecosystems, climate change, rural energy, socioeconomic, gender and policy issues in Sub-Saharan Africa, with emphasis on Ethiopia.

The book presents evidence-based knowledge and scalable practices which can be tailored to different biophysical, socioeconomic, policy, and institutional contexts. The technologies and practices described in this book include promising options by considering varying contexts and demands, which can potentially enhance accelerated restoration of degraded landscapes, sustainable agricultural production and food-nutrition-energy security while contributing to resilient ecosystems and societies to climate change. The book also provides frameworks and strategies, which improve informed decision-making and facilitate accelerated adoption and scaling up of the technologies and practices in Ethiopia and the SSA. The book highlights approaches, which are timely and critical towards achieving national and regional development strategies in SSA, while contributing to global initiatives, such as Sustainable Development Goals (SDGs), and Forest Landscape Restoration. The important information of the book can be used by different users, such as researchers, extension staff, local communities, practitioners, academics, and policy makers.

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Abbreviations and Acronyms

ADB	Asian Development Bank
ADLI	Agricultural Development-Led Industrialization
AGP	Agricultural Growth Program
ANOVA	Analysis of Variance
ATA	Ethiopian Agricultural Transformation Agency
ATT	Average Treatment Effects
AVHRR	Advanced Very High Resolution Radiometer
A-WRA	Australian Weed Risk Assessment
BM	Dry biomass
BM_INUE	Irrigation-Nitrogen Use Efficiency (for biomass)
CA	Conservation Agriculture
CBD	Convention on Biological Diversity
CC	Carrying Capacity
CDM	United Nations Clean Development Mechanism
CER	Certified Emission Reduction
CFC	Chlorofluorocarbon
CGIAR	Consultative Group for International Agricultural Research
CIAT	Centro Internacional de Agricultura Tropical
CII	Construction Industry Institute
CO2e	Carbon dioxide equivalent
CPRs	Common Pool Resources
CPSCSA	Climate-smart, Productive and Sustainable approaches
CRGE	Climate-Resilient Green Economy
CRS	Climate Resilience Strategy
CSA	Climate-Smart Agriculture
CSE	Conservation Strategy of Ethiopia
CSF	Climate-Smart Forestry
CS-ISM	Climate-smart integrated soil fertility management
CSLM	Climate-smart land management
CS-TPA	Climate Smart Technologies, Practices and Approaches
DAP	Diammonium phosphate
DAs	Development Agents
DCM	Drought Cycle Management
DECSI	Dedebit Credit and Saving Institute
DESIRE	Desertification Mitigation and Remediation of Land
DRR	Disaster Risk Reduction
ECS	Ecosystem Carbon Stock
EESRC	Ethiopian Energy Study and Research Center
EIA	Environmental Impact Assessment
EPA	Environmental Policy of Ethiopia
EPACC	Ethiopia's Program of Adaptation to Climate Change
EPE	Environmental Policy of Ethiopia
FAO	Food and Agriculture Organization of the United Nations
FDRE	Federal Democratic Republic of Ethiopia
FGD	Focused group Discussion
FMNR	Farmer Managed Natural Resources
FSS	Food Security Strategy
G_INUE	Irrigation Nitrogen Use Efficiency (for grain)
G_IWUE	Irrigation Water Use Efficiencies (for grain)
GDP	Gross Domestic Product
GES	Green Economic Strategy
GHG	Greenhouse gas
GIS	Geographic Information Systems
GIZ	Deutsche Gesellschaft für Internationale ZusammenarbeitH
GIZ-SUN	GIZ-Scaling Up Nutrition
GmbH	German Corporation for International Cooperation
GMP	GHG Mitigation Potential
GoE	Government of Ethiopia
GTP	Growth and Transformation Plan
GTP-1	Growth and Transformation Plan
GTZ	German Technical Cooperation Agency
GWP	Global Warming Potential
HARIA	Horn of Africa Risk Transfer for Adaptation
HH	Household
H-WRA	Hawaiian Weed Risk Assessment
ICRAF	World Agroforestry
IFAD	International Fund for Agricultural Development
IFPRI	International Food Policy Research Institute
IIRR	International Institute for Rural Reconstruction
INUE	Irrigation- Nitrogen Use Efficiency
IPCC	Intergovernmental Panel on Climate Change
ISDR	International Strategy for Disaster Reduction

ISFM	Integrated Soil fertility Management
IV	Instrumental Variable
IWM	Integrated Weed Management
IWMI	International Water Management Institute
IWSD	Integrated Watershed Development
IWUE	Irrigation Water Use Efficiency
JIRCAS	Japan International Research Center for Agricultural Sciences
LPG	Liquid Petroleum Gas
MAP	Mean Annual Precipitation
MAR	Mean Annual Rainfall
MCE	Multi-Criteria Evaluation
MEFCC	Ministry of Environment, and Forest and Climate Change
MERET	Managing Environmental Resources to Enable Transition to More Sustainable Livelihood
MoARD	Ministry of Agriculture and Rural Development
MoFED	Ministry of Finance and Economic Development
MoME	Ministry of Mines and Energy
NAP	National Action Programme
NAPA	National Adaptation Program of Action
NBSAP	National Biodiversity Strategy and Action Plan
NCS	National Conservation Strategy
NDF	National Desertification Fund
NDVI	Normalized Difference Vegetation Index
NGOs	Non-governmental Organizations
NPPE	National Population Policy of Ethiopia
NRM	Natural Resources Management
NSC	National Steering Committee
NUE	Nitrogen Use Efficiency
NUE_BM	Nitrogen Use Efficiencies for Biomass
NUE_G	Nitrogen Use Efficiencies for Grain
OLS	Ordinary Least Square
PASDEP	Plan for Accelerated and Sustained Development to End Poverty
PFM	Participatory Forest Management
PIER	Pacific Islands Ecosystems at Risk
PRM	Participatory Rangeland Management
PSM	Propensity Score Matching
PSNP	Productive Safety Net Program
PV	Photovoltaic
R&D	Research and Development
RARIs	Regional Agricultural Research Institutes
RDPS	Rural Development Policy and Strategies
REDD+ (UN)	Reducing Emissions from Deforestation and Forest Degradation
REF	Rural Electrification Fund
REST	Relief Society of Tigray
RTPCs	Rural Technology Promotion Centers
RUSLE	Revised Universal Soil Loss Equation
SDGs	Sustainable Development Goals
SFM	Sustainable Forest Management
SLM	Sustainable Land Management
SNNPR	Southern Nations, Nationalities and Peoples' Region
SOM	Soil Organic Matter
SRTM	Shuttle Radar Topography Mission
SSA	Sub-Saharan Africa
SWC	Soil and Water Conservation
TBoARD	Tigray Bureau of Agriculture and Rural Development
UEAP	Universal Electricity Access Program
UMMNB	Urea Molasses Multi-Nutrient Block
UNCCD	United Nations Convention for Combating Desertification
UNDP	United Nations Development Programme
UNFAO	United Nations Food and Agriculture Organization
UNFCCC	United Nations Framework Convention on Climate Change
USDA-NRCS	United States Department of Agriculture Natural Resources Conservation Service
WFP	World Food Programme
WHO	World Health Organization
WII	Weather Index Insurance
WOCAT	World Overview of Conservation Approaches and Technologies
WRA	Weed Risk Assessment
WV	World Vision
WVA	World Vision Australia

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This document is the result of a multi-institutional collaboration involving specialists from various disciplines. It was initiated by researchers from World Agroforestry (ICRAF) in Ethiopia in collaboration with its partner institutions including Oregon State University (OSU), Japan International Research Center for Agricultural Sciences (JIRCAS), Mekelle University, WeForest, and Cascadia Editing. The book editors would like to acknowledge all professionals who participated during the book writeshops and all contributors during the successful preparation and publication of the book. Our sincere thanks also go to all reviewers who reviewed several drafts of the book chapters and the entire book, and provided valuable scientific inputs and feedback which enriched the content of the book. We are also grateful to the editorial team at OSU (Caryn M. Davis, Sarah Hershberger, Will Burnard, and Alex Hughan) for their work on an early draft of this document.

We are very grateful to all institutions involved in the preparation/publication of the book and to donors, for example, IrishAid which first inspired the preparation of the book writeshop for documenting lessons learned from long term ICRAF-led projects implemented in Ethiopia with supports from the Government of Ireland through IrishAid/Ireland Embassy in Ethiopia. Our thanks also go to the Government of Ethiopia (GoE) for successfully owning and mainstreaming an ICRAF initiated National Agroforestry Platform (NAP) to its programs/systems in its relevant Ministries. At some stage, the document preparation also benefited from facilitations by the GoE in organising a national level stakeholder discussions to enhance resilient and sustainable green growth through accelerating nation wide adoption and scaling of innovative, proven and best-fit CSA technologies, practices and strategies—already documented in the book—which contribute to and align well with the country's priority development targets and strategies including, but not limited to: Climate Resilient Green Economy (CRGE), food security and poverty reduction strategies as well as an initiative to restore 15 million ha by 2030.

We are also indebted to contribution and support provided by the Government of Japan through its contribution to ICRAF and JIRCAS which benefited the book during the final stage of the book compilation. We would also like to thank to our other partners (e.g., NICFI/Norwegian Embassy in Ethiopia; Australian Centre for International Agricultural Research – ACIAR/Australian Embassy in Ethiopia; DGIS/Netherlands Embassy in Ethiopia; IFAD, EC, Packard Foundation and others) which directly and indirectly contributed to the successful preparation and publication of the book, and aligning it with national, regional (afr100) and global (e.g., SDGs and Forest-Landscape Restoration (FLR), as well as with international conventions and organizations, including, the United Nations Framework Convention on Climate Change (UNFCCC), the United Nations Convention to Combat Desertification (UNCCD), the Convention on Biological Diversity (CBD), the Consortium of International Agricultural Research Centers (CGIAR), and the World Bank.

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Foreword

In Sub-Saharan Africa (SSA), as in many areas of the developing world, the majority of the population depends on subsistence rainfed farming for their livelihoods. However, SSA is one of the most highly vulnerable regions to current climate variabilities. Most likely, it will continue to be vulnerable to worsening impacts from climate change. In 2011, for example, East Africa encountered the worst drought of the last 60 years, which was caused by sporadic seasonal rainfall due to "La Niña." This devastating drought reportedly affected about 12 million people.

Such an event should serve both as a warning and as a call for priority action to the national, regional and global scientific and development communities. Appropriate mitigation strategies must be prepared and implemented to address these recurring climate change impacts and to build more resilient farming systems, landscapes, and livelihoods.

Subsistence smallholder farming systems should build on the best of local agroecological knowledge and practices, while they also integrate improved technologies and practices, in order to curb the negative impacts of climate change and achieve food security. The sustainability and resilience of smallholder agriculture is highly dependent on the health of the local natural resources. Thus, it is important to consider integrated technologies and practices that not only increase resilience at the farm level, but also at the landscape level as well.

Approximately 90% of the population in SSA, particularly in Ethiopia, lives in areas that are characterized by land degradation and stagnant or declining agricultural productivity. Hence, climate-smart agricultural innovations are critical for solving food insecurity and the associated problems caused by the changing climate.

The concepts of climate-smart agriculture (CSA) and climate-smart forestry (CSF) have been endorsed as appropriate strategies contributing to ensuring food security and climate resilient ecosystems in a number of recent global, continental and regional summits and conferences. The leaders of many nations, particularly from developing countries, along with donors, international research organizations, and NGOs are now giving priority attention to CSA, CSF, forest and landscape restoration, and other relevant climate-smart innovations.

The concept of climate-smart agriculture was introduced by the Food and Agriculture Organization of the United Nations (FAO) in 2009. It defined CSA as an "agriculture that sustainably increases productivity, enhances resilience, reduces greenhouse gases, and enhances the achievement of national food security and development goals." The CSA approach encourages the creation of enabling environments that improve access for farmers to appropriate agricultural technologies. These include improved crop varieties and livestock breeds that are more adapted to the changing climate; the integration of useful trees and shrubs into farming systems through evergreen agriculture; other improved agroforestry practices such as trees on field boundaries; conservation agriculture practices, including crop rotation, continuous soil cover through mulching, intercropping, and zero or minimum tillage; improved fodder production and management; holistic and sustainable grazing systems; improved water management techniques, particularly in rainwater harvesting; and other climate-smart innovations such as CSF.

The potential contribution of CSA to sustainable green growth development has now been well-recognized by international conventions and organizations, including the United Nations Framework Convention on Climate Change (UNFCCC), the United Nations Convention to Combat Desertification (UNCCD), the Convention on Biological Diversity (CBD), the Consortium of International Agricultural Research Centers (CGIAR), and the World Bank.

This book compiles and reviews the available CSA technologies, practices, and approaches for enhancing improved agricultural production systems, sustainable land resources management, and resilient ecosystems and communities in SSA, with a particular focus on Ethiopia. Many chapters of the book include case studies with important insights on how farming communities are better coping with variable and changing climates by adopting and adapting improved, integrated farming practices coupled with local practices, to restore their land and manage their ecosystems. These approaches are also very useful lessons for farming communities in other developing countries as well.

The book presents critical information to policy makers on evidence-based CSA practices that should be strongly supported. It provides them the basis for informed decision-making, for high-return investments, and for crafting essential policies and strategies to meet local, national, and regional development targets and challenges.

This book also provides timely and important knowledge that can enhance our understanding of the nature and scale of historical climate trends, as well as to improve the adoption and scaling up of CSA practices in SSA and other developing regions. It provides useful information to farmers, researchers, extension officers, and educators, not only about the consequences of climate change, but also about implementing appropriate strategies to effectively and sustainably address climate change impacts, while increasing food security and the resilience of ecosystems and livelihoods. I congratulate the editors and the authors for their great vision and hard work to create this excellent volume. It is full of material that will contribute to an evergreening and food secure future in Ethiopia and other SSA countries.

Dr. Dennis Garrity

Drylands Ambassador, UN Convention to Combat Desertification (UNCCD),

Senior Fellow, World Agroforestry (ICRAF),

Senior Fellow, World Resources Institute (WRI),

Chair, EverGreening Global Alliance, and

Chair, Landcare International

Preface

Background and Objective of the Book

Smallholder farming systems in Sub-Saharan Africa (SSA) have been characterized by their heavy reliance on ecosystems services– water, soil, and natural resources. During the last few decades, while the populations of some SSA countries have doubled, the agricultural productivity has stagnated (Pretty et al. 2011). Accommodating the growing demand for food, fuel, and income sources for the fast-growing population therefore has had to be met by expansion of agricultural land through clearing forestland and/or by increased cropping intensity through reduced fallows and mining of soil nutrients. Consequently, soil degradation has been increasingly threatening the resilience of ecosystems, on which African smallholder farmers have depended for their food security and livelihoods. African smallholder systems that have already been stressed by unsustainable use of the natural resources are increasingly threatened further by climate change.

There is a strong need for approaches and interventions to address the multiple needs of SSA smallholder farmers in order to simultaneously achieve increased productivity, enhanced resilience to climate risks and shocks, and reduced impacts on ecosystems, including soil degradation and greenhouse gas (GHG) emissions (Lipper et al. 2014, Thornton et al. 2018). Climate smart agriculture (CSA) has emerged and evolved as a relatively new concept since 2009 to advocate for better integration of the "three pillars" — productivity, adaptation, and mitigation — to sustainably achieve food security in the era of climate change (Lipper and Zilberman 2018). Today many countries, including those in SSA, have embraced the concept of CSA, as evidenced by the fact that by 2016, 32 out of the 189 countries that had submitted Intended Nationally Determined Contributions (INDC) for the Paris Agreement specifically referenced CSA, while approximately 50 countries have endorsed, or even prioritized, actions intended to harness the potential synergies between mitigation and adaptation in agriculture (FAO 2017).

While the principles of CSA are simple, as summarized in its three pillars, the practices, technologies, and policies of CSA form a diverse set ranging from soil and water management at the plot/farm scale and watershed/landscape natural resource management to policy mechanisms for low-carbon agriculture (FAO 2017). A recent study that reviewed CSA in 33 developing countries from Africa, Asia, and Latin America indicates that technologies considered climate-smart demonstrate synergies between productivity, adaptation, and mitigation pillars, revealing opportunities for co-benefits and potential "triple-wins" (Sova et al. 2018). At the same time, the study highlighted the fact that there is no "one-size-fits-all" CSA that can be universally applied, but instead, the smartness of a system depends on locally specific contexts in which it is deployed (Sova et al. 2018). Indeed, given a significant heterogeneity in African smallholder systems in terms of agro-ecological contexts and institutional/political settings, there is no silver-bullet CSA for all situations. Furthermore, CSA can be an approach for integrating locally appropriate bundles of interventions across different spatial/temporal scales rather than just a set of single interventions (Lipper et al. 2014; Scherr et al. 2012, Sova et al. 2018).

For example, in Ethiopia, with its wide ecological variability that ranges from arid and semiarid tropical lowlands to cool afro-alpine highlands and mountains, smallholder farming systems exhibit a significant heterogeneity with diverse degrees of crop-livestock integration, from extensive pastoral, extensive agro-pastoral, to intensive mixed crop-livestock production systems. Climate-smart landscape restoration can take different forms of interventions in pastoral systems in lowlands (e.g., integrated rangeland management) vs. agro-pastoral systems in highlands (e.g., exclosure), with distinctive institutional arrangements to mobilize communities. Similarly, one CSA can yield triple-win outcomes in one context, but trade-offs in another context, unless an integrated set of CSA interventions is introduced. For instance, the introduction of conservation agriculture in agro-pastoral systems may create competitions for crop residues between covering crops and grazing animals, unless grazing management is also transformed to zero-grazing, along with the introduction of improved animal breeds and fodder species. The scaling up of CSA practices, technologies, and policies in Ethiopia therefore requires a deliberate strategy to allow stakeholders to match between locally specific food-security climate-related challenges and the most appropriate sets of CSA interventions, along with efforts to create enabling environments and tools to support stakeholders' decision making.

There is an urgent need to provide stakeholders with guidance on how to identify an optimal portfolio of CSA approaches appropriate to locally specific contexts in order to address multi-faceted challenges to achieve food security under climate change (Lipper and Zilberman 2018). Especially, there is a strong demand for guidance among SSA countries, including Ethiopia, and stakeholders to match and prioritize which specific climate-smart technologies, practices, and policies or a mix of them could effectively address productivity, adaptation, and mitigation simultaneously and, if necessary, how to tailor integrated CSA interventions to locally specific contexts with an appropriate set of enabling conditions. The primary objective of this book is to provide such guidance for academic, policy, research, outreach and development stakeholders to select specific, and if possible, evidence-based, climate-smart technologies, practices and policies or a mix of them to sustain smallholder food production systems and ecosystem services in SSA countries, with a special focus on Ethiopia.

Document Preparation

This book was initiated by World Agroforestry (ICRAF), in collaboration with Oregon State University, Mekelle University, WeForest, and Japan International Research Center for Agricultural Sciences (JIRCAS) to bring expertise from different disciplines and compile the evidence on available CSA technologies, practices, and policies in Ethiopia and beyond. The scope of the topics and arguments included in each chapter were determined after thorough discussions with expertise from universities, research institutions, government ministries, NGOs, and private individuals in Ethiopia. The lead authors for each chapter were selected based on their experience and knowledge on that specific thematic area.

Then, a one-week intensive writeshop, which involved 31 researchers and field practitioners from different parts of the country, was organized in Mekelle, Tigray, in northern Ethiopia, sponsored by ICRAF Ethiopia office. During the writeshop, five teams were established based on participants' expertise (climate-smart crop production, climate-smart landscape management, livestock production and agro-pastoral development teams, climate-smart tree production, and socioeconomics and policy). Based on their expertise, the contributed draft manuscripts were given to the respective team for review and discussion. Copies of each draft manuscript were subsequently given to two other participants within the team, who critically reviewed it and suggested areas of improvement. During the writeshop, the participants generated ideas for new topics that were not included in the first draft. These were drafted by individuals who had relevant experience and knowledge.

Afterwards, the team leaders and content editors helped each of the chapter lead authors to revise and edit each manuscript by incorporating the comments received during the writeshop. The edited manuscripts were then desktop-published to produce a second draft. Before publishing, each chapter was further reviewed by senior experts, university professors, and researchers who are in the same disciplines.

Structure of the Book

In order to facilitate readers in finding the selection of CSA approaches in this book most suitable to their interests, the book has been divided into six Parts (Figure P1) which respectively correspond to the rationales for why CSA approaches are needed in Ethiopian context and beyond, as is described in detail in Chapter 1.

Part I - Setting the scene

Part I sets the scene for the book by introducing the definitions and conceptual frameworks of CSA and elaborating rationales of CSA in SSA in general, and in Ethiopia in particular.

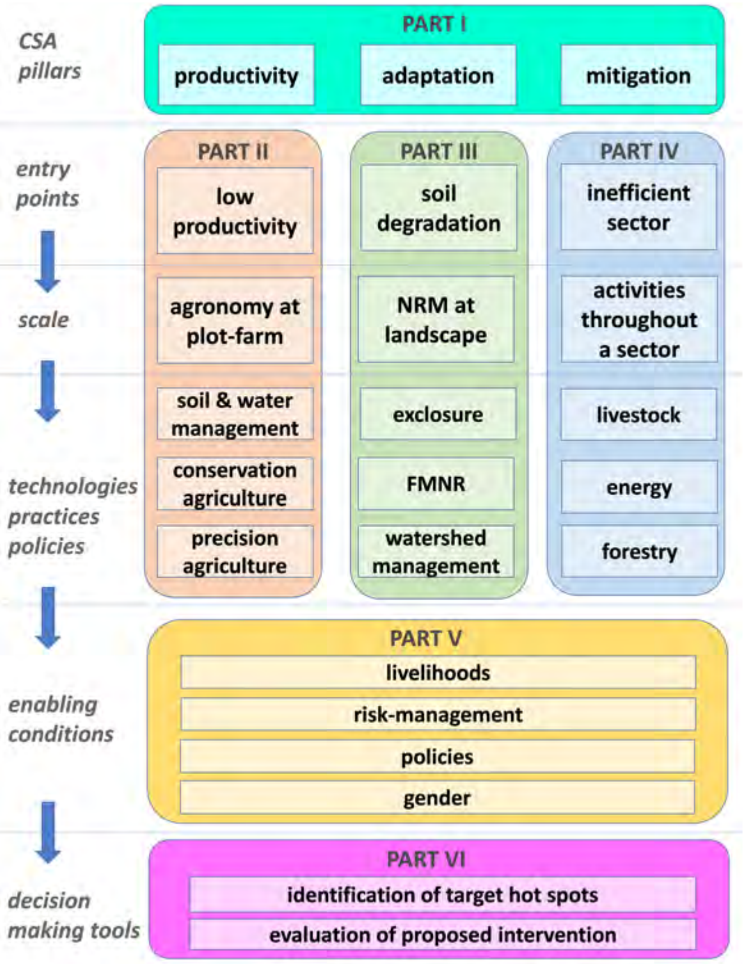

Figure P.1 Organization of the book.

Chapter 1 gives an overview of the challenges facing the conventional rain-fed, smallholder subsistence farming systems in SSA (e.g., chronic low agricultural productivity, deforestation and land, soil, natural resource degradation, and increasing difficulty to meet food and nutrition security needs of the growing population) under ever-changing climatic conditions. Then by introducing a theoretical overview of CSA principles and concepts, the chapter elaborates rationales why CSA approaches are needed in Sub-Saharan African countries, especially in Ethiopian context, not only to achieve productivity, adaptation and mitigation goals but also simultaneously to address root causes of low, stagnant productivity and soil degradation. The chapter defines CSA by scale, e.g., those addressing productivity constraints at plot-farm scale (conservation agriculture, precision agriculture etc.), those aiming at climate-smart natural resource management at landscape scale (exclosure, farmers managed natural regeneration, etc.), and those advocating for a sectorial approach (livestock, energy, forestry). Then it argues the importance of enabling factors and decision-making tools for effective scaling up of CSA given limited resources.

Chapter 2 explores a variety of plot-farm (field-farm) level CSA practices including soil, nutrient and water management, along with agroforestry, livestock husbandry, forest and grassland management practices. While individual CSA technologies, practices, and policies at the plot-farm level can achieve productivity, adaptation and/or mitigation goals, the integration of different CSA approaches from the plot-farm scale to the landscape scale can even have larger multiplier impacts through the diversity of land use and their interactions at the landscape scale. This chapter elucidates the key features of integrated climate-smart landscape restoration and management approaches and elaborates how diversity of land uses at landscape scale contributes to climate change mitigation and adaptation through enhancing ecosystem services. Institutional mechanisms required for the implementation of integrated climate-smart landscape approaches are also reviewed.

Part II - Improving productivity and resilience of smallholder agriculture at plot-farm scale

Part II consists of the three chapters to introduce CSA technologies that specifically address sustainable and efficient water and nutrient uses at the farm-plot scale in locally specific contexts to achieve improvement in crop productivity and the resilience of smallholder agriculture.

Chapter 3 reviews the benefits of practicing conservation agriculture (CA) to minimize land degradation and hydrological challenges, to improve livelihood of smallholder farmers, and to promote better soil carbon sequestration in Ethiopian contexts. CA is a system that simultaneously combines the three pillars of agricultural production, namely minimal soil disturbance, retention of crop residues, and crop rotations. While CA practice in Ethiopia is in its infancy, the chapter highlights its potentials, especially through its integration with *in situ* soil and water conservation methods such as contour plowing, furrow and raised beds systems locally adopted by smallholder farming communities in the drylands. Enabling conditions to facilitate wider adoption of CA by smallholder farmers in Ethiopia are discussed, especially the need to tailor the management schemes to the existing diversity of agro-ecological and socioeconomic farm settings.

Chapter 4 presents the results of the two-year experiment in northern Ethiopia to investigate the optimum amount of irrigation water and rate of nitrogen fertilizer under two different soil types for the production of teff (*Eragrostis tef*), the major food crop in Ethiopia. The results indicated that teff responded well to simultaneous application of supplemental irrigation water and nitrogenous fertilizer in both Cambisols and Vertisols, while increased water application without increased N did not increase teff yield and the vice versa. The productivity of teff has been subject to negative impacts of climate change and land degradation. In view of climate change projections, in-depth understanding of the agronomic practices, particularly the water and nutrient management options is urgently required.

Chapter 5 presents evidence of the positive impacts of climate-smart integrated soil fertility management (CS-ISFM), which is defined as a kind of precision agriculture practices characterized by applying critical nutrient levels optimized for different soil types, integrating soil moisture management, and integrating legumes in the cropping systems. CS-ISFM approaches have the potential to sustainably enhance agricultural productivity while improving ecosystem health and societal resilience to climate shocks and contributing to the reductions of GHG emissions in Ethiopia and beyond. The authors call for further research on the spatial variability of soils, establishing critical nutrition levels and optimized fertilization, and developing optimal CS-ISFM in order to have evidence-based planning, and implementation, and scaling-up of CS-ISFM adapted to specific and local contexts.

Part III - Enhancing ecosystem resilience at landscape scale

Part III features four chapters that provide case studies on evidence-based, climate-smart natural-resource management interventions at the landscape level, with an elaboration of the principles and/or analysis of factors that could contribute to successful adoption/scale-up.

Chapter 6 reviews the historical process of landscape restoration in Tigray and discusses key factors, especially direct and indirect benefits of land restoration, which have contributed to sustainable adoption and scale-up. With reference to a community that is now globally recognized as a "degraded land restoration model," the chapter highlights the importance of enabling institutions, including coordinating programs and policies for extension approaches among key stakeholders on watershed restoration, as well as establishing and enacting local bylaws for the mobilization of community members, including women, the elderly, and youth.

Chapter 7, which is based on case studies from the highlands of Tigray, northern Ethiopia, synthesizes the evidence of exclosures for effectively restoring degraded landscapes, especially increasing soil carbon, nitrogen and available phosphorous contents, while reducing soil erosion and restoring vegetation, thereby improving the provisioning, regulating, supporting, and cultural ecosystem services. The author further presents the case that the net present value of the exclosure ecosystem services over a period of 30 years would be higher than alternative wheat production, justifying benefits of the exclosures to achieve improved, resilient, and sustainable production systems, livelihoods, and ecosystems.

Chapter 8 discusses farmer managed natural regeneration (FMNR), a rapid and effective method of landscape restoration that involves the selection and pruning of regrowth from tree stumps, roots, or seeds. FMNR is highly replicable and is believed to be an appropriate and climate-smart option for restoring and rehabilitating degraded landscapes in Ethiopia and other areas with similar problems. The authors present principles, practices, merits, advantages, and implementation modalities of FMNR as a technique/

tool for enhancing agroforestry, and synthesize experiences with and lessons learned from FMNR in restoring degraded lands in Ethiopia. Some evidence is also presented on the effectiveness of landscape restoration and its positive economic, social, and environmental benefits, drawing on case studies from northern and southern Ethiopia.

Chapter 9 introduces constructability concepts as an organized way of guiding farmland reclamation using reservoir sediments, with examples from its application in northern Ethiopia. In the last few decades, the Ethiopian government has led a campaign to construct water-harvesting technologies in critical watersheds to address water constraints facing smallholder farmers. Such benefits, are often short-lived, however, due to severe soil erosion that provides sediments and siltation to downstream reservoirs. One of the potential strategies for solving water and soil nutrition challenges is the reclamation of farmland by using reservoir sediments through periodic harvesting for rehabilitating degraded soil. Like any other intervention, an appropriate project concept with sound design and planning can significantly reduce the risks or at least minimize problematic factors involved reducing life-spans of reservoirs, as is discussed.

Part IV - Making livestock, energy and forestry sectors climate smart

Part IV discusses climate smart sectoral approaches, with two chapters out of six dedicated to livestock, energy, and forestry sectors.

Chapter 10 defines and elaborates the application of integrated technical and non-technical best-fit options of livestock production system. The best-fit technology options focus on modifying livestock diversity and number and improved management, breed, and feed, while the non-technical options include developing and implementing appropriate policies, local bylaws, and indigenous knowledge on livestock production systems. Integrating these approaches, together with effective surveillance and rapid response strategies, could play a major role in developing climate change adaptation and mitigation strategies and help build a resilient livestock system.

Chapter 11 discusses the concepts of participatory rangeland management, drought cycle management, and rangeland carrying capacity in the pastoral context of Ethiopia with a focus on achieving climate-smart pastoral and agropastoral development. With the rising concern of climate change and the rapidly increasing human population, the sustainable utilization of arid and semi-arid rangelands in Ethiopia and other countries in Sub-Saharan Africa is of great concern. It is crucial to develop participatory rangeland management tools through relevant policies, legislation, and other decision-making processes that can enhance the future productivity, sustainability and resilience of rangelands.

Chapter 12 examines women's workload in rural areas, vis-à-vis the collection and use of fuelwood, based on the analysis of quantitative and qualitative data collected from a survey of female-headed households in northern Ethiopia. The results revealed that women significantly participated in fuelwood collection and other household activities. Most rural Ethiopians rely on fuelwood as a primary source of energy. The high demand for fuelwood not only causes sustainability concerns but also highly gendered resource allocation challenges. The authors call for empowering women through developing and improving access to human and physical capital/assets to help them make wiser decisions on allocation of their limited time and resources.

Chapter 13 introduces concepts of climate-smart energy approaches based on a review of pertinent literature. The chapter discusses four climate-smart energy options: biogas, agroforestry, use of improved or fuel-efficient biomass cookstoves, and switching (transiting) to modern/renewable energy sources. Climate smart energy use is among the potential approaches for simultaneously achieving sustainable food production and consumption, reducing GHG emissions, and increasing carbon storage to make agriculture and landscape systems more resilient to the negative impacts of climate changes. Integrating climate-smart energy approaches into agriculture and improved landscape restoration can offer multiple benefits, including improved food security, livelihood and ecosystem resilience.

Chapter 14 uses household surveys to examine the potential role of forests for farm households to cope against erratic weather and idiosyncratic health shocks at the margins of protected forests in the northern highlands of Ethiopia. Analyses of the household survey data revealed that the households affected by idiosyncratic and covariate shocks were significantly more dependent on forest resources as a source of their incomes than those not affected, broadly confirming a significant role of forests as "insurance" by providing households with safety nets. Climate change projections would necessitate urgent actions for communities to collectively hedge against climate risks through climate-smart sustainable forest management.

Chapter 15 elaborates on the principles and potentials of climate-smart forest (CSF) management as a means to achieve multiple livelihoods and ecosystem benefits, while helping residents in SSA adapt to the new realities of climate change. The authors call for considerable efforts to enhance the capacities of communities to make CSF a reality, in order to help realize sustainable development goals.

Part V - Tailoring climate smart approaches to livelihood contexts to enhance adoption and scale-up

The five chapters in Part V review and examines factors that can prevent the adoption and wider scale up of CSA among smallholder farmers.

Chapter 16 provides a critical synthesis on key biophysical, social, economic, and policy constraints that affect farmers' investments in the adoption of climate-smart land management technologies and practices. These constraints are grouped into three broad categories: incentives to invest (e.g., net and relative returns, risks, discount rate and biophysical factors); capacity to invest (e.g., landholding, labor, finance and physical capital); and external factors (e.g., technology, extension services, land policy, political instability, and infrastructure programs) in order to help guide and facilitate the design of informed policies.

Chapter 17 presents a case study that examines the impact of weather index insurance on smallholder farm input investments to see the relation between new technologies and productivity in Adiha, Northern Ethiopia. Among the constraints that affect incentives to invest among smallholder farmers, unfavorable weather is considered the single most important risk. Index-based agricultural insurance has been viewed as a viable risk-management tool for low-income farmers to address weather risk. The findings of this study revealed that participants who had this type of insurance were more likely to adopt yield-enhancing inputs than were their counterparts, suggesting the potentials of appropriately designed risk management mechanisms would offer significant economic incentives for farmers to adopt CSA technologies.

Chapter 18 explores the ways in which the capacity to invest (e.g., landholding, labor, finance, and physical capital) in new agricultural innovations can be significantly affected by gender, as women are often disadvantaged in terms of access to technologies, resources, information, and power in current African rural contexts. The authors argue that not only conventional agriculture technology interventions but also CSA approaches often fail to take in to account the differences in the needs and capabilities of men and women to adapt to climate change, but instead have an implicit male bias in the distribution of opportunities and resources. Hence, this chapter aims to foster the understanding of the various roles and responsibilities of women in designing and implementing gender-sensitive CSA interventions to achieve a sustainable food-energy system.

Chapter 19 reviews and assesses current macroeconomic policies, strategies, and development approaches in Ethiopia and whether they contribute to climate change adaptation by expanding livelihood opportunities and reducing vulnerability. The author of this chapter discusses the special importance of policies for decent economic performance for reducing poverty and to build farmers' wealth, assets, and access to institutional services, and explores how this is fundamental to enable farming communities to adopt CSA for strengthening livelihoods.

Chapter 20 synthesizes relevant latest national policies, strategies, and programs related to agriculture, climate change, and sustainable natural resource management in Ethiopia. It also highlights global conventions and initiatives that Ethiopia has adopted to support agricultural development and sustainable natural resource management. Ethiopian national policies and institutions have been gradually evolving in favor of scaling up of CSA. However, stakeholders are often unaware of these policy developments thus cannot take advantages of these enabling conditions. A common understanding of latest policy environment is critical for all the stakeholders to achieve political goals through wide-scale adoption of climate-smart agricultural approaches.

Part VI - Facilitating decision-making

Part VI introduces potentially useful tools to help stakeholders, especially policy makers, and donors implement ex-ante assessment in prioritizing target areas for CSA practices, technologies, and policies, or introduce new technologies, especially non-native species, into specific local conditions.

Chapter 21 presents the benefits of utilizing long-term satellite data to analyze the potentials of targeted land management and restoration measures for improving land productivity in SSA. This approach and framework can be used to design suitable land-use planning for the restoration of degraded hotspots and to perform detailed cost-benefit and trade-off analysis of various interventions. Using land degradation hotspots identified by satellite and climate data (covering the period of 1982-2003), the study simulated the potentials of different management measures in tackling land degradation in SSA. Scenario analysis results show that about 14 million people can benefit from the application of sustainable land management techniques, although this intervention requires considering the needs of about 8.7 million people in so-called "marginal" areas.

Chapter 22 uses practical experiences with *Jatropha curcas* L. to explore biofuel crops invasiveness risk assessment. Biofuel crops are highly promoted as economic solutions to satisfy global energy needs and as an alternative means to fight climate change and reduce GHG emissions. Some studies have warned about the risk of biological invasions and environmental damage in tropical habitats as a consequence of land conversion to biofuel crops. In this context, there is a need to develop ways to select and manage biofuel crops as components of resilient agro-ecosystems, which balance economic profits and ecosystem wellbeing in the changing climate. The authors of the chapter present effective methodologies on how to assess the invasiveness risk of biofuel crops in the field, based on field experiences from southern and western Africa.

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PART I. Setting the Scene

Photos (clockwise, from top left): landscape, Amhara Region, Northern Ethiopia; agroforestry practices in Southern Ethiopia; collecting Frankincense in dryland forest dominated by Boswellia papyrifera, Central Tigray; and women participating in soil and water conservation practices, East Oromia (all photos by Aklilu Negussie).

1. Climate-Smart Agriculture for Ethiopia and Beyond

Kidane Georgise[a], Aklilu Negussie[b], Emiru Birhane[c], Kiros Meles Hadgu[d], Badege Bishaw[e], and Miyuki Iiyama[f,g]*

Summary

Smallholder farming systems in Sub-Saharan Africa (SSA) have been characterized by low crop yields as well as their reliance on ecosystem services. With chronically stagnant productivity, accommodating the growing demand for food, fuel, and income sources for a population that has doubled in the last decades has mainly been accomplished by the expansion of agricultural land (through clearing forestland) and/or by increasing cropping intensity through reduced fallows and mining of soil nutrients. Consequently, soil degradation has increasingly threatened the resilience of the ecosystems on which African smallholder agricultural systems have critically depended for their food security. African smallholder systems, which have already been stressed by unsustainable use of natural resources, are further threatened by climate change. The climate-smart agriculture (CSA) approaches advocate for the use of locally evolved and/or improved technologies, practices, and policies that can result in increased yield per unit area, as well as sustainable environment; combined, these approaches can meet the needs of growing populations while also maintaining resilient ecosystems. There is a broad range of diverse, climate-smart interventions, yet their individual efficacies may depend on how well they align with locally specific livelihood needs and contexts. The primary objective of this book is to provide guidance for academic, research, outreach, policy and development stakeholders to select specific (if possible) evidence-based CSA technologies, practices, and policies, or a mix thereof, to improve smallholder food production and sustain ecosystem services in Ethiopia and SSA countries. This chapter specifically elaborates on the rationales for why CSA approaches are needed, in the context of Ethiopia and SSA countries, to not only improve agricultural productivity and advance climate adaptation and mitigation goals, but also to simultaneously identify and address root causes of low soil fertility, high rates of soil erosion on farmlands, overall landscape degradation, and low and stagnant agricultural productivity, which often result in household food insecurity and poverty.

Keywords: climate smart agriculture (CSA), CSA at plot-farm scale, CSA at landscape scale, sectoral CSA approach, adoption and scale-up, decision making tools

1.1 Introduction

Smallholder agriculture sectors in Sub-Saharan Africa (SSA) have been characterized by a high degree of heterogeneity and diverse combinations of crop and livestock activities with diverse degrees of integration corresponding to locally specific agroecological conditions (IAC 2004, Giller 2013). One of the key common features of smallholder farming systems in SSA is the heavy reliance on ecosystem services—soil, water, and other natural resources (Mijatović et al. 2013)—combined with a low level of agricultural inputs and consequent low or stagnant crop yields, compared with the rest of the world (Tittonell and Giller 2013, Vanlauwe et al. 2014).

Over the last 30 years, the population in some African countries has doubled, with an increasing demand for food, energy, and sources of income (Himeidan and Kweka 2012). With stagnant growth of agricultural productivity in the smallholder sectors, accommodating this growing demand has been met by the expansion of agricultural land through clearing forestland and/or by increased cropping intensity through reduced fallows and mining soil nutrients without replenishing them through organic and inorganic fertilizers. Consequently, severe soil degradation has increasingly threatened the resilience of the ecosystems on

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[a] Ethiopian Institute of Agricultural Research (EIAR), Addis Ababa, Ethiopia

[b] WeForest, Ogentroostlaan 15, B-3090 Overijse, Belgium

[c] Mekelle University, College of Dryland Agriculture and Natural Resources, Department of Land Resource Management and Environmental Protection, P.O. Box 231, Mekelle, Ethiopia

[d] World Agroforestry (ICRAF) - Ethiopia, c/o ILRI Ethiopia, P. O. Box 5689, Addis Ababa, Ethiopia

[e] Oregon State University, Corvallis, OR 97331 USA

[f] Japan International Research Center for Agricultural Sciences (JIRCAS), Ohwashi, Tsukuba, Ibaraki 305-8686, Japan

* *Correspondence:* Miyuki Iiyama (email: miiyama@affrc.go.jp)

which African smallholder agricultural systems depend for food, energy, and sources of income (Debela et al. 2015, Muller 2014, Perrings and Halkos 2015). Soil degradation is one of the key constraints for crop yield improvement in SSA smallholder systems because it nullifies the effects of investments in improved seeds, fertilizers, and irrigation (Tittonell and Giller 2013). Further, the region's population is projected to grow at the fastest rate in the world by the year 2050 (United Nations Department of Economic and Social Affairs, Population Division 2017), posing enormous challenges in achieving food security for current and future generations, unless ecosystem functions are maintained or rehabilitated and farm productivity is improved (Pretty et al. 2011, Tittonell and Giller 2013).

African smallholder systems are already stressed by the unsustainable use of natural resources and are also increasingly threatened by climate change. Climate change directly affects smallholder farmers in rainfed systems by increasing the risk of crop failure due to widespread changes in rainfall and temperature patterns, as well as frequent and extreme drought and flooding events (Lipper et al. 2014). Increased climatic variability challenges farmers' coping abilities, while the impacts of extreme climate events can be long-lasting. Increased climate uncertainty also affects investment incentives for farmers and reduces the likelihood of effective farm innovations (Lipper et al. 2014). Such climate threats and risks are even worse in SSA countries, where many rural people still live in extreme poverty (Debela et al. 2015). A business-as-usual modus operandi is no longer an option in the face of climate change, which is posing higher risks to food security (Lipper et al. 2014). Therefore, SSA smallholder farming systems need to sustainably produce more food, energy, and sources of income from the same areas of land in order to support the growing population, while simultaneously reducing the negative environmental impacts of land use. At the same time, they must also increase their contributions toward sustaining ecosystems, which is essential for adapting to and mitigating increasing climate risks (Pretty et al. 2011, Lipper et al. 2014). It is of paramount importance for African smallholder farming systems to consider climate change when devising core interventions for restoring soils and the natural resources, thereby sustaining food production and ecosystem services (Lipper et al. 2014, Debela et al. 2015).

Recently, climate-smart agriculture (CSA) has attracted great interest from governments and research and development stakeholders in SSA countries that seek to increase sustainable production and build and strengthen farmers' resilience to climate shocks, while also reducing agricultural greenhouse gas (GHG) emissions and increasing carbon sequestration (Thornton et al. 2018). CSA approaches advocate the use of improved technologies and practices by considering and building on traditional ecological knowledge. This can result in increased yield per unit area and foster a sustainable environment that enables policymakers to assist land managers in meeting people's food, energy, income, and other needs, while maintaining the natural ecosystem. In application, CSA calls for a set of actions by decision-makers, from the farm to the global level, to enhance the resilience of agricultural systems and livelihoods, which reduces the risk of food insecurity now, as well as in the future (Lipper et al. 2014). In turn, there exists a range of diverse technologies, practices, and policies that can be "climate-smart," yet their efficacy may depend on whether they match with locally specific livelihood needs and contexts (Iiyama et al. 2018). There is a strong demand for guidance among SSA countries and stakeholders in how to best prioritize which specific climate-smart technologies, practices, and policies would effectively address specific issues, and if necessary, how to tailor these approaches to locally specific contexts with an appropriate set of enabling factors (Thornton et al. 2018).

The primary objective of this book is to provide such guidance for academic, research, outreach, policy, and development stakeholders in selecting specific, if possible, evidence-based and climate-smart technologies, practices, and policies that can be used to sustain smallholder food production and ecosystem services, with special focus on Ethiopia and other SSA countries. This chapter introduces a theoretical overview of CSA principles and concepts and also elaborates on the rationales for why CSA approaches are needed in the Ethiopian context and beyond.

1.2 Climate Smart Agriculture – Principles and Concepts

1.2.1 Three principles of CSA

Climate smart agriculture is an approach to guide the management of agriculture in the era of climate change, while its definitions and applications are often coined on the ground with sustainable agricultural development strategies (Lipper and Zilberman 2018, FAO 2018). This book generally adopts the definition of CSA used in Lipper et al. (2014), integrated with the definition of sustainable intensification (SI) from Pretty et al. (2011), which supports efforts, from local to global levels, for agricultural systems to achieve food and nutrition security for all people, at all times, while maintaining ecosystem services and ecosystem resiliency. According to Lipper et al. (2014) and Thornton et al. (2018), CSA's goal is to achieve sustainable agricultural development for food security via three "pillars", i.e., productivity, adaptation, and mitigation, as elaborated below:

- Sustainably increasing agricultural productivity from crops, livestock, and fish to contribute to achieving food and nutritional security, as well as higher incomes, while reducing negative environmental impacts and, at the same time, increasing contributions to natural capital and the flow of environmental services
- Adapting to climate change, with a focus on reducing exposure to short-term risks, enhancing capacity to adapt and develop in the face of shocks and long-term stresses, and maintaining healthy ecosystems that provide environmental services to farmers
- Reducing and/or removing greenhouse gas emissions where possible, including through reducing emissions for each kilogram of food, fiber, and fuel produced; avoiding deforestation from agriculture; and managing soils and trees in ways that enhance their potential as carbon sinks, thereby absorbing CO_2 from the atmosphere.

1.2.2 Conceptual elements to prioritize CSA interventions

There are diverse CSA practices, technologies, and policies, ranging from soil and water management at the plot/farm scale and watershed/landscape natural resource management to policy mechanisms for low-carbon agriculture. According to Thornton et al. (2018) and FAO (2018), some CSA practices, such as integrating N-fixing agroforestry species, can simultaneously produce "triple-win" outcomes: increased productivity in combination with reduced impacts to climate risks and shocks and mitigation of climate change through reduced GHG emissions. In turn, others more often involve trade-offs between the three pillars. For example, the introduction of conservation agriculture in agro-pastoral systems may create competition for crop residues between covering crops and grazing animals, unless grazing management is also changed to zero-grazing and improved animal breeds and fodder species are also introduced. As such, given a significant heterogeneity in African smallholder systems in terms of agro-ecological contexts and institutional/political settings, there are no CSA practices that will fit all situations. In other words, CSA is not a "one-size-fits-all" approach that can be universally applied, but involves different elements embedded in local contexts (FAO 2018). More often for sectoral interventions, CSA is rather an approach for integrating multiple interventions across different spatial/temporal scales and value chains instead of just a set of single practices, technologies, and policies (Lipper et al. 2014, Scherr et al. 2012). This, in turn, takes advantage of maximizing ecosystem services derived from different components, as elaborated in Chapter 2.

Prioritizing research-for-development activities is crucial given the need to utilize scarce resources as effectively as possible (Thornton et al. 2018). In this book, we have adopted some of the conceptual elements proposed by Thornton et al. (2018), which are (1) identifying system entry points and impact pathways, and (2) defining the spatial and temporal scales of the research. In this chapter, we modified the conceptual elements to categorize and prioritize climate-smart technologies, practices, and policies across scales (Figure 1.1).

First, the problems identified are considered as entry points for interventions, along with the hypotheses and assumptions regarding the way in which such interventions can lead to desired outcomes (behavioral change). Appropriate entry points may relate to specific challenges of low and stagnant productivity due to nutrient depletion or inadequate water supply in cropping systems, as well as soil degradation due to extensive forest clearing and/or uncontrolled exploitation of natural resources. Second, the spatial scales of research and interventions must be defined, given that specific activities have different spatial (and time) scale dimensions, while a combination of different activities often has impacts over multiple scales. For example, agronomic interventions to address soil nutrient depletion to improve crop productivity may operate at the plot-farm scale, requiring provisions and guidance of appropriate inputs, as well as enabling conditions for farmers to adopt technologies and practices. The restoration of degraded soil ecosystem services, however, may require interventions not only at the farm scale, through conservation agriculture practices (i.e., applying mulch, minimum tillage, and cover crops), but also at the landscape scale, calling for institutional and policy arrangements to mobilize communities and common resources.

Thornton et al. (2018)'s conceptual framework, noted above, continues with the following numbered steps: (3) to determine research questions; (4) to estimate production, adaptation, and mitigation; (5) to estimate other environmental and social impacts; and then (6) to assess enabling factors for research outputs to achieve impact. However, for this book chapter we have instead adopted the following steps with respective conceptual elements:

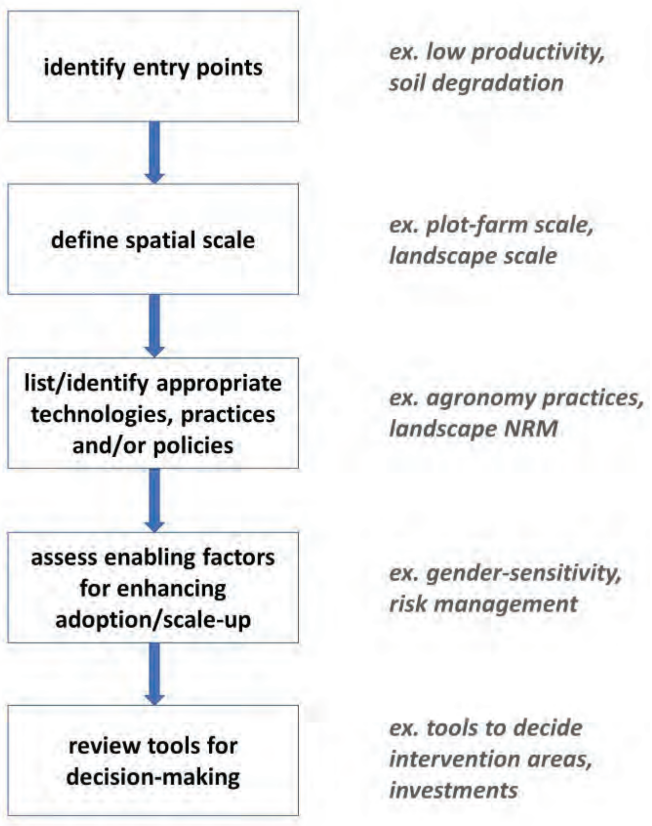

Figure 1.1 Conceptual elements in the CSA priority-setting framework (modified from Thornton et al. 2018).

to list/identify appropriate technologies, practices, and/or policies; to assess enabling social, economic and political factors for enhancing adoption and scale-up of proposed interventions; and then to make an inventory of tools to facilitate decision making, for example, to identify target areas and to invest in particular climate-smart approaches.

1.3 CSA Interventions for Ethiopian Context and Beyond

1.3.1 Setting the Scene

Ethiopia, located in the tropics, has wide ecological variability that ranges from arid and semiarid tropical lowlands to cool afro-alpine highlands and mountains (Mekasha et al. 2014, Hurni et al. 2016), as shown in Figure 1.2. Accordingly, smallholder farming systems and associated land uses exhibit significant heterogeneity. Reliable crop production in the warmer and drier lowlands in the southeast, eastern, and northeastern part of the country is constrained by low and erratic rainfall, and thus, these lands are used for extensive pastoral livestock production. On the other hand, the highland plateau and mountains above 1,500 m.a.s.l., which constitute less than 40% of the total land area of the country, are frequently under extensive mixed crop-livestock production systems. In between these two systems, there are transitional areas, known as agro-pastoral areas, that share the properties of both pastoral and mixed crop-livestock systems (Mekasha et al. 2014).

With an estimated population of over 107 million in 2018, Ethiopia is the second-most populous country in Africa after Nigeria (FAOSTAT 2018). The Ethiopian economy is significantly agriculture-based. The agriculture sector contributed 34% of the country's GDP and accounted for 68% of its employment, as of 2017 (World Development Indicators 2018). The sector is dominated by rainfed smallholder farming practices of mixed crop-livestock farming (Georgis et al. 2010). Still, 45% of the population is below the poverty level with USD $5.5 per day, while in 2015 the figure was 27%, at USD $3.2 a day (WDI); the majority is found in rural areas. Over the last few decades, deforestation and forest degradation have increased, driven by agricultural expansion to meet the growing demand for food, fuel and income by the growing population, along with free grazing, urbanization, industrialization, and a weak policy framework (Gashaw et al. 2015; 2017). Deforestation and forest degradation, in turn, have led to soil degradation and soil erosion. Soil erosion has been the most serious ecological problem observed in Ethiopia, degrading the precious soil resources, which are the basis for improving agricultural production and also for enhancing numerous other ecosystem services. Most soil erosion in the country has occurred on cultivated land, especially on steep slopes, as well as along gullies, in the form of sheet and rill erosion. This has resulted in annual soil losses estimated at over 45 t/ha and up to 237 t/ha year–1, which is much higher than the tolerable limit of 10 t/ha. It has also occurred on rangelands and even in forests that have not been properly managed (Hurni et al. 2016, Tamene et al. 2017, Gashaw et al. 2017).

Most rainfed agriculture in Ethiopia is characterized by a highly variable rainfall distribution and low soil fertility (Mekonnen and Abebe 2014). For millennia, farmers in Ethiopia have coped with drought and famine through their traditional ecological knowledge, for example, by using different drought-resistant varieties and shortening farming seasons by using early crop varieties. Recently, however, climate change is posing increasing threats to the food and nutrition security of Ethiopian smallholder farmers, who are facing greater difficulties in adapting to changing climate patterns, shocks, and disasters (Debela et al. 2015). There is evidence that food production trends in the country are highly correlated with rainfall patterns;

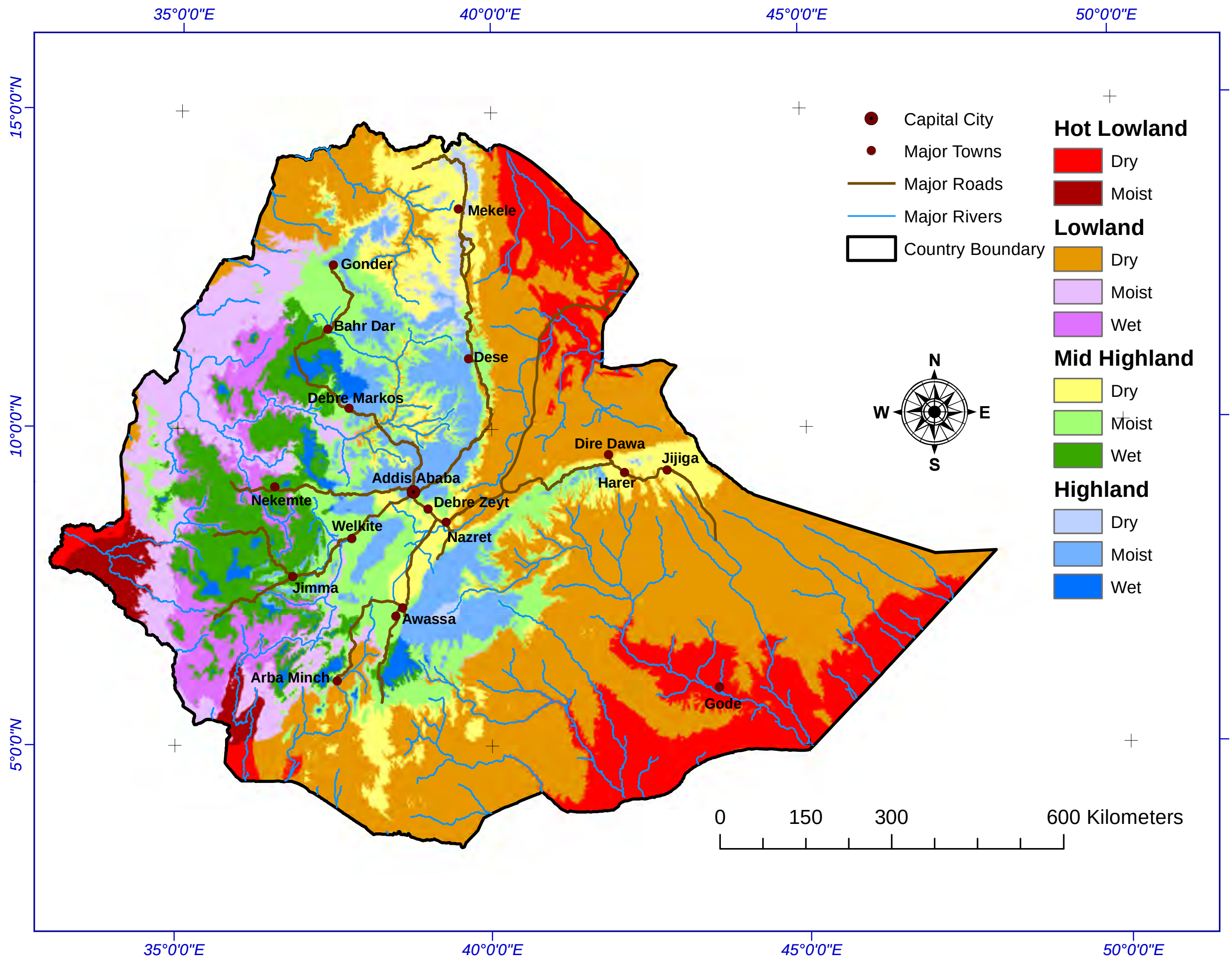

Figure 1.2 Ethiopia agro-ecological map (after Hurni et al. 2016).

the effects of this relationship have resulted in reduced yields and increased incidence of crop failure (Alemu and Desta 2017). The effects of climate change have been aggravated by soil degradation, which contributes to the loss of ecosystem services and makes the Ethiopian smallholder systems more vulnerable to climate and livelihood shocks.

With the trend of an increasing population, at a rate of 2+% annually (United Nations Department of Economic and Social Affairs, Population Division 2017), the country's per capita natural resource bases may consequently decrease as well. If this issue is not addressed in a timely and sustainable way, the disasters caused by an increasing population coupled with the problems of climate change and soil degradation will pose a challenge to attaining Ethiopia's envisioned Sustainable Development Goals (SDGs) to reduce poverty through achieving food and nutrition security. To address these challenges, Ethiopia needs to adopt CSA approaches to not only improve productivity, adaptation, and mitigation goals, but also to simultaneously identify and address key root causes (e.g., low soil fertility, high rates of soil erosion on farmlands, overall landscape degradation, and low and stagnant agricultural productivity) that often result in food insecurity and poverty. Due to the diverse agroecologies and heterogeneous crop-livestock systems across the country, there will not be a single, silver-bullet CSA technology, practice, or policy that will address all of these problems. The country should, therefore, consider appropriate sets of CSA interventions at relevant scales that are selected and tailored to local specific contexts and livelihood needs. Guided by the conceptual elements discussed in Section 1.2.2 and referring to Figure 1.3, the rest of this section discusses and elaborates on the rationales for selecting and adopting the diverse sets of CSA interventions most urgently needed in Ethiopia.

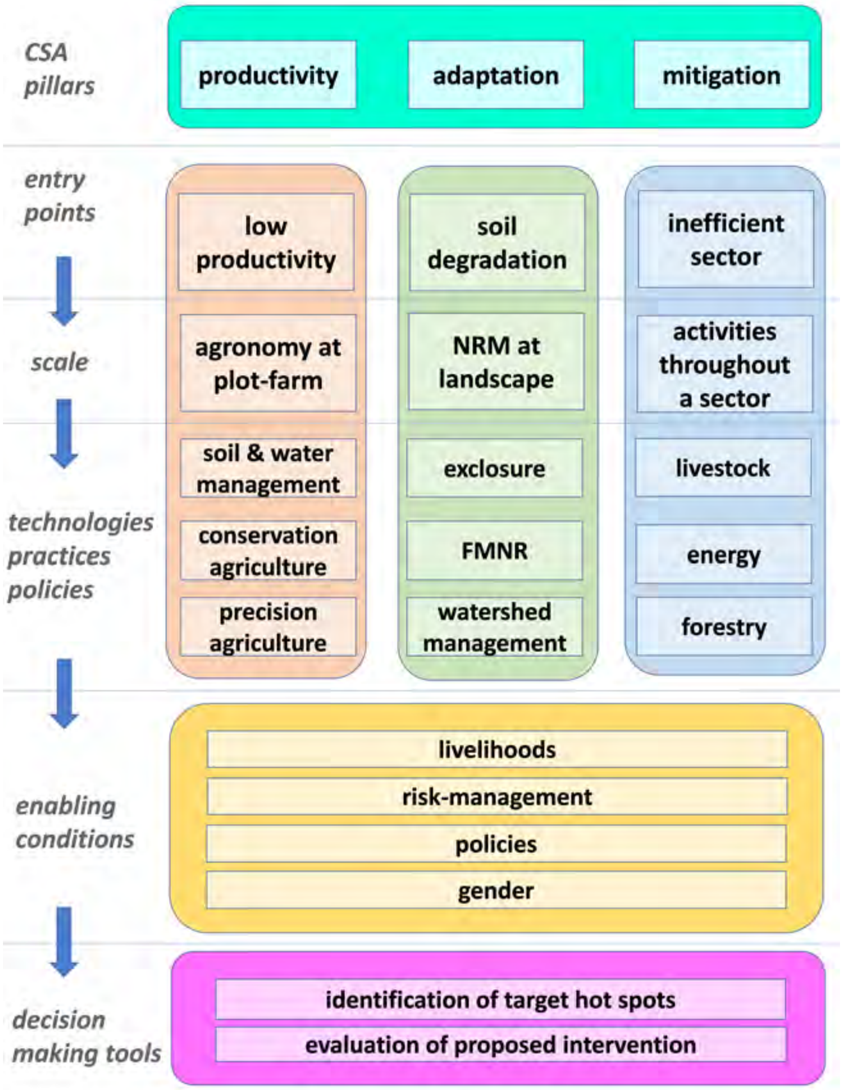

Figure 1.3 Climate-smart agriculture (CSA) interventions for an Ethiopian context—a conceptual framework.

1.3.2 Improving productivity and resilience of smallholder agriculture at plot-farm scale

Traditionally, livelihood security among smallholder farmers in Ethiopia is dependent on rainfed agriculture. However, inadequate and erratic moisture distribution during the growing season has been a major constraint for crop production (Yemenu et al. 2014, Yosef and Asmamaw 2015). Furthermore, the conventional cultivation practices, such as excessive tillage, overgrazing, and the complete removal of crop residue at harvest, leave the soil unprotected and trigger soil erosion, particularly during rainy seasons. Consequently, soil fertility is declining at an alarming rate, which is a key challenge contributing to the reduction of agricultural productivity in most parts of Ethiopia (Vanlauwe et al. 2010).

To meet the increasing demands for food in Ethiopia, applications of fertilizers have been recommended in order to restore the low soil fertility of farms along with *in situ* soil and water conservation during the growing season to increase the amount of available soil moisture, which in turn determines nutrient uptake and crop yield. However, the significant spatial variability of soils within farms and the wide variability in crop responses to organic and inorganic fertilizers mean that the application of fertilizer should not be a blanket recommendation for all areas of all farms. The application of the same rates of fertilizer to all farms results in a less effective but more expensive approach (Kihara et al. 2016). The soil type and texture, as well as the history of land use determine the type and amount of nutrient application for the soil (Vanlauwe et al. 2015). However, a limited understanding of the spatial variability of soils and knowledge gaps regarding the appropriate levels of nutrients and water to apply to different crops under various soils in Ethiopia have prevented resource-poor farmers from adopting appropriate integrated water and soil fertility management practices.

Given climate change projections for increasing variability of precipitation patterns, an in-depth understanding of agronomic practices and management options, particularly water and nutrient management options, is urgently required to improve and stabilize crop yields and, thus, to achieve food security in Ethiopia. It is, therefore, of paramount importance to promote locally specific and agroecology-based CSA technologies and practices that will contribute to water management and soil fertility enhancement at the plot-farm scale (Vanlauwe et al. 2015). To improve sustainable agricultural production as well as adaptation to and mitigation of climate change, CSA technologies and practices at the plot-farm scale should consider and build on existing, local agroecological practices and knowledge. As one example of CSA technologies and practices at the plot-farm scale, sustainable intensification practices that build on existing agricultural lands have considerable adaptation potential because they improve livelihoods, as well as mitigation potential, because they reduce the conversion of forests and wetlands (Lipper et al. 2014). Other examples include *in situ* and ex situ water harvesting technologies; integrated soil fertility management through the use of legumes for enhancing nitrogen fixation and the efficient use of mineral fertilizers; precision agriculture, which optimizes soil and water management to locally specific conditions; and the integration of conservation agriculture (CA) into *in situ* crop residue management (Kidane et al. 2012, Gebreegziabher et al. 2009, Lemma 2005, Mekonnen and Abebe 2014). To increase crop production, it is important to consider local demand and context-specific CSA technologies and practices, for example, by selecting drought tolerant, early maturing, and drought resistant crops, as well as by integrating multipurpose tree/shrub species that provide multiple benefits.

1.3.3 Enhancing ecosystem resilience at landscape scale

In Ethiopia, natural resources and their habitats are highly degraded (Perrings and Halkos 2015). Agricultural expansion and free grazing have driven deforestation and forest degradation. Most notably, deforestation is causing accelerated soil erosion, which negatively affects agricultural production and income sources. In the Ethiopian highlands, Zeleke and Hurni (2001) reported an estimated soil loss of 1,493 million tons per year, while Taddese (2001) indicated grain yield loss of up to 1.5 million tons per year. In Nile basin watersheds, Gashaw et al. (2017) estimated annual soil losses of up to 237 tons ha^{-1}. Erkossa et al. (2015) reported on the loss of grain yield of maize (*Zea mays*), and projected that farmers in Nile basin watersheds might lose up to USD 220 ha^{-1} (Erkossa et al. 2015). Sonneveld and Keyser (2003) forecast a 10% reduction in the production potential of the agricultural lands in Ethiopia in 2010 and a further reduction of 30% in 2030. Consequently, the value added per capita per year in the agricultural sector in the country might decrease from USD 372 ha^{-1} in 2010 to USD 162 ha^{-1} in 2030 (Sonneveld and Keyser 2003).

In order to make the degraded areas resilient and productive, restoration at the landscape level should be prioritized through integrating CSA technologies and practices for creating a climate-smart landscape that provides multiple ecosystem services (Warren 1998). CSA technologies and practices not only improve productivity, as well as the adaptation to and mitigation of agricultural systems to climate change (Lipper et al. 2014), but also that of landscapes, which support multiple ecosystem services. For conserving natural resources at a landscape level and for increasing agricultural productivity in the lower slope of the landscape, Georgis (2009) reported on integrated watershed approaches, which can be used as examples of landscape-level CSA applications. Furthermore, a study by Seka and Mohammed (2016) in Southern Ethiopia showed that the implementation of soil and water conservation structures in sloppy areas in the upper landscapes reduced the sediment yield by 50%, compared to landscapes with no conservation structures. In addition, integrating trees into landscapes can help to reduce soil erosion, increase nutrient availability in soils, and sequester carbon. As one example of CSA technologies and practices, the use of trees at both the plot-farm and landscape scales were found to increase the resilience of ecosystems, while also storing carbon in the soil and tree stems (Iiyama et al. 2017a).

To optimize the multiple benefits of trees, it is important to promote tree planting and regeneration at the landscape scale, which requires some institutional arrangements and coordination at community-landscape levels. Promising landscape natural resource management (NRM) approaches in the Ethiopian context include exclosures, which prohibit people and livestock interference on hillsides and mountainous areas protected for restoration purposes, and farmer managed natural regeneration (FMNR), which is a systematic regeneration and management of underground vegetation with live roots and seeds within the soil. These practices have already been successfully applied in some parts of northern and southern Ethiopia, but they should also be considered and applied in other parts of the country that have similar agroecologies. To ensure sustainability of tree planting at the landscape scale and enhance scaling up, it is essential to consider enhancing enabling institutions and policies that support the mobilization of communities and their resources.

1.3.4 Making livestock, energy and forestry sectors climate smart

In Ethiopia, livestock, energy, and forestry sectors are all integral parts of agriculture through their significant contributions to the economy, as well as their strong interconnectedness with social and cultural values. The development of technologies, practices, and policies in one of these sectors can drive land-use changes that may positively or negatively contribute to the impacts of climate change on that sector but may also have multiplier effects in the other sectors.

For example, rearing livestock is not only the main livelihood of pastoralists, but also represents the main component of the GDP of the Ethiopian economy (Tessema et al. 2011, SOS Sahel Ethiopia 2008). Climate change affects livestock production by affecting water accessibility, animal nutrition, and health, while also putting pastoral and agro-pastoral communities in Ethiopia in marginal arid and semi-arid agro-ecologies (Harris 2010). Poor livestock management can also negatively affect ecosystems; negative effects may include free-grazing problems that cause land degradation due to excess removal of vegetation, which results in deforestation, and overstocking for a long period, which causes a trampling effect on soils. In addition, animal production contributes to climate change by emitting GHG, such as methane and nitrous oxide.

Energy and forests are also essential for supporting the livelihoods of people. Forests, woodlands, and shrub lands are essential in the provision of ecosystem goods and services (Iiyama et al. 2017a). A substantial proportion of the Ethiopian population relies on wood fuels from forests and woodlands as its primary energy source. Most rural households use fuelwood as a main source of energy and as a safety net when facing risks. Recent urbanization has seen a massive increase in the demand for charcoal, produced by harvest from trees, which thus drives deforestation and degradation across extensive rural landscapes (Iiyama et al. 2017b). Furthermore, high returns from alternative land uses and a lack of payments for ecosystem services from forests provide incentives for deforestation. According to the recent report of the REDD+ secretariat (REDD+ secretariat 2016), Ethiopia has recorded a net loss of forest cover, losing an estimated 70,000 ha of forest cover annually (which accounts for 1-1.5% of the total forest cover of the country), compared to the annual forest gain of 30,000 ha /year.

With the increasing threat of climate change, transforming livestock, energy, and forestry sectors into more sustainable systems through the application of a range of climate-smart technologies, practices, and policies becomes imperative. Integrating climate-smart sectoral approaches into different sectors can offer multiple benefits, including improved food security, livelihoods, and ecosystem resilience, by making the whole agriculture-livestock-energy-forestry systems more sustainable and productive. The implementation of integrated climate-smart sectoral approaches requires the mobilization of individual farmers and communities, for example, to collectively invest in sustainable rangeland and forest resource management, as well as to promote the adoption of efficient, climate-smart technologies and practices across the sectors.

1.3.5 Tailoring CSA approaches to livelihood contexts to enhance their adoption and scale-up

The CSA approaches reviewed, so far, include proven, economically viable, and traditionally available technologies and practices such as soil and water management, conservation agriculture, landscape-scale natural resource management, agroforestry, integrated livestock management, sustainable forest management, and more. The wide-scale adoption and scaling-up of CSA approaches, however, has been rather limited to date (Lipper et al. 2014, Hurni et al. 2016). Smallholder farmers in Ethiopia, similar to those in SSA, often face multiple biophysical, social, economic, and policy challenges which affect farmers' investments and the adoption of CSA technologies and practices. Smallholder farmers are often trapped in poverty and are extremely resource-constrained, without any livelihood capital assets. In addition, agricultural innovations often fail to consider the locally specific, varying socio-political and gender contexts that influence farmers' decision-making. Consequently, smallholder farmers tend to adopt too risk-averse behaviors, which prevent the farmers from venturing into climate-smart innovations, if they are not supported by enabling institutional and policy arrangements, including risk-management mechanisms. Adequate, coherent, and supportive policies must also be in place to promote and implement CSA in farming and pastoral communities. To overcome barriers to the adoption of CSA technologies and practices, research embedded in development plays key roles that include, for example, identifying the underlying adoption barriers and designing appropriate adoption strategies by considering locally specific and varying contexts (Thornton et al. 2018, Iiyama et al. 2018).

1.3.6 Facilitating decision-making

CSA technologies, practices, and policies have gained increased interest and attention from Ethiopian policymakers as well as their SSA counterparts. Because implementation of CSA technologies and practices requires resources, Ethiopian policymakers often have to face trade-offs in order to select the most effective interventions for specific contexts and localities. Selecting effective interventions may contribute to achieving the country's development targets, which include improved productivity, adaptation, and mitigation, as well as meeting the Sustainable Development Goals (SDGs). To implement and achieve the multiple benefits of CSA technologies, practices, and policies, ex-ante and operational decision-making tools should be considered. These provide important guides for the selection of improved and appropriate CSA technologies and practices that fit local demands and contexts, not only in Ethiopia but also in many SSA countries (Thornton et al. 2018). At the same time, the introduction of new technologies and practices, especially new crop, tree, and livestock varieties, requires a quick yet thorough environmental assessment prior to their introduction. Stakeholders, including policymakers, development practitioners, and farmers, should be equipped with the appropriate tools, along with improved capacity development in making decisions, in order to adopt optimal portfolios of CSA technologies, practices, and policies based on locally specific resources, contexts, and demands.

1.4 Conclusions

Agriculture is essential for food security and income generation in SSA countries, including Ethiopia. Agriculture is vulnerable to the impacts of recent climate change, which is mainly associated with changing rainfall patterns, repeated frequent floods and droughts, alterations in plant life cycles, outbreaks of pests and diseases, and reductions in fodder and livestock productivity. At the same time, agriculture is one of the principal drivers of deforestation in developing countries and is the second largest source of GHG emissions. With the growing uncertainties of climate change due to both natural and anthropogenic factors, feeding people has become a challenge. Agriculture can play a strategic role in climate change responses, including both adaptation and mitigation approaches, through the implementation of appropriate technologies, which enhance productivity without causing negative impacts on ecosystem services. CSA is both a tool and a strategy that can help achieve the triple win: improved agricultural productivity along with adaptation to and mitigation of climate change. It is an integrated approach that sustainably increases productivity, ecosystem services, and societal resilience; reduces GHG emissions; and enhances achievement of national food security and development goals. The CSA approach seeks to maximize benefits and minimize negative tradeoffs across multiple objectives within agriculture, including food security and climate change adaptation and mitigation.

CSA is gaining increased attention as an advanced approach that addresses the challenges of both climate change and agriculture. Developing countries such as Ethiopia should be encouraged to adopt a range of activities that promote CSA. Currently, there are still knowledge gaps in CSA strategies and efforts to prepare smallholder farmers, both men and women, to cope with climate change and avoid further environmental degradation, however. This book aims to address these knowledge gaps by providing guidance for academic, research, outreach, and policy and development stakeholders to select specific, if possible, evidence-based CSA technologies, practices, and policies, or a mix of them, to sustain smallholder food production, ecosystem services, and livelihoods improvement.

As this chapter reviewed, CSA approaches include a variety of technologies, practices, and policies at different and often overlapping scales. For example, plot-farm scale CSA approaches include agronomy practices to sustainably and effectively utilize soil and water resources, while landscape and sectoral approaches include livestock grazing as well as grassland and forest management through institutional mechanisms. Indeed, the application of CSA approaches should consider a range of plot-farm to landscape scales at different times, while individual CSA technologies, practices, and policies at the plot-farm level can achieve productivity, adaptation, and/or mitigation goals. The integration of different CSA approaches from the plot-farm scale to the landscape scale or even throughout a sector can have large multiplier impacts through the diversity of land uses and activities, as well as their interactions at the landscape/sector scale. To integrate CSA approaches at these scales requires multi-level interventions that involve different stakeholders and actors. The next chapter will explain the key features of integrated climate-smart landscape restoration and management approaches and elaborates on how the diversity of land use at the landscape scale can contribute to climate change mitigation and adaptation through enhancing ecosystem services.

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2. Integrating Climate-Smart Approaches across Landscapes to Improve Productivity, Climate Resilience, and Ecosystem Health

Ayele Almaw Fenta[a]*, Gebrerufael Hailu[b], and Zelalem Hadush[a]

Summary

Climate change is expected to affect agricultural production and food security through changes in rainfall and temperature. The magnitude of the impacts of climate change on vulnerable communities could be significant in the developing world, the economy of which depends heavily on agriculture—which in turn, is also a major source of greenhouse gas (GHG) emissions. On the other hand, the agricultural sector has a large potential to be part of the solution for adapting to and mitigating the effects of climate change, if climate-smart agriculture (CSA) is successfully adopted. CSA approaches require a variety of field and farm practices including soil, nutrient, and water management, along with agroforestry and livestock husbandry. While individual CSA technologies, practices, and policies can achieve productivity, adaptation, and/or mitigation goals, the integration of different CSA approaches from the field-farm scale to the landscape scale can have even larger multiplier impacts. This chapter elucidates the importance of the integrated climate-smart landscape restoration and management approaches in developing countries for achieving productive, sustainable, and climate-resilient ecosystem services. The definition of a climate-smart landscape follows, and is used to guide our arguments. A good climate-smart landscape is characterized by three key features: (1) practices at the field and farm scale, (2) diversity of land use across the landscape, and (3) the management of land use interactions at the landscape scale. The chapter concludes with a call for further research to facilitate scale-up of climate-smart landscape restoration and management.

Keywords: multi-scale maintenance, integrated landscape restoration, climate-smart, ecosystem health, climate change, Ethiopia

2.1 Introduction

Globally, climate change is one of the most serious environmental threats to agricultural productivity (Zabel et al. 2015). Climate change is expected to affect the two most important factors in agricultural production: rainfall and temperature. These factors are crucial to the livelihoods of farmers in most developing countries, where the majority of the population relies on agriculture. Developing countries are expected to suffer the most from the negative impacts of climate change (IPCC 2007). Based on some projections, changes in rainfall, temperature, and severe weather events are expected to substantially affect agricultural production and food security in many regions of the developing world, particularly sub-Saharan Africa (Gornall et al. 2010). The impact of climate change in developing nations is further exacerbated by the countries' low adaptive capacity, which is the limited human, institutional, and financial capacity to anticipate and respond to the direct and indirect effects of climate change (Gebrehiwot and van der Veen 2013a). The magnitude of the impacts of climate change on vulnerable communities could be significant in the developing world, the economy of which depends heavily on smallholder agriculture (Nigussie et al. 2018).

While the agriculture sector is most vulnerable to climate change, it is also a major source of greenhouse gas (GHG) emissions, and contributes about 14% of GHG emissions to the atmosphere; this contribution rises to approximately 30% when forest land is converted to agricultural land (IPCC 2007). Agricultural practices are very different between developing and developed counties, which results in variations in the agriculture sector's contribution to climate change. In developing countries, GHG emissions from

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[a] Mekelle University, College of Dryland Agriculture and Natural Resources, Mekelle, Ethiopia

[b] Mekelle University, Institute of Geo-Information and Earth Observation Science (I-GEOS), Mekelle, Ethiopia

* *Correspondence:* Ayele Almaw (email: almawayele@yahoo.com)

the agriculture sector are much higher than from other sectors because of the large number of cattle, inadequate manure management, improper use of agro-chemicals, and mismanagement of the land (Yohannes 2016).

On the other side, the agriculture sector has a large potential to be part of the solution, and thereby help people not only to feed themselves, but also to adapt to and mitigate the effects of climate change. To this end, adopting climate-smart agriculture seems to be a suitable strategy to achieving food security, while also mitigating and adapting to climate-related risks. Climate-smart agriculture (CSA) includes many of field-based and farm-based sustainable agricultural land management practices (Scherr et al. 2012). However, climate-smart agriculture requires action beyond the field or farm scale and must take a landscape approach. The basic concept of climate-smart landscape restoration and management is a multi-scale maintenance or enhancement landscape for sustainable food production, improved livelihoods, and ecosystem resilience, while also adapting to existing and future climate change and simultaneously reducing GHG emissions (FAO 2010, Beddington et al. 2012, Scherr et al. 2012). Climate-smart landscape restoration and management focuses on landscape-based practices, technologies, and approaches, including climate-smart, integrated, and synergized planning (among other methods) on land, on water, and in agriculture, forests, and fisheries (Baily and Purcel 2012, Scherr et al. 2012).

In countries like Ethiopia, where the agriculture sector supports about 68% of employment and 34% of the gross domestic product (World Bank 2017), development of the sector must undergo a significant transformation. Previous studies (e.g., Bishaw et al. 2013, Gebrehiwot and van der Veen 2013b) have shown that ensuring food security and improving the livelihoods of members of the farming community in the face of climate change is becoming a challenge. Thus, to cope with this existential threat, Ethiopia is undertaking a massive landscape restoration programme, and also has declared its commitment to a green growth strategy, becoming the first African nation to do so. Ethiopia's government is now emphasizing climate-smart agriculture for enhancing resilient and adaptive systems to climate change (Yirgu et al. 2013).

This chapter elucidates the importance, in developing countries, of climate-smart landscape restoration and management approaches, for achieving productive, sustainable, and climate-resilient ecosystem services. The definition of a climate-smart landscape from Scherr et al. (2012) is used to guide our arguments: a good climate-smart landscape is characterized by three key features: (1) practices at the field and farm scale, (2) diversity of land use across the landscape, and (3) the management of land use interactions at the landscape scale. Firstly, key climate-smart practices, technologies, and approaches at field- and farm-scales are described. The following sections elaborate how diversity of land use at the landscape scale contributes to climate change mitigation and adaptation through enhancing ecosystem services, and thus, why landscape approaches should be followed when moving towards climate-smart restoration and management. Next, we discuss the importance of multi-stakeholder negotiations, planning, and policy and financial options. Case studies are presented for illustrating climate-smart, productive and sustainable landscape practices, technologies, and approaches, which are successfully practiced in different parts of Ethiopia. The chapter concludes with a call for further research to better understand the tradeoffs, and to seek compromise in cases where multiple and conflicting objectives of landscape approaches exist in order to scale up climate-smart landscape restoration and management.

2.2 Practices at Field and Farm Level

Climate-smart landscape restoration and management approaches require a variety of field and farm practices on different land and tenure types. These practices may include soil, nutrient, and water management, along with agroforestry and livestock husbandry (FAO 2010, Branca et al. 2011).

Controlling soil erosion: Soil erosion by water and wind removes the most productive topsoil, and it has significant ecological and socioeconomic impacts. Although no region is immune, soil erosion is more severely affecting least developed countries (Borrelli et al. 2017) where livelihoods predominantly depend on agriculture. Adoption of appropriate soil erosion control measures is important to strengthening numerous ecosystem services such as improving water quality and renewability, increasing biodiversity, enhancing soil resilience to climate change, and mitigating climate change by sequestering carbon in soil and reducing the emission of GHGs (Lal 2014). Depending on site-specific conditions, effective soil erosion control measures include conservation agriculture, and minimum- or no-tillage farming practices, combined with a range of soil and water conservation measures that include improving vegetation cover with adapted species; using rotational grazing to sustain rangeland vegetation; contour farming using bunds and diversion ditches; enhancing the roughness of the soil surface; and use of windbreaks. On steeper slopes, soil erosion control requires additional measures, including reducing the degree and length of slopes with progressive and bench terracing; planting cross-slope vegetation; using structural measures, such as terraces, bunds, and tied ridges to enhance water storage and infiltration; and creating grassed waterways to discharge excess water safely off the slopes.

Soil nutrient management: Managing soil nutrients is critical for increasing agricultural productivity and landscape resilience to climate change. This can be done by utilizing minimum tillage, composting, manuring, and crop residues, as well as by using legumes for natural nitrogen fixation (Hobbs and Govaerts 2009, Milder et al. 2011). Such practices increase organic nutrient inputs and are fundamental for reducing the need for mineral fertilizers, which are expensive and thus inaccessible to smallholders (Milder et al. 2011). Maintaining and enhancing the soil organic matter content is also essential for increasing the soil carbon sequestration potential, as soils are the third largest carbon pool on the Earth's surface (Scherr and Sthapit 2009).

Water harvesting and use: For attaining adaptation and livelihood goals of climate-smart, productive and sustainable production systems, more efficient water management is critical. Improved water-use efficiency (e.g., proper irrigation systems) and water harvesting techniques (e.g., pools, dams, pits, and tied- ridges, and roof water harvesting) are fundamental for increasing production and addressing increased irregularity of rainfall patterns (FAO 2010). Investment in irrigation for increasing agricultural production, particularly in semi-arid and arid environments, is therefore important (Nkonya et al. 2011).

Agroforestry: Agroforestry systems provide permanent tree/shrub cover in agricultural lands and can enhance physical, chemical, and biological soil characteristics, thereby improving soil fertility, controlling erosion, and enhancing water availability (FAO 2017). Furthermore, agroforestry can contribute to livelihoods in rural communities through the provision of a variety of food, fodder, and tree products and, hence, can increase the resilience of communities to climatic shocks, including drought and food shortages, as well as help mitigate the effects of climate change (Milder et al. 2011, Bishaw et al. 2013).

Livestock management: Livestock management strategies, such as improved pasture and grassland management (including rotational grazing, stall feeding through a cut-and-carry system, and controlled grazing), can help regenerate vegetation and restore degraded pasture lands, which are critical components for climate change adaptation and mitigation (Biryahwaho et al. 2012). For better manure management, converting manure to biogas provides the added benefit of an alternative energy source with fewer negative health impacts than traditional fuel sources for cooking, heating, and lighting (Scherr et al. 2012).

2.3 Diversity of Land Use Across the Landscape

This feature of climate-smart landscapes includes land use/land cover and species and varietal diversity of plants and animals. According to Scherr et al. (2012), diversity of land use in a landscape has several climate mitigation and adaptation functions, including (1) reducing the risk of crop failures and livelihood losses from harsh climatic conditions; (2) utilizing areas of the landscape strategically, i.e., as food, feed, fuel, and income reserves, at times of emergency; and (3) sustaining minimally disturbed habitats within the landscape, which also serve as a carbon sink.

Reduction of risks of crop failures and livelihood losses: Monocropping systems pose ecological risks such as pest and disease outbreaks and vulnerability to unexpected weather conditions. Introducing a poly-culture or poly-cropping of multi-cropping through crop and varietal diversification can be an option for climate change adaptation (Baily and Purcel 2012). Genetic diversity in crops improves the capacity of some varieties to withstand environmental stresses that are caused or aggravated by climate change (Jackson et al. 2010). Moreover, varietal diversification provides a portfolio of diverse food and income sources from crops, livestock, trees, and non-cultivated lands which can cushion households and communities from climatic (and other) shocks (Bernazzani et al. 2012).

Provision of multi-service functions: Access to diverse sources of food, feed, and employment during episodes of adverse climatic conditions enhances livelihood resilience of households and communities. Wild plant species in farms, forests, and wetlands contribute significantly to the diets of many of the poor in developing countries (Bharucha and Pretty 2010). These food sources, particularly the "famine foods" such as wild greens, tree fruits, and roots, play an important role in supplementing diets during periods of climate-induced scarcity. Bush meat found in forests and fish from freshwater resources can also be important sources of protein when adverse climate conditions drastically impact agricultural systems (Bharucha and Pretty 2010).

Sustaining of perennial habitat as carbon stocks: In addition to annual plant species, maintaining other types of land cover throughout the landscape, such as that found in perennial grasslands, woodlands, forests, and wetlands, improves ecological resilience in terms of watershed function, as well as serves as a habitat for wildlife species, which are important for local livelihoods, tourism, and biodiversity conservation. Maintenance or expansion of land area in these types of perennial systems is one of the most effective ways to sequester carbon and reduce emissions (Scherr and Sthapit 2009).

2.4 Benefits of Climate-Smart Management of Land-use Interactions

One of the important features of climate-smart, productive, and sustainable landscape practices, technologies, and approaches is the management of land-use interactions to enhance climate change adaptation and mitigation. Stakeholders and planners must identify, negotiate, and manage the impacts of land use and management systems on other land uses (and users) of and within a landscape. In this regard, Scherr et al. (2012) identified the benefits that can be derived from managing land-use interactions: (1) enhanced field-level benefits from climate-smart practices, (2) secured ecosystem functions, and (3) enhanced effectiveness of climate mitigation efforts.

Enhanced field-level benefits of climate-smart practices: Agricultural productivity is impacted by land uses around the farmlands, where field margins, riparian buffers, and forest edges can harbor pests, as well as beneficial insects (Harvey 2007). To enhance field-level outcomes, planning of the spatial arrangements of landscape elements is important. For example, forest fragments adjacent to agricultural land uses enhance pollination services. Agrochemicals and sediment should be controlled in order to protect downstream fisheries, while upstream crop, livestock, and forest production can be managed for improving the flow of water for irrigation purposes downstream.

Secured ecosystem functions: Natural habitats such as riparian areas, woodlands, and wetlands can be sited and managed to provide ecological connectivity for water and nutrient flows and improve habitat conditions for wild plant and animal species and beneficial microorganisms. As climate change intensifies, connectivity of wildlife habitats and hydrological resources will become increasingly important as an adaptation strategy (Millar et al. 2007). Agricultural production practices should also support, rather than block, this connectivity.

Enhanced effectiveness of climate change mitigation efforts: In addition to its importance for climate change resilience, managing land-use dynamics across the landscape is critical for ecological rehabilitation efforts. Within the climate community, the land-use interaction of the most prominent concern is that between agricultural and forest systems—specifically within the context of efforts to develop Reduced Emissions from Deforestation and Degradation (REDD) programs. Participation of farmers and other stakeholders in agricultural systems is crucial for climate change mitigation and adaptation practices that seek to sustain forest cover. Although agricultural practices sequester relatively small quantities of GHG compared to forest conservation practices, an integrated landscape and livelihood strategy, which combines agriculture and forest practices, can reduce deforestation and GHG emissions more effectively and sustainably (Scherr et al. 2012).

2.5 Institutional Mechanisms for Implementation of Climate-Smart Landscape Practices

Implementation of climate-smart, productive and resilient landscape practices, technologies and approaches requires at least four institutional mechanisms: (1) multi-stakeholder planning, (2) a supportive policy environment, (3) the promotion of landscape investments through finance options, and (4) measuring and monitoring landscape dynamics to determine whether social, economic, ecological, and climate goals are met at different scales (Scherr et al. 2012; FAO 2013).

Multi-stakeholder planning: Ensuring the participation of all stakeholders is a key step for sustainably restoring and managing landscapes. Facilitating participatory planning and decision-making processes is needed for improved negotiation priorities through recognizing legitimate interests at local, regional, and national levels (Aggarwal et al. 2010). These processes can also provide the opportunity for landscape-based planning, program implementation, and progress monitoring. In addition, a multi-stakeholder process can serve as a means of developing partnerships, consolidating resources, sharing knowledge, building coalitions, and pooling investments (Reed et al. 2016). In climate-smart landscape planning, multiple sectors, including water, agriculture, livestock, energy, and land, as well as stakeholders from environmental finance, planning authorities, producer groups, civil society businesses, and private investors, must be involved (FAO 2013).

Supportive policy environment: Achieving multiple objectives at the landscape level requires a more supportive policy environment. Climate-smart landscapes should be supported by enabling a policy environment in which local stakeholders make key planning decisions that incorporate local needs and priorities (FAO 2013). Science-based decisions by local institutions and organizations increase the achievement of improved landscape restorations and managements, which eventually benefit the local communities. Property rights, use and access rights, and secured land-use systems and resource ownerships are also critical for the successful long-term restoration and management of landscapes, which assists in building a profitable and climate-resilient system (FAO 2010). In contrast, insecure property rights pose a barrier to the adoption of climate-smart practices, as there is little incentive to invest time and money to adopt such practices and transform landscapes (Scherr et al. 2012). In this regard, the current land tenure system in Ethiopia has multiple shortcomings, including the lack of security rights of tenure, absence of equitable access to land over time, and few incentives for investment in improvements or conservation. As a result, Ethiopia's land tenure system has detrimental effects on agricultural productivity and natural resource conservation (Nega et al. 2003).

Promoting landscape investments through financial options: Achieving financial viability for development initiatives assists stakeholders in operating at the landscape level by ensuring they have enough financial resources to do so; this prevents them from engaging in activities detrimental to local ecosystems and sustainable livelihoods (FAO 2013). Public and private investment programs that support climate-smart landscapes may be supported through climate financing programs, which might be incorporated into sectorial funding sources or through a special window of inter-sectorial funding of activities that have climate co-benefits (Scherr et al. 2012). Agricultural investments typically target production and supply chains for particular products based on growing conditions, institutional context, and market infrastructure (Reed et al. 2016). Spatially targeted investments in agriculture can be linked to payment for ecosystem services that further incentivize ecological management and climate resilience (Scherr et al. 2011).

Measuring and monitoring landscape dynamics: It is necessary to measure and monitor the multiple benefits of climate-smart landscape interventions. For investors to invest in climate-smart landscapes, they must understand and able to first communicate the multiple benefits of climate-smart landscape management, which include yield improvements, food and energy security, climate change adaptation and mitigation, human health improvements, biodiversity conservation, and other ecosystem services (Spearman and McGra 2011). Thus, climate-smart landscape initiatives should monitor not only climate indicators, but also the whole suite of climate-smart, productive, and sustainable objectives, as well as the effectiveness of key institutions for achieving the current and future results. Monitoring objectives must be locally defined and cover livelihoods, biodiversity, and ecosystem services. When embarking on climate-smart landscape restoration, the landscape dynamics and the principles and processes of landscape monitoring should be agreed upon among the actors, based on consultative and participatory processes (FAO 2013).

2.6 Conclusions

Integrated landscape restoration and management is fundamental for achieving the multiple objectives of climate-smart landscapes, namely adaptation and mitigation goals, along with improvements in livelihoods and healthy ecosystems. The features of integrated landscape restoration and management include climate-smart, productive and sustainable practices, technologies, and approaches, diversity of land uses, and their management at multiple scales (i.e. field, farm, and landscape scales). Scaling up successful and sustainable landscape restoration and management practices must accommodate driving factors, such as economic, social, ecological, and institutional issues, to support implementation of technologies and practices (e.g., soil and water conservation, exclosures, and afforestation and reforestation) at larger scales. In addition, multi-stakeholder planning, a supportive policy environment, financial options for supporting climate-smart landscapes, and the measurement and monitoring of landscape dynamics determine the achievements of social, economic, ecosystem, and climate goals at different scales. Community-based landscape restoration and management efforts (see Case Study 2.1 on Abreha we Atsebeha, northern Ethiopia, and Case Study 2.2 on Konso, southwestern Ethiopia) demonstrate diverse contexts of landscape restoration, which in turn illustrate the importance of climate-smart landscapes for achieving multiple benefits from climate change mitigation and adaptation practices. Landscape approaches may have multiple and conflicting objectives—for example, conservation versus agriculture, issues relating to emission reductions, biofuel production, and many more. Further research is therefore

Case Study 2.1 Community Restored Landscape in Abreha we Atsebeha, Tigray, Northern Ethiopia

Abreha we Atsebeha covers around 67.65 km^2 in the Tigray region of northern Ethiopia. The area is characterized by a semi-arid climate with a mean annual rainfall of around 565 mm, mean temperature of 21°C, and an altitude of between 1,989 and 2,528 m.a.s.l. Because the area was very degraded and unproductive, the community of Abreha we Atsbeha had experienced recurrent crop failure and had been receiving relief assistance for many years. In the 1990s, the community faced a terrible choice: to relocate, rather than depend on food aid year after year, or to restore the degraded land and enhance productivity. The community preferred the latter alternative.

The landscape approach

In northern Ethiopia (particularly in the Tigray region), community-based land-rehabilitation programs have been widely implemented since 1991 to reverse the condition of the degraded, unproductive land. This was implemented through soil and water conservation, exclosures, reforestation, construction of water harvesting structures, and the establishment of community woodlots. Abreha we Atsbeha is now a model community in the region, and is known for restoring its degraded lands through integrated natural resource conservation and development work. The community worked on three interconnected interventions: soil erosion control, water harvesting, and protecting the hillsides from livestock grazing and fuelwood harvesting. The restoration effort has achieved erosion control and natural resources rehabilitation measures that were absolutely astonishing. They initially built hundreds of kilometers of soil and stone bunds to reduce the flow of water down the hills. Moreover, each family dug a 4 × 4 m pond to conserve water at the household level. In small gullies, the community constructed stone and trench bunds to slow the flow of water and chains of check dams and ponds to trap water and allow infiltration. In each river, they constructed nine check dams. The first three catch silt and the last six hold water, which allows 80% of the community to irrigate crops in the dry season from 650 hand-dug wells. Community members understood that they were banking water for the dry season in the soil, ponds, check dams, and the groundwater. To complement these changes and improve their livelihoods, households planted multi-service tree, shrub, and fruit species.

Benefits of the landscape approach

Improve ecosystem services

Landscape rehabilitation provides ecosystem services, such as increased vegetation cover, groundwater recharge in the flat lands, maintenance of soil fertility, and erosion and sedimentation control. Shallow, hand-dug wells were recharged from water that infiltrated from the upper catchment because of physical and biological conservation interventions. The rehabilitated areas currently have good vegetation cover and can act as a carbon sink, absorbing and storing GHG from the atmosphere to help mitigate climate change, as well as attract interest from the carbon market (Biedemariam 2012).

Livelihood improvement

Livelihood strategies have increasingly focused on ensuring food security and income generation. Landscape rehabilitation has resulted in increased production of wood and tree products, such as vegetables, and fruits, which help to ensure food security and also provide an additional source of income. For example, scattered trees of *Faidherbia albida* (Momona) have multiple benefits in terms of the sale of soil fertility enhancement, fodder for livestock, firewood, timber, and fiber (Biedemariam 2012). Modern beehives integrated into the rehabilitated landscapes enable households to earn additional income from selling organic honey. The community has also established a market chain to sell the honey in Europe at premium prices. The community adopted fuel-saving cooking-stoves to reduce the consumption of firewood. Moreover, the community introduced improved dairy cattle through artificial insemination.

To find out more: see M Biedemariam, KM Hadgu, AA Fenta, E Ayenkulu, K Gebrehiwot and E Birhane. 2017. Landscape level rehabilitation for improved agricultural productivity and ecosystem services in Abreha-we-Atsibeha, northern Ethiopia. *Journal of the Drylands* 7(1): 633–643.

Case Study 2.2 Indigenous Landscape Management in Konso, Southern Ethiopia

Land management in Ethiopia has evolved into various farming systems with different levels of intensification. Indigenous land management is the major feature of Ethiopia's agriculture, which is said to have begun over 2,000 years ago. The indigenous agricultural system in Konso is exemplary: it is characterized by stone-based terraces and well-integrated agroforestry practices. The Konso Cultural Landscape is an arid property of stone-walled terraces and fortified settlements in the Konso highlands of Ethiopia covering about 230 km2. It constitutes a spectacular example of a living cultural tradition stretching back 21 generations (more than 400 years) that is adapted to its dry, hostile environment. Stone terracing provides a typical soil and water conservation structure, covering most of Konso, and land management is highly integrated and implemented within watershed development system.

The landscape approach

The Konso people have developed a combination of soil and water conservation structures, including stone terraces, water harvesting, manuring, intercropping, and agroforestry, in order to obtain food from land that they cultivate permanently and that has fairly low and unpredictable levels of rainfall. As such, the system combines crops, livestock and tree production with interrelated management practices. In Konso, stone terraces have been built through self-motivation and local institutions and from the personal experience of the people, without any external influences or forced labor programs.

Benefits of the landscape approach

Soil and water conservation terraces help to control land degradation, reduce run-off/soil erosion, improve micro-climate, enhance water infiltration, safely discharge excess water, restore soil nutrients, enhance biodiversity, and create terraced fields that are used for agriculture. The terraces cover major parts of the agricultural land in Konso, stretching over tens of thousands of kilometers. The agroforestry pattern developed in the area plays an important role in soil fertility management and food and feed production. The relationship between the stone terraces and the towns of the Konso Cultural Landscape, with its highly organized social system, is an outstanding illustration of traditional human settlement and land use based on common values that have formed the cultural and socioeconomic foundation of Konso.

Policy implications/relevance

Indigenous soil and water conservation methods in Konso are recognized as among the "best practices, " and they contribute to the natural resource conservation strategy of the country. To ensure the protection of these indigenous practices, the Konso people established a traditional code of management that is also recognized and supported by the current administrative system. Management committees have been formed at different levels — both community and district — and a Konso Cultural Landscape Management Office with governmental personnel has been established on site, primarily to address planning, funding, supervision, and conservation tasks. The success of the conservation approaches in the Konso landscape demonstrates the shared values, social cohesion, and engineering knowledge of its communities. Management strategies addressed from within the community may be more beneficial to the community itself.

To find out more: see EE Watson. 2009. *Living Terraces in Ethiopia: Konso Landscape, Culture and Development*. James Currey, Oxford.

important to better understand the tradeoffs in reconciling these objectives to scale up climate-smart landscapes. Even more important is the need to deliberately consider opportunities for synergies between these objectives in order to enhance efficiencies.

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PART II. Improving Productivity and Resilience of Smallholder Agriculture at the Plot-Farm Scale

Photos (clockwise, from top left): plot-level conservation agriculture trials at Mekelle University, Tigray (by Miyuki Iiyama); traditional oxen ploughing, West Shoa, Oromia Region (by Aklilu Negussie); apple cultivation in the Northern Highlands, Tigray Region, Ethiopia (by Aklilu Negussie); and a farmer on a plot, Abraha Atsbeha village, Tigray Region (by Miyuki Iiyama).

3. Conservation Agriculture for Enhancement of Livelihoods and Environments in Ethiopia

Tesfay Araya*

Summary

Traditionally, livelihood security among smallholder farmers in Ethiopia is strongly dependent on rainfed agriculture, with which over 95% of the food is produced. Conventional soil cultivation practices, such as excessive tillage, overgrazing, and complete removal of crop residues at harvest leave the soil unprotected, and therefore trigger land degradation. Practicing conservation agriculture (CA) can help to minimize land degradation, i.e., soil erosion, soil fertility decline, and hydrological challenges, through simultaneously practicing activities such as minimal soil disturbance, crop residue retention, and crop rotation. In addition, CA can help to improve the livelihoods of smallholder farmers while promoting better soil carbon sequestration. Generally, uptake of CA by smallholder farmers is persistently low in Ethiopia due to low degrees of mechanization, a lack of soil fertility management options, and competition for crop residues with other end uses. In turn, smallholder farming communities of the drylands have developed skills and experiences of *in situ* soil and water conservation, such as contour plowing and furrow and raised beds systems, which can be integrated with CA for improved productivity and profitability. To facilitate wider adoption of CA by smallholder farmers in Ethiopia, tailoring the management schemes is crucial to fit the existing diversity of agroecological and socioeconomic farm settings.

Keywords: conservation agriculture, dryland, environment, food security, livelihood, soil carbon sequestration

3.1 Introduction

Subsistence farming systems, which are mostly characterized by small farm sizes and low agricultural outputs, due to minimum inputs, are the mainstay of livelihoods for most people living in rural Ethiopia. Food shortages and poverty prevail in the drylands, largely because of low crop yields (Araya et al. 2015, Stroosnijder 2009). Low crop yields are, in turn, mainly associated with water-related deficiencies, i.e., insufficient rainfall in relation to crop water requirements; poor soil water-holding capacity and infiltration problems that generate blue water losses; and erratic rainfall distribution due to short and long dry-spells, which also results in green water losses (Falkenmark and Rockström 2008). A significant amount of rainwater is also lost in the form of evaporation (non-productive water loss) in dryland areas, limiting water availability for transpiration (productive green water loss) and, thus, for crop production. Climate change has aggravated the situation, and it is being manifested in different forms, including recurrent droughts, floods, and famines that have threatened millions of people and livestock in recent decades and are forcing people to change their farming practices. For example, climate change has forced smallholders to change planting calendars for annual crops in the highlands of Ethiopia. As a result, farmers have switched from farming late-maturing crop varieties, such as maize and sorghum (which used to be sown in April and May), to early maturing crop varieties, such as wheat and barley (Meze-Hausken 2004).

Another major factor defining food insecurity and poverty in the drylands of Ethiopia is severe land degradation (Araya et al. 2015, Stroosnijder 2009). The main causes of land degradation in Ethiopia are primarily related to

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* University of Fort Hare, Department of Agronomy, PBX1314, 5700 Alice, South Africa.
Correspondence email: tesfayw2002@yahoo.com, tesfayaraya@gmail.com

conventional soil cultivation practices (Stroosnijder 2009, Gebregziabher et al. 2006). These practices include excessive tillage, aftermath overgrazing, and the complete removal of crop residue at harvest, leaving the soils barren and unprotected; the use of crop straw for fuel; and consequent low vegetation cover and deforestation. Excessive tillage accelerates the oxidation and depletion of soil organic matter (SOM), which degrades soil structure, leads to water and wind erosion, and reduces water infiltration and water holding capacity (Araya et al. 2011). The complete removal of crop residue comes as a result of meeting the feeding requirements for the large number of domestic animals required to meet the power demand of the current conventional tillage system, which also contributes considerably to land degradation (Gebregziabher et al. 2006). Land degradation also contributes to aggravating human-induced climate change by preventing biomass from being returned to the soil (Meze-Hausken 2004) and weakening the natural ability of ecosystems to adapt to climate change. Land degradation, frequent droughts, and unreliable rainfall in the country have caused agricultural productivity to decline (Bewket et al. 2007). As a result, food security and livelihoods of smallholder farmers are adversely affected.

Land degradation is especially severe in the northern highlands of Ethiopia, where conventional cultivation on steep slopes has accelerated severe soil erosion through the removal of the fertile topsoil by water erosion (Nyssen et al. 2004). In a substantial portion of the Ethiopian highlands (60% of the total area), the general slope is greater than 16% (Cloutier 1984). To restore the productivity of degraded lands and to overcome crop failure through reducing soil loss and runoff, afforestation and SWC efforts have been made, although their success to date is limited (Nyssen et al. 2011).

To reduce land degradation, minimize the effects of climate change and variability, and improve water productivity and nutrient availability, it is crucial to implement climate-smart practices, including conservation agriculture (CA) integrated with *in situ* soil and water conservation (SWC) (Araya et al. 2012) and agroforestry practices (Bayala et al. 2011, Akinnifesi et al. 2011). According to the United Nations Food and Agriculture Organization (FAO) (2014), “CA is a concept for resource-saving agricultural crop production that strives to achieve acceptable profits together with high and sustained production levels while concurrently conserving the environment." CA is defined therein as a system that simultaneously combines three pillars of agricultural production, namely, minimal soil disturbance, retention of crop residues, and crop rotations (FAO 2014). CA practices help to achieve food security at the national level (as well as other developmental goals) through increasing productivity and incomes, enhancing resilience of livelihoods and ecosystems (adaptation), and reducing levels of greenhouse gas (GHG) emissions to the atmosphere (FAO 2015). Indeed, CA systems have been successfully adopted by farmers in countries such as the USA, Latin America, Europe, and certain parts of South Asia (Derpsch et al. 2010). Results following implementation indicate CA systems improve SWC, reduce labor and energy needs, and increase crop yield. Estimates of the size of crop fields under CA worldwide were close to 125 million ha (FAO 2014), thus comprising 12.8% of the 1.6 billion ha of crop land on Earth. However, the CA area covered under smallholders’ farms is only 0.3% of the total area under CA worldwide (Derpsch et al. 2010).

Interest in CA from policy makers, NGOs, and farmers has increased in Ethiopia, as it can potentially reduce soil losses, thereby preventing catastrophes such as the widespread famine of 1983-1985 in northern Ethiopia (Tigray and Wello) that took more than 1,000,000 lives and was caused by recurrent droughts (Araya 2012). Increasing soil organic matter and moisture using different SWC practices and integrating them with CA can restore degraded land enable carbon sequestration in soil (Araya et al. 2012). However, CA practices in Ethiopia are in their infancy. Compilation of the available evidence and identification of challenges will help guide policies and research to facilitate wider adoption of CA by smallholder farmers in Ethiopia.

This chapter discusses the importance of CA for soil moisture conservation and nutrient availability in order to guide its dissemination in Ethiopia as a climate-smart practice. First, the key components of CA are explained, as well as the potential to improve effectiveness of CA by integrating it with other conservation practices. Then, effects of CA integrated with *in situ* SWC on improving soil and water retention, as well as productivity and income, are reviewed. The chapter then discusses how to scale up CA in Ethiopia by addressing the challenges of implementing it.

3.2 Components of Conservation Agriculture

Climate change is mainly the result of increasing CO_2 emissions in the atmosphere (Liu et al. 2008). CA is one of the core components of the climate smart practices used to assist farmers in climate change mitigation and adaptation. Its mitigation goal is achieved by sequestering soil organic carbon (SOC) pools through deliberately avoiding excessive plowing, crop residue removal, and biomass burning. The adaptation strategies of CA systems result in improved green water resources, increased soil fertility, and minimized impact of the declining rainfall and increased dry spells on crop yields. Converting current conventional practices, which are characterized by intensive tillage, complete removal of crop residue at harvest, and subsequent over grazing, to a CA system, which combines the practices of minimum soil disturbance, residue retention, and rotations, can reduce and reverse the degradation of soil and water resources (Araya et al. 2016a). Below, we compare the components of CA practices against conventional cultivation practices.

3.2.1 Minimum or zero-tillage

In order to understand the benefits of minimum soil disturbance, one needs to understand conventional tillage practices in Ethiopia. The non-reverting animal-drawn *ard* plough, locally known as *mahresha* in Tigrigna or *mahresha* in Amharic, is the most widely used farm implement in Ethiopia (Figure 3.1). When tilled with the *ard* plough, the soil is not inverted, as it is with the mouldboard plough. Instead, the soil is broken or fractured (Figure 3.1), lifted, and then pushed to the sides, forming a V-shaped furrow, by the two narrow, wooden side-wings attached to each side of the ploughshare. The ground between the furrows, which remains untouched, is broken up by subsequent plowings carried out at slightly different angles across a plot. Side wings help to increase soil loosening efficiency (Nyssen et al. 2009).

Generally, farmers in Ethiopia conduct primary and secondary tillage operations (Araya et al. 2015; personal observation, author). Primary tillage, the initial soil-breaking operation, is done with the oxen-drawn *ard* plough (see below) at about 15 cm deep in order to break the soils and clean the field by uprooting weeds. Secondary tillage refers to the additional operations used for seedbed preparation to control weeds, smooth the farmland, create a clod-free soil surface, and mix in plant residues. Conventional tillage in smallholder farming systems in Ethiopia typically includes a sequence of soil plowings, with 2 to 12 passes, to get a fine seedbed for ease of crop germination and weed control, which improves farm productivity (Gebregziabher et al. 2006, Mouazen et al. 2007). The plowing frequency in Ethiopia depends on soil and crop types. In the north,

Figure 3.1 Farmer applying conservation agriculture with derdero using mahresha in May Zeg-zeg catchment in northern Ethiopia. Photo by Tesfay Araya.

it is usually performed three times for barley (*Hordeum* sp.), wheat (*Triticum* sp.), and sorghum (*Sorghum bicolor* L.), and four to seven times for teff (*Eragrostis tef*) (Araya et al. 2011); in the central parts of Ethiopia, wheat and teff farmland is prepared by ox-plow three to five times before planting (Ito et al. 2007, Temesgen et al. 2008). Frequent tillage practices do allow easier sowing/planting, weed control, and soil aeration, and accelerate the mineralizing of nutrients, reduce compaction, and increase infiltration of water during the early rainfall events before crust formation (Araya et al. 2011). Tilling also helps to control some soil-borne diseases and incorporates residues and animal manures into soils.

Selective cultivation (e.g., inter-tillage, locally called *shilshalo*) is used to remove weeds after the crop has been planted or has emerged from the soil (Nyssen et al. 2011). Also, *shilshalo* enables greater porosity in the fields, increasing infiltration and reducing runoff, and thus, increases soil moisture availability in the soil. Overall, however, the negative effects of repeated tillage outweigh the benefits (Araya et al. 2012).

Tillage facilitates the breakdown of plant material, reducing C-stabilization, exposing the residues to microbial decomposition and mineralization, and thus, leads to increased GHG emissions (Dendooven et al. 2012). The loss of SOM by oxidative degradation and erosion leads to a decrease in soil biological activity, and over time, a possible reduction in crop productivity. Excessive soil manipulation using *mahresha* leads to a deterioration of soil structure, accelerates soil erosion and runoff, and as a result, reduces crop yields (Araya et al. 2015, Gebregziabher et al. 2006, Lal 1998).

By contrast, no-till practices, combined with the production of crop residues under CA, are thought to sustain beneficial microorganisms involved in the formation of stable organic compounds, promoting C-sequestration (Dendooven et al. 2012). The impact of CA on soil biochemical properties and GHG emissions is not only dependent on management factors, but on certain biophysical factors, which include soil type, amount, and quality of residues and climate. Chivenge et al. (2007) observed that SOM loss due to tillage was much higher under sandy soils compared to fine-textured soils. This was attributed to the lack of physical protection of the SOM under sandy soils, as opposed to that found in clay soils. Implementation of CA by some farmers in the Vertisols of northern Ethiopia that avoided repeated tillage dramatically reduced soil erosion, while slowing the pressures of physical, chemical, and biological soil degradation (Araya et al. 2012, Figure 3.2).

3.2.2 Crop residue management

Crop residue retention, which involves keeping at least 30% of the soil surface covered by crop residue, with the ultimate goal of protecting the soil from erosion and eventually enabling long-term sustainable production, distinguishes CA from conventional agriculture and other conservation systems (Olson et al. 2014). The amount of crop residue retained on the farmland, in turn, depends on the crop type. For example, it is not possible to retain legume residues, such as grass peas, because the pods containing grains are found at the lower part of the stem, and hence, the plant must be harvested all together. Short stubble crops, such as teff, require that smaller amounts are retained in order to fulfill the objective of CA, while long stubble crops such as wheat and barley, the harvest of which enables 20 cm-high stubble to be retained, easily exceed the minimum soil cover of 30% (Figure 3.2, Araya 2012). Stubble retention from wheat and barley at harvest could help minimize splash erosion and thus increase water infiltration (Govaerts et al. 2006). In turn, crop residue is less abundant when teff and grass peas are grown in rotation, but this phenomenon is inherent to CA for such crops (Araya et al. 2012, Araya et al. 2016a).

Furthermore, stubble retention cannot be applicable at all times, everywhere, as there are many places where crop residues are used as sources of animal feed. Therefore, a trade-off does exist in the allocation of these scarce resources in Ethiopia where mixed crop-livestock smallholder farming systems are dominant and self-competitive. Free grazing, in which farmers rear their animals in the place where crop residues are retained, is technically wrong, since it leads to soil compaction and structural disturbance mainly due to animal trampling and over-grazing. Implementing CA systems through integration of fodder trees and forage grass can help avoid these kinds of conflicts of interest.

3.2.3 Crop rotation

The ultimate goal of crop rotation in CA is to employ diverse economically and biologically viable rotations. The main purpose of using proper and profitable crop rotations in CA systems is to avoid pest transmission from one season to the next, mainly from leftover straw. While diversifying food crops, crop rotation helps to interrupt the propagation of crop pests between subsequent crops. At the same time, regular addition of soil organic matter may increase microbial activity, increase nutrient cycling, lower the concentrations of easily available nutrient sources, increase microbial diversity, and enhance natural disease

Figure 3.2 Crop residue of wheat retained by smallholder farmers demonstrating systems based on conservation agriculture that integrate derdero practices at Gum Selasa in northern Ethiopia. Photo by Tesfay Araya.

suppression (van Bruggen et al. 2006). A well-balanced rotation involving cereals and legumes (e.g., maize and beans) can reduce pest buildup by increasing diversity of beneficial organisms that minimize infestations of insects, pests, diseases, and weeds. Moreover, integrating legume crops with crop rotation practices can also improve soil fertility significantly through N fixation.

Crop rotation practices are different in different socio-agroecological systems. Traditionally, some Ethiopian farmers mix cereal and leguminous crops in one production season, while others go for double cropping, by planting legume crops as soon as the principal crops mature and before harvesting. These variations determine the quantity and quality of crop residue biomass that can be retained and thus also determine accumulation of SOM, nutrient availability, mechanization, pest and weed control, and mineralization processes that occur in the soil. The rate of SOM accumulation depends largely on the quantity and quality of organic matter input. Crops such as maize and sorghum can leave higher amounts of biomass while little crop residue biomass is retained from teff, and no biomass is retained during legume crop growing (Araya et al. 2015). Farmers implementing CA should grow crops with high crop residue biomass (high C:N ratio) (e.g., maize, sorghum, wheat, barley) in the 1st and 2nd year, especially in drylands areas, where soil moisture stress is a determining factor for crop yield. This is because the crop residue retained plays a large role in reducing weed infestation and soil moisture loss by evaporation and runoff (Araya et al. 2015). Inclusion of legumes (low C:N ratio) in CA rotations results in the improvement of soil N-fertility through biological N-fixation, potentially reducing fertilizer requirements. Moreover, if farmers are going to grow legumes in the rotation system, this should be planned starting at least from the 3rd year. However, some agroecological zones have a limited choice of crop options (only two or three) to rotate in their cropping system, while other agroecological zones have more cereal and legume crop options.

3.3 Integrating Conservation Agriculture with Other Practices

The crop yield under CA systems is not only dependent on the local adaptability of CA but is also affected by some agronomic practices, such as planting method, planting time, use of fertilizer, and weed control. For example, in Brazil, where CA has been widely adopted, the availability and affordability of herbicides such as glyphosate has enhanced CA adoption (Bolliger et al. 2006). Conservation agriculture must be tailored to integrate with other agronomic practices to solve niche-specific problems that hinder its adoption. This indicates that the three principles of CA, alone, may not be the best approach on all farms. For example, Vanlauwe (2004) redefined CA for the specific context of smallholder farmers in Sub-Saharan Africa. This new definition involved enhanced uptake by adding "appropriate use of fertilizer" as a fourth principle. Some believe that small-scale mechanization of planters for CA can assist its adoption and should be considered as the fourth principal component of CA in Sub-Saharan Africa (Sims and Kienzle 2015). Others advocate trees (agroforestry) as the fourth principle of CA for better soil and water management and for further adaptation and mitigation to climate change, as well for improving food security (Bayala et al. 2011, Akinnifesi et al. 2011). Below, the need for CA-based systems to be integrated with other agronomic practices and/or technologies, depending on socio-agroecological conditions, is illustrated for the purpose of improving its adoption by smallholder farmers in Ethiopia.

3.3.1 Raised bed planting

No-till approaches improve the soil's physical condition, leading to enhanced water infiltration and reduced runoff during each rainfall event (Araya et al. 2011). In turn, CA implementation in poorly drained soils, such as Vertisols, requires measures such as raised-bed cultivation to avoid crop yield losses due to water-logging (Araya et al. 2015). The origin and use of raised-bed cultivation systems has traditionally been associated with water management issues (Nyssen et al. 2011, Sayre 2004). Generally, bed planting has advantages over flat planting, as bed planting is more water efficient, easier for weed control, and has a lesser seed rate requirement for seeding. Farmers worldwide have developed *in situ* raised-bed cultivation systems for moisture conservation based on generations of local experience that can increase the soil's ability to store water for plant use, reduce vulnerability to drought, and help stop soil erosion and degradation.

In northern Ethiopia, farmers in Tigray have practiced *in situ* SWC tillage practices, locally called *terwah* and *derdero* (Figure 3.1, Figure 3.2, Araya et al. 2012). *Terwah*, with contour furrows at 2 to 4-m intervals, usually on teff fields, allows the elongated furrows to trap and store rainwater for later use by teff during dry spells instead of being lost as runoff (Araya et al. 2011). Farmers also use a *derdero* system, especially for the production of fenugreek (*Trigonella foenum-graecum*), wheat (*Triticum* sp.), lentils (*Lens culinaris*), and teff on Vertisols (Nyssen et al. 2011). In the *derdero* system, farmers prepare beds and furrows along the contour after surface broadcasting of seeds at planting. When refreshing the furrow with the *mahresha* plough at planting, some soils are moved from the furrows to the top of the raised seedbeds together with the seeds that were sown manually into the furrows. These seeds are then buried in the raised seedbeds in order to protect them from pests and birds. Plants are subsequently grown on the ridges, where they are protected from water-logging, while excess water drains off via furrows, where it ponds and then infiltrates the soil (Nyssen et al. 2011). Therefore, in *derdero* systems, the bed structures serve as physical barriers against runoff and the furrows provide temporary storage for water ponding. The *derdero* system, with permanent raised-bed cultivation, has a larger capacity for excess water storage than the *terwah* system. Integrating CA with no-till on top of permanently raised beds of *derdero* was demonstrated to minimize soil disturbance (Figure 3.3; Araya et al. 2012).

In *derdero* as well as *terwah* systems, however, traditionally, all straw is harvested, the stubble is grazed, and the furrows and beds are destroyed and reshaped yearly by tillage. These systems should be better implemented with other components of CA to maximize soil and water conservation benefits.

3.3.2 Conservation agriculture with trees

Conservation agriculture with high-value trees harnesses and combines the synergies of rapid improvement of livelihoods with sustainable crop production and productivity, as well as environmental resilience (Bayala et al. 2011, Akinnifesi et al. 2011). The CA system with trees derives its strength from the complementary principles of CA and agroforestry together, and is based on five important principles: (1) minimize soil disturbance, (2) maintain land/soil cover, (3) practice crop rotation, (4) follow good agronomic management practices, and (5) incorporate nitrogen-fixing trees and high-value trees (World Agroforestry Centre 2015). The addition of trees to CA is crucial for reducing soil erosion, improving soil fertility by bringing nutrients from deeper soil layers, mitigating climate change by storing carbon, increasing soil infiltration capacity, and improving green water resources that support improvement in crop yield. For example, incorporating *Faidherbia albida* perennial trees into cropland in northern Ethiopia improved soil fertility (Birhane et al. 2018). Therefore, implementing CA integrated with *F. albida* can potentially be recommended in Ethiopia to obtain the aforementioned benefits of CA with tree-planting systems.

Figure 3.3 Systems based on conservation agriculture that integrate derdero practice, demonstrated by farmers at Egrimulo in May zeg-zeg catchment, enhance ponding; the wheat crop has just germinated and grows on the ridges; the farmland is sloping down to the right (Lanckriet et al. 2012). The raised beds are shaped by using the local ard plough, mahresha.

3.4 The effect of Conservation Agriculture on Soil and Water Management and Productivity

3.4.1 The effect of conservation agriculture on runoff and soil loss

Conservation agriculture has the greatest potential in the highlands of Ethiopia, where erosion rates are the highest, due to high rainfall erosivity and soil erodibility (Araya et al. 2012). However, crop residue retention through CA alone is insufficient for controlling erosion on very steep slopes; other physical measures, such as contour bunds, are needed to reduce the slope length (Araya et al. 2012). Cloutier (1984) reported that about 60% of the highlands of Ethiopia have a slope of greater than 16%. The effectiveness of CA practices depends on the prevailing topographic and climatic conditions. Runoff and soil loss in CA treatments in the semi-arid region on Vertisols (3% slope) were lower than for the same CA treatments on Vertisols in sub-humid regions with steeper (6.5%) slopes (Araya et al. 2012). The differences were mainly related to the higher slope gradients and rainfall amounts in the sub-humid area, which contributed to higher runoff and soil loss rates and ultimately to higher nutrient loss. The time to ponding is higher in the lower slope gradient, which gives time for infiltration to occur and decrease runoff. On the other hand, in areas with steep slopes, ponding occurs quickly and rainwater tends to flow downhill more rapidly. This indicates that CA practices should be integrated with *in situ* SWC practices, especially in steep-slope farms, to improve their effectiveness for SWC (Araya 2012).

The CA-based *derdero* practice (see section 3.3.1) has been found to consistently reduce runoff and soil loss in Ethiopia (Araya et al. 2012, Araya et al. 2011). Araya et al. (2016a, 2016b) reported that, based on over 9 years of data in the semi-arid area of Tigray, the mean soil loss on a 3% slope where CA was integrated with *derdero* practice was below 4 t ha^{-1}, compared to 17 t ha^{-1} under a conventional tillage system. There is a clear relationship between the retention of crop residues and the reduction of runoff and soil losses by erosion (Araya et al. 2012, Lal 1998, Erenstein 2002). Crop residue retained in the form of standing stubble in the CA systems that integrated *derdero* reduced runoff while adding SOM, which contributed to the reduction in soil crust formation and increase in infiltration capacity. Furthermore, the implementation of CA in crop fields located at the upper catchment can also have catchment-scale impacts in reducing siltation to nearby reservoirs, thus helping to extend the lifespan of those reservoirs. Lanckriet et al. (2012) reported, based on catchment-scale CA modeling in Tigray region, that CA has multiple advantages, including extending the lifespan of reservoirs and reducing maintenance costs, as well as reducing gully erosion, and therefore, reducing rural road maintenance costs (Haregeweyn et al. 2006, Nyssen et al. 2008).

3.4.2 The effect of conservation agriculture on soil rainwater balance

Rainfall variability affects drought-associated food shortages in Ethiopia (Bewket et al. 2007). The distribution of rain, rather than the total amount of rainfall in the semi-arid areas is of major importance because dry spells in the rainy season strongly depress crop yield (Rockström et al. 2009, Rockström 2000). About 70%–85% of rainfall is lost as blue water in the form of direct runoff and as deep percolation and white water losses in the form of evaporation and thus, less water is available for crops, the so-called "green water" (Figure 3.4). Water losses through direct runoff, deep drainage, and evaporation are unproductive water losses, while water loss through transpiration is considered as productive water loss (Araya et al. 2015). Runoff rates are higher in areas where there is physical deterioration of the soil quality (Araya et al. 2012, 2015; Stroosnijder 2009) and absence of effective *in situ* water conservation measures (Araya et al. 2015) that limit infiltration capacity and soil moisture availability, and thus, result in low crop yield. Water productivity in rainfed agriculture has to increase to meet the fast-growing population's demand for food (Araya et al. 2015).

Rainwater loss through evaporation is estimated to be 30%–50 % of the total rainfall (Figure 3.4). Increasing the amounts of crop residues on the soil surface as a cover reduced evaporation rates and increased duration of drying up of the soil except after extended drought (Krishna et al. 2004). On the other hand, repeated tillage can cause moist soil to move to the surface, which favors loss of soil moisture by evaporation (Aase and Siddoway 1982). CA increases SOM and thus increases water holding capacity of the soil, where more rainwater can be stored without losing it by evaporation. Rainwater loss in the form of surface runoff accounted for 10%–25 % of the total rainfall (Figure 3.4). Crop residue, especially retained in the form of standing stubble, can reduce runoff, while mulching gives better coverage against evaporation. Increasing SOM can reduce soil crust formation and increase infiltration capacity, thereby reducing runoff throughout the rainy

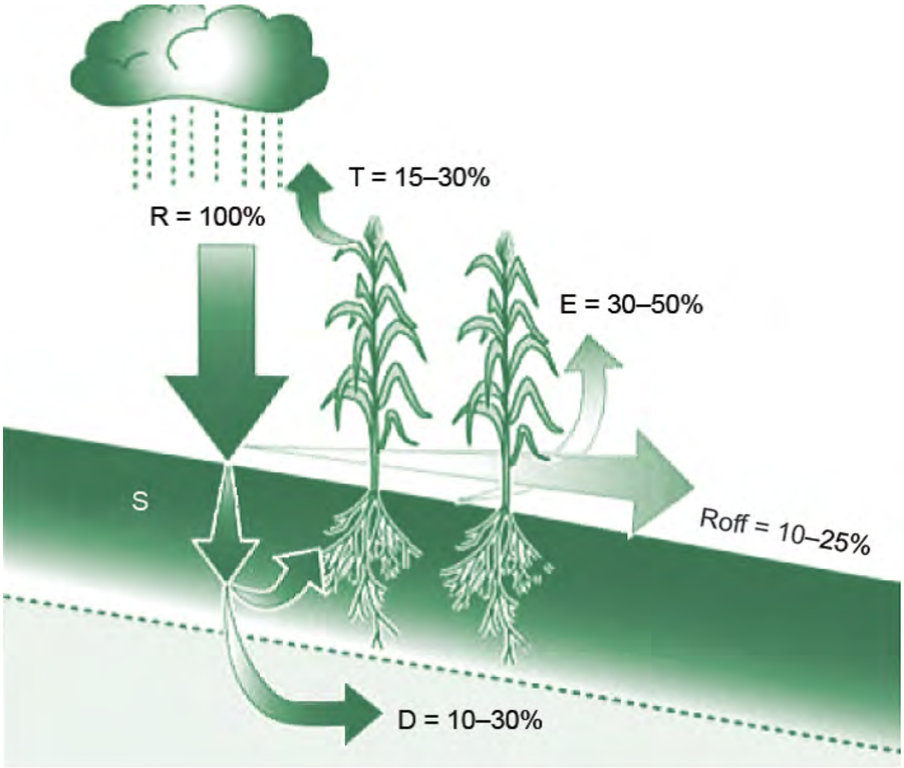

Figure 3.4 On-farm rainfall partitioning in dryland cropping systems in Sub-Saharan Africa, adopted from Falkenmark and Rockström (2008). R is rainfall, T is transpiration, E is evaporation, S is soil-moisture storage, R off is runoff and D is drainage (or deep percolation out of the root zone).

season (Araya et al. 2012; 2015). Water draining below the rootzone is estimated to be 10%–30% of the total rainfall (Figure 3.4). Similarly, increasing SOM increases the soil's water holding capacity and increases the green water resources in the rootzone that can improve food production (Opolot et al. 2014, Araya et al. 2015, Ngigi et al. 2006). However, CA farming systems increased in deeper drainage (as more rainwater entering to the soil) compared to conventional tillage systems (Azooz and Arshad 1996) due to the establishment of stable biopores that are not broken through cultivation. The increase in deep drainage resulted in feeding the blue water resource, i.e., the water in dams, lakes, rivers, and aquifers, at the expense of green water resources (Casenave and Valentin 1992). Rockström (2008) reported that the remaining 15%–30% of the total rainfall was used by the plant for growth as transpiration. Productive rainwater losses through transpiration flow exhibit a linear relationship with crop yield. CA improved soil water storage in the rootzone compared to conventional tillage systems (Ngigi et al. 2006), especially in years with low precipitation and dry spells (Araya et al. 2015).

Conservation agriculture that integrates raised beds practice helps to drain off excess rainwater from raised beds into furrows, where it is stored for later use by crops during dry spells. Unlike the conventional tillage system, CA with raised bed contributes to consistently smaller runoff by avoiding repeated plowing, thereby retaining crop residue and storing moisture (Araya et al. 2015, Erenstein 2002, Sayre 2004). Reduced runoff means an improvement in the soil water status in the rootzone and a subsequent reduction in soil loss, which in turn leads to reduced land degradation and reduced crop water stress (Araya et al. 2015, Stroosnijder 2009, Rockström 1997). However, Erkossa et al. (2006) reported higher runoff in the central highlands of Ethiopia with the use of broad beds and furrows compared to conventional tillage. This could be attributed to the graded furrows, which are constructed to drain excess water from the fields, and which may have aggravated soil water erosion processes.

3.4.3 The effect of conservation agriculture on soil fertility

Minimal soil disturbance in CA systems can help reduce soil fertility losses. Araya et al. (2016a and 2016b) reported that a significant reduction in C and N losses by water erosion occurred when using CA with *derdero* planting systems compared to conventional tillage practices in northern Ethiopia. Faster improvement of soil fertility was also observed in Tigray when raised beds were integrated with CA practices than when CA was practiced alone (Araya et al. 2016b). Likewise, Govaerts et al. (2006) also reported that CA improved soil C, N, K, and Zn concentrations in topsoil. Another study corroborated that an increased soil C content was observed in the second year of CA practices implementation (Oicha et al. 2010). Improved soil organic matter increases soil cation exchange capacity and plant nutrient availability. Several studies reported that CA improves soil nutrients, mainly C, N and P, leading to increased crop yield (Araya et al. 2016b, Erkossa et al. 2007).

3.4.4 The effect of conservation agriculture on crop productivity

According to First ACCA (2014), CA resulted in higher and more stable crop yields over time. Pittelkow et al. (2015) also reported that CA increased rainfed-crop productivity in dry climates. Similarly, several studies in Ethiopia revealed that farmers using CA had equivalent (Ito et al. 2007) or higher crop yields than those of conventional tillage systems with application of glyphosate herbicide (Araya et al. 2011, Araya et al. 2016a, Nyssen et al. 2011, Erkossa et al. 2006), especially for teff yields on Vertisols (Erkossa et al. 2006, Fufam et al. 2001, Habtegebrial et al. 2007, Sasakawa Global 2002) if herbicide, fertilizer, and mulching were applied. Because one of the beneficial effects of CA is improving water productivity through improved infiltration and reduced evaporative water losses, CA systems can also minimize the effects of dry spells and water-logging on crop yield (Araya et al. 2012).

Crop yield improvements in the short-term are important because they play a large role in determining the attractiveness of CA to farmers. However, significant improvements in crop yield in CA systems only began to emerge 3 to 5 years after implementation (Araya et al. 2016a, Araya et al. 2012, Govaerts et al. 2005). Improvements in crop yield in CA-based treatments in northern Ethiopia required a period of at least 3 years of cropping before they became significant, whilst on a steeper slope and in a cooler climate (in a nearby sub-humid area with the same treatments), improvements began after 5 years (Araya et al. 2012). Under dryland conditions, where moisture limits crop yields, CA can improve yields in the short term (Araya et al. 2015, Sayre 2004, Rockström and Falkenmark 2000), although the full yield benefits of improved water availability are only realized after improvements in soil fertility (Rockström and Barron 2007). The variability in short-term crop responses to CA is due to the interacting effects of water, nutrients, and climate requirements for a given crop (Giller et al. 2009), whether using CA is being used alone or in a CA-based system, as well as the ability of farmers to practice CA properly (Araya et al. 2016a).

3.4.5 The effect of conservation agriculture on economic profitability

Economic analysis can provide information about the sustainability of a practice for increased productivity and enhanced resource use efficiency when measured against investment input costs involved in a given period (Senkondo et al. 2004). Conservation agriculture implies higher capital input in the form of weed control and opportunity costs (in the form of crop residue normally used as livestock feed), while CA systems with herbicide application imply a lower labor investment, due to reduced tillage and less need for oxen as a source of draught power (Araya 2012). Eventually, the cost of plowing was found to be higher than the opportunity cost of the crop residue retained to cover at least 30% of the crop field soil surface. Significant improvements in crop biomass after 3 to 5 years of CA implementation also increased the straw feed available for livestock. Several studies concluded that the gross margin was significantly higher in CA systems than in CT systems (Erkossa et al. 2006, Tulema et al. 2008) (Tables 3.1 and 3.2). In addition to avoiding repeated tillage, CA saves 10 to 11 oxen-span days per ha and thus reduces the demand for oxen draught power (Araya 2012).

3.5 Challenges of CA Implementation in Ethiopia

Although there has been good evidence of successful CA integrated with *in situ* SWC (as reviewed above), its adoption rate has remained low in Ethiopia (Araya et al. 2012, Giller et al. 2009). The reasons for the low adoption rate include the lack of smallholder CA equipment, low short-term crop yield response, lack of knowledge among farmers and agricultural development agents, the proliferation of free grazing, and lack of inputs, such as non-selective herbicide and fertilizers (Araya et al. 2016a, Giller et al. 2011). Indeed, planting through the soil cover under a zero-tillage system is possible using direct seeding, direct planting, or broadcasting of seeds into the soil cover. Suitable implements are available for manual and animal-drawn agriculture (FAO 2014). Still, unless supported by policies and incentives, the benefits of CA do not adequately outweigh farmers' immediate needs in the short term, which is partly due to low short-term crop yield response.

Lack of knowledge of how to properly implement CA technologies also plays a significant role in slowing and opposing its adoption. There is growing evidence that the full benefits CA come from the interaction of reduced tillage with mulching and crop rotations (Thierfelder et al. 2013). Farmers are undertaking one or two of the CA principles in an isolated fashion without applying all three principles together. Minimizing tillage and the maintenance of soil cover are the two least adopted CA principle(s) by many smallholder farmers in Ethiopia, which prevents the realization of the full benefits of CA (Figure 3.5). Giller et al. (2009) and Ito et al. (2007) reported that essential aspects of CA are also sometimes omitted in experimental CA trials in order to meet the minimum requirements (Figure 3.5).

Farmers in the drylands of Ethiopia do not leave ample quantities of crop residue that can be used as mulch for suppressing weeds, since, in a free grazing system, crop residue is extensively used for animal feed. Therefore, farmers face trade-offs between using crop residue for soil mulching or for livestock feeding (Araya et al. 2012). Policies, strategies, and other development initiatives should, therefore, consider the alternatives suggested by farmers while providing options for addressing the free grazing issues. These options include enhancing forage development and stallfeeding.

Lastly, in zero tillage practices, weed infestation is a major problem for crop yield loss (Araya et al. 2016a) and

Table 3.1 Grain yield performance in CA/CA-based systems under different cropping systems and agroecological zones.

Crop types & rotation	Soil type	P(mm)	Grain yield	Source
Wheat-teff-wheat-barley-wheat-teff-grass pea-teff	Vertisol	500	Significantly higher in CA-based systems than CT after 3 yrs	Araya et al. 2011
Wheat-grass pea-wheat-hanfets –grass pea-wheat-grass pea	Vertisol	750	Significantly higher in CA-based systems than CT after 5 yrs	Araya et al. 2012
Wheat-lentil-teff-wheat-lentil-teff	Vertisol	900	Significantly higher from 1st year	Erkosa et al. 2006
Sorghum (no herbicide)	Vertic Luvisol	849	Lower yield in CA	McHugh et al. 2007
Teff (no herbicide)	Nitisol		Equivalent with CA	Tulema et al. 2008
Teff (no herbicide)	Vertisol		Equivalent with CA	Tulema et al. 2008

Table 3.2 Grain yield, straw yield, and gross margin in different locations in Ethiopia.

			Grain yield (t ha^{-1})		Straw yield (t ha^{-1})		Gross margin (USD)	
Description of the experiment	Year	Crop types	CA/CA-based	CT	CA/CA-based	CT	CA/CA-based	CT
9 years (2005-2013) long-term trial at Adigudem in northern Ethiopia (Araya et al. 2016a)	2005	Wheat	2.0a	1.5a	6.2a	4.3a	541a	441a
	2006	Teff	0.7b	1.2a	2.4b	3.8a	33b	246a
	2007	Wheat	2.8a	1.7b	5.2a	3.5b	588a	281b
	2008	Barley	0.7a	0.5b	0.5a	0.2b	-109a	-250c
	2009	Wheat	2.6a	1.6c	5.2a	3.7c	568a	300b
	2010	Teff	1.5a	1.4a	4.a3	4.0a	365a	210b
	2011	Grass pea	1.8a	1.3b	2.0a	1.6b	413a	197b
	2012	Teff	1.1a	0.9b	5.3a	4.3a	3979a	213b
	2013	Wheat	4.2a	2.8b	12.2a	6.5b	1394a	619b
6 years (2005-2010) long-term trial at DoguaTembien in northern Ethiopia (Araya et al. 2012)	2005	Wheat	3.1a	2.8a	-	-	-	-
	2006	Grass pea	2.1b	2.9a	2.8b	4.1a	-	-
	2007	Wheat	3.0a	2.9a	6.8a	6.9a	-	-
	2008	*Hanfets*	2.0a	1.9a	3.1a	3.0a	-	-
	2009	Grass pea	2.2ab	2.0b	3.9ab	3.5b	-	-
	2010	Wheat	5.2a	4.0b	6.7a	4.7b	-	-
2 years trial at Weldiya in northern Ethiopia with Sorghum planted in the 2nd year (McHugh et al. 2007)	2004	Sorghum	0.6a	0.7a	-	-	-	-
2 years trial in a Vertisol at Gare Arera in Central Ethiopia (Tulema et al. 2008)	2001	Teff grain and biomass yield was reported as non-significant					-	-
	2002	Teff	1.9b	2.3ab	6.9b	7.6ab	520b	1319a
2 years trial in a Nitisol at Gare Arera in Central Ethiopia (Tulema et al. 2008)	2001	Teff grain and biomass yield was reported as non-significant					-	-
	2002	Teff	0.9b	1.3a	3.3b	4.6a	-108b	1374a

Means with the same letter in a same column and year are not significantly different, and (-) indicates missing data.
CA-based systems in the case of Araya et al. (2016a) and Araya et al. (2012) adds permanently raised beds as parts of CA.

is a major challenge for the wider adoption of CA. Weed control requires much more knowledge, which makes the appropriate use and dosage of herbicide of utmost importance (Araya et al. 2016a). Constraints related to spraying herbicides for weed control are knowledge—as well as capital-intensive—technologies. Dependency on the herbicide in CA systems can be reduced through integrated weed management practices including the use of proper agronomic practices (i.e., mulching, fertilizer, crop rotation, sowing date, and weeding).

Given the challenges above, the introduction and adoption of CA in Ethiopia requires more research to provide evidence-based and contextually fit CA technologies in order to facilitate knowledge-based decision making, and strengthen local institutions. Adopting CA requires substantial changes not only in practices, but also in the mindsets of practitioners and proponents. Based on this

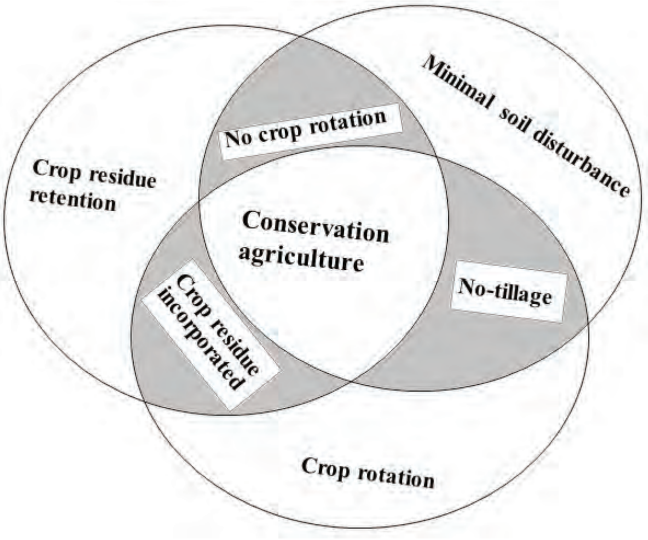

Figure 3.5 Diagram representing the different components of conservation agriculture and the components that are commonly practiced during implementation by smallholder farmers.

analysis, the following recommendations are made for CA implementation:

- Implement CA through integration of *in situ* SWC practices, such as raised beds and furrow structures (Araya et al. 2016a) and/or with trees (Bayala et al. 2011).
- Shift from repeated tillage culture to minimal soil disturbance by enhancing awareness of the benefits of CA and by working to break the current and traditional perception that a farmer who plows less is lazy.
- Properly implement CA without omitting any of the three principal components.
- Encourage smallholder farmers to retain an ample amount of crop residue in order to cover at least 30% of the soil's surface.
- Introduce zero grazing systems by promoting stall-feeding through increasing feed availability so that crop residue is left in the field and avoids the soil compaction, which is caused by animals trampling soils.
- Apply mineral fertilizers, such as di-amonium phosphate (DAP) and urea, which may significantly boost crop yield from CA fields, particularly during the first year. With the long-term (i.e., over 10 years) implementation of CA, the application of fertilizers might be reduced as it can be compensated by improved soil fertility enabled by CA.
- Establish a market chain of non-selective herbicides at affordable prices at different levels in the country and apply the herbicides until effective crop residue is established and the seed bank of weeds is sufficiently reduced in order to avoid weed infestation. The herbicide that has been widely available (through the Ethiopian government agricultural extension) to smallholder farmers over the last two decades is *2-4-D*, which is used to control broad leaf weed. Until recently, there were no herbicides available for controlling grass weed species (Araya et al. 2016a).

3.6 Conclusion

Conventional agricultural practices are responsible for depleting soil organic matter, increasing runoff and soil erosion, and reducing the water storage capacity of soils, leading to lower crop productivity. Conservation agriculture can help minimize land degradation (i.e., soil erosion, soil fertility decline, and hydrological challenges), and thus improve crop productivity and promote better soil carbon sequestration through the simultaneous practice of its three principal components, which are minimal soil disturbance, crop residue retention, and crop rotation. Smallholder farmers in the drylands of Ethiopia have developed skills and experiences of *in situ* soil and water conservation that can be integrated with CA. For example, farmers in the northern Ethiopian highlands use traditional *in situ* SWC conservation by creating surface depressions at the moment of planting (*terwah*, *derdero*). Integrating improved local tillage practices (i.e., *derdero* and *terwah)* with CA systems can help in reducing runoff, soil loss, and nutrient loss, while improving green water availability, crop yield, and ecosystem health. The short-term crop yield improvements in CA-based practices are largely dependent on the steepness of the slope and the agroecological conditions. Because of this, the restoration of soils and improvements in crop yields under CA take longer on steep slopes than on plains areas. Conservation agriculture requires lower labor investments, due to reduced tillage and less need for oxen as a source of draught power. In general, the economic return of CA-based planting systems is greater than that of conventional tillage farming. However, the improvement in soil fertility is not immediate, and the full benefit of permanent raised beds, plus the retention of crop residues, can only be expected after several years. Generally, the adoption of CA by smallholder farmers is persistently low due to low degrees of mechanization, the lack of soil fertility management options, and competition for crop residues with other end uses. However, addressing these issues should be part of the long-term strategy for implementing CA. Customizing CA systems to fit different topographical, agroecological, and socioeconomic settings is crucial, and CA should be adopted and scaled-up throughout Ethiopia to ensure food security, better livelihoods, and environmental protection.

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4. Enhancing Teff (*Eragrostis tef*) Production and Productivity through Water and Nitrogen Management in Northern Ethiopia

A. Araya[a]*, Isaya Kisekka[b], Aklilu Negussie[c], Kiros Meles Hadgu[d], A. J. Foster[e], Solomon Habtu[f], and Lucieta Guerreiro Martorano[g]

Summary

The availability of soil nutrients and water is the major determinant for crop production under resource-constrained smallholder rainfed farming systems in northern Ethiopia. In view of climate change projections, in-depth understanding of the agronomic practices, particularly water and nutrient management options, is urgently needed in order to improve and stabilize crop yields, and thus, achieve food security. An experiment was carried out for two years in northern Ethiopia to investigate the optimum amount of irrigation water and the optimum rate of nitrogen fertilizer under two different soil types, viz., Cambisols and Vetisols, for teff (*Eragrostis tef*) production. The experiment had three water level treatments and three nitrogen applications arranged in a randomized, complete block design. The results showed that teff responded well to the application of supplemental irrigation water and nitrogen fertilizer in both Cambisols and Vertisols, while increased water application without increased N did not increase teff yield, and vice versa. This study does not recommend a higher rate of N (i.e., above 60 kg ha^{-1}) due to a severe lodging problem associated with higher N levels during good seasons and limited N uptake during periods of inadequate soil moisture availability in low rainfall seasons.

Keywords: nitrogen, optimum resource management, production, productivity, irrigation, teff

4.1 Introduction

Landscape degradation, caused by humans and natural disasters, results in the plummeting availability of resources (e.g., soil nutrients, water, land, etc.), thereby affecting agricultural productivity and rural livelihoods in developing countries, such as in Sub-Saharan Africa. The impact of landscape degradation is severe in the highlands of Ethiopia, particularly in the semi-arid, agroclimatic zone, where more than 50% of Ethiopia's landmass is located (Elahi 1992). Especially in the northern highlands of Ethiopia, crop production and productivity have been severely challenged by poor soil fertility (Stroosnijder and Slegers 2008, Stroosnijder 2009). At the same time, erratic rainfall patterns, which produce insufficient, uneven, and unpredictable rainfall that increasingly, begins late and ends early, due to climate change and variability, have further constrained rainfed crop production systems (Araya et al. 2010a, Araya and Stroosnijder 2012). Late season drought, which results in a short growing period, has posed a major challenge to agricultural productivity in recent decades (Araya et al. 2010a and 2010b; Araya and Stroosnijder 2012).

Teff belongs to the grass family of the genus *Eragrostis* (Abebe 2000, Tulema et al. 2005) and is also well known as a gluten-free food source (Spaenij-Dekking et al. 2005). Despite its importance and increasing demand for teff in local and global markets, teff production and productivity have remained low mainly due to inadequate soil water availability and poor soil fertility in the growing regions (Habtegebrial and Singh 2006, Araya et al. 2011). Although local teff yield could potentially reach greater than 2,400 kg ha^{-1}, yield-limiting factors have contributed to a lower average teff yield, i.e., below 800 kg ha^{-1}, especially under

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[a] Kansas State University, Manhattan, KS, USA

[b] University of California Davis Department of Land, Air, and Water Resources and Department of Biological and Agricultural Engineering, Davis, California, USA

[c] WeForest, Ogentroostlaan 15, B-3090 Overijse, Belgium

[d] World Agroforestry (ICRAF) - Ethiopia, c/o ILRI Ethiopia, P. O. Box 5689, Addis Ababa, Ethiopia

[e] Lamb Weston, Tri-Cities, WA, USA

[f] Mekelle University, College of Dryland Agriculture and Natural Resources, P.O. Box: 231, Mekelle, Ethiopia

[g] Embrapa Eastern Amazon, Belem, Para, Brazil

* *Correspondence:* A. Araya (email: arayaalemie@gmail.com)

rain-fed conditions (Balcha et al. 2006, Tulema et al. 2005). Efficient use of water is essential for enhancing production and productivity of crops (Oweis et al. 2000), including teff, since responses to soil nutrients such as nitrogen depend on the soil water status as well as the soil type (Habtegebrial and Singh 2006). In light of the aggravating impact of land degradation combined with climate change projections in northern Ethiopia, in-depth understanding of the agronomic practices, particularly potential water and nutrient management options, is urgently required in order to improve and stabilize crop yields, and thus, achieve food security in Ethiopia.

This study hypothesized that in areas where water for crop production is limited, such as in northern Ethiopia, optimum water and fertilizer application options can help to improve crop yield. The objectives of this study were, therefore, to investigate the optimal application rates of water and the combinations of water and nitrogen; evaluate the effect of water and nitrogen use on yield and dry biomass of teff; and recommend optimum N and water application rates for Cambisols and Vertisols in the study site.

4.2 Materials and Methods

4.2.1 Study site description

The study was conducted in Mekelle, which is located in Tigray, northern Ethiopia at latitude 13° 28′ N and longitude 39˚ 06′ E. The study site is categorized as a semi-arid climatic zone (Araya et al. 2010a). The mean annual rainfall is about 600 mm, of which 70% is received between the months of June and September. The evapotranspiration rate during the growing season ranges between 3 and 5 mm per day. The total water requirement for teff in the Mekelle area ranges between 260 to 338 mm per growing season depending on the planting date, cultivar, and rainfall conditions (Araya et al. 2011). Although it varies with seasons, cultivar, and soil types, the long-term mean net supplementary irrigation demand of teff in Mekelle was estimated to be 75–100 mm (Araya and Stroosnijder 2012). The experimental sites had Cambisol and Vertisol soils with physic-chemical characteristics of sandy clay and clay loam; 1.2 and 2.5% organic matter contents; 0.08 and 0.15% total nitrogen contents; and 6.7 and 7.98 pH, respectively.

4.2.2 Experimental setup and treatments

A local cultivar of teff, "*Keyh,*" was sown by broadcasting on July 31, 2009, and August 2, 2010. The experiment had three water treatments, including W1 (rainfed), W2 (60 mm water in four supplementary irrigations after cessation of rainfall, in which approximately 15 mm per irrigation event were applied), and W3 (100 mm water in eight supplemental irrigations after cessation of rainfall, in which approximately 15 mm per irrigation event were applied for the first four irrigations and 10 mm per irrigation event were applied for the remaining four irrigations). Irrigation water was applied manually, using a calibrated bucket, by fetching water from a nearby water source of known volume. The irrigation interval was every 3 to 5 days. The Irrigation amount was estimated based on the average crop water demand and was calculated as the product of teff crop coefficient and reference evapotranspiration (Doorenbos and Pruitt 1977, Doorenbos and Kassam 1979, Araya et al. 2010b). Reference evapotranspiration was estimated based on the FAO-Penman-Monteith method (Allen et al. 1998).

In addition, the three nitrogen rates used in this experiment were 30, 60, and 90 kg ha^{-1} of N, which are symbolized by N1, N2, and N3, respectively. The irrigation and nitrogen rates were designed to explore the interaction effects between various levels of N and water. Rates of nitrogen fertilizer were broadcasted in split applications (i.e., half at sowing and the other, half a month after sowing). N was applied as Urea. To all plots, phosphorus was applied at sowing in the form of DAP at a rate of 46 kg ha^{-1}. The three levels of nitrogen were combined with the three rates of water in a randomized, complete block design. The control in this experiment was rain water alone (i.e. with no supplementary irrigation), to which 30 kg ha^{-1} N was applied.

Manual weed control was undertaken twice, at three and at seven weeks after sowing. All other cultural practices for teff cultivation were practiced as per the recommendations of the local Bureau of Agriculture.

4.2.3 Data collection and analysis

Measuring the normalized difference vegetation index (NDVI) of crops/vegetation is one way of analyzing crop and vegetation conditions (Shamudzarira et al. 2014). The NDVI technique has been applied within the field of remote sensing by using satellite technology, and it has been reported as a robust method for assessing ground crop conditions (Cilia et al. 2014). Although the principles are similar, the bands used in GreenSeeker could differ from those applied in satellites. Higher NDVI (close to 1) values would indicate more greenness, and likely more photosynthesis, at the time of measurement. For example, the NDVI value was used to monitor the change in crop nitrogen status (NTech 2007). In our case, a GreenSeeker instrument (NTech 2007) was used to measure the greenness of the plants after water and nitrogen treatments when the crop reached the heading stage.

The grain yield and dry biomass of teff were measured after harvest from a plot area of 2.25 m^2. The lodging percentage was estimated by dividing the area covered by lodged plants at maturity from the total area of each plot, multiplied by 100. The area covered by lodged plants was manually delineated and measured using a measuring tape.

Irrigation water-use efficiencies for grain (G_IWUE) and for dry biomass (BM_IWUE) were estimated as irrigated grain and dry biomass yield minus the respective rainfed grain and dry biomass yield divided by the irrigation water applied. Similarly, the nitrogen use efficiencies for grain (NUE_G) and dry biomass (NUE_BM) were estimated as grain and dry biomass obtained from a given area minus the respective grain and dry biomass in the control treatment and divided by the nitrogen applied over that area. The interaction effects of irrigation and nitrogen on grain and dry biomass yield of teff were an important indicator of the farm resources optimizing strategy. Accordingly, the combined irrigation-nitrogen use efficiencies for grain (G_INUE) and for dry biomass (BM_INUE) yield were estimated as presented in Eq. 4.1 and Eq. 4.2, respectively:

$$G\_INUE = \left[\frac{(G_{IN} - G_R)}{G_R} \right] \times 100 \qquad [4.1]$$

$$BM\_INUE = \left[\frac{(BM_{IN} - BM_R)}{BM_R} \right] \times 100 \qquad [4.2]$$

Where, G_INUE is the combined irrigation-nitrogen use efficiency for grain yield; BM_INUE is the combined irrigation-nitrogen use efficiency for dry biomass; BM is the dry biomass yield; G is the grain yield; G_{IN} is the grain yield from an irrigated and fertilized field; BM_{IN} is the dry biomass yield from an irrigated and fertilized field; and BM_R and $G_{R,}$ are the dry biomass and grain yield from less fertilized (N1) and non-irrigated (W1) fields, respectively.

Analysis of variance (ANOVA) was carried out to test differences in dry biomass, grain yield, NDVI, and percent (%) of lodging between the treatments based on a General Linear Model using Minitab Statistical Software.

4.3 Results

4.3.1 Effects of supplemental irrigation and nitrogen on yield and yield components of teff grown on Vertisols

Table 4.1 shows the effect of supplemental irrigation on yield and yield components and irrigation water-use efficiencies of teff grown on Vertisols in 2009 and 2010. In both years, grain yield was not significantly affected by water levels, although a slight improvement was observed under full supplementary irrigation (W3). In 2010, dry biomass was significantly (p <0.05) improved by the application of full supplementary irrigation (W3), when compared to rain-fed (W1).

As presented in Table 4.2, application of N3 has improved teff grain yield significantly ($p < 0.05$) in both years compared to the yield obtained under N1. However, there was no significant difference between the yields obtained under N2 and N3. Similarly, N3 had significantly ($p < 0.05$) increased teff dry biomass yield over N1 in both 2009 and 2010. A significant lodging percentage was observed under different N levels in 2009. Although there were no significant differences in lodging between N2 and N3, the lodging effect was significant and lower in N1 than N2 and in N3. In contrast, N2 and N3 significantly affected NDVI values in 2009, which implied that N2 and N3 were greener than N1. This shows that NDVI values could be used as an index for assessing the N status in teff fields. In 2009 and 2010, there was a relatively higher nitrogen-use efficiency (G_NUE) for grain at N2 as compared to N3. Similarly, relatively higher dry biomass nitrogen-use efficiency (BM_NUE) was recorded in 2009 at N2 as compared to N3 (Table 4.2).

The highest irrigation-nitrogen use efficiency for grain (G_INUE) was found in a treatment combination of N3W3 in 2009 and N3W2 in 2010. The G_INUE ranged between -9.9% and 48.6% and -19.5% and 63% in 2009 and 2010, respectively (Table 4.3). The lowest G_INUE was found in a treatment combination of N1W2 (-9.85%) in 2009 and N1W3 (-19.5%) in 2010. This implies that applying low N under good water-available conditions, or applying high N under poor water-available conditions, could result in low yield (due to negative interaction effects). The highest irrigation-nitrogen use efficiency for dry biomass (BM_INUE) was found in a treatment combination of N3W3 in 2009 and N3W2 in 2010 (Table 4.3), whereas the lowest BM_INUE was found in a treatment combination of N1W2 (-4.9%) in 2009 and N1W3 (-2%) in 2010.

4.3.2 Effect of irrigation water and nitrogen on yield and yield components of teff grown on Cambisols

As indicated in Table 4.4, there were no significant differences among the water treatments in 2009 for teff grain yield. However, there were significant differences among the water treatments in the same year for teff dry biomass yield. In 2010, there were significant differences among the water treatments for grain yield, although the water treatments for dry biomass yield did not show any significant

Table 4.1 Effect of supplemental irrigation on yield and yield components and irrigation water-use efficiencies of teff grown on Vertisols in 2009 and 2010.

	2009							2010			
W levels	NDVI	G (gm^{-2})	G_IWUE (gmm^{-1})	BM (gm^{-2})	BM_IWUE (gmm^{-1})	HI	Lodge (%)	G (gm^{-2})	G_IWUE (gmm^{-1})	BM (gm^{-2})	BM_IWUE (gmm^{-1})
W1	0.65a	178.9a	-	543.7a	-	0.33a	51.8a	50.9a	-	388.5a	-
W2	0.66a	167.4a	-0.2	519.5a	-0.4	0.32a	51.2a	58.7a	0.13	444.4ab	0.9
W3	0.63a	190.5a	0.1	568.0a	0.2	0.34a	52.2a	67.1a	0.16	502.7b	1.1

Levels not connected by the same letter are significantly different. G is grain yield; BM is dry biomass yield; G_IWUE is irrigation water-use efficiencies for grain and BM_IWUE is irrigation water-use efficiencies for dry biomass; W1 is zero irrigation or rain-fed, W2 is deficit supplementary irrigation, and W3 is full supplementary irrigation. NDVI is normalized difference vegetation index.

Table 4.2 Response of teff yield and yield components to various levels of nitrogen in Vertisols during the 2009 and 2010 cropping seasons.

	2009							2010			
N levels	NDVI	G (gm^{-2})	G_NUE ( )	BM (gm^{-2})	BM_NUE ( )	HI	Lodge (%)	G (gm^{-2})	G_NUE ( )	BM (gm^{-2})	BM_NUE ( )
N1	0.58a	145.2a	-	428.0a	-	0.31a	35.9a	45.4a	-	359.7a	-
N2	0.67b	195.7b	8.4	570.7b	23.8	0.34b	52.2ab	63.5ab	3.0	443.3ab	13.9
N3	0.69b	195.9b	5.6	632.4b	15.9	0.35b	67.1b	67.8b	2.5	532.6b	19.2

Levels not connected by the same letter are significantly different. G is grain yield; BM is dry biomass yield.
For nitrogen application treatments: N1 is 30, N2 is 60, and N3 is 90 kg ha^{-1} N; HI is harvest index; NUE_G is nitrogen use efficiencies for grain and NUE_BM is nitrogen use efficiencies for dry biomass.

Table 4.3 Combined irrigation-nitrogen-use efficiency of teff in Vertisols during the 2009 and 2010 cropping seasons.

	2009				2010			
N and W levels	G (gm^{-2})	G_INUE (%)	BM (gm^{-2})	BM_INUE (%)	G (gm^{-2})	G_INUE (%)	BM (gm^{-2})	BM_INUE (%)
N1W1	145.2ab	-	428a	-	49.17ab	-	350.8a	-
N1W2	132.9a	-9.9	407.1a	-4.88	47.53ab	-3.3	384.7a	9.7
N1W3	157.6ab	8.1	449.0a	4.9	39.57a	-19.5	343.5a	-2.1
N2W1	195.9ab	34.3	570.7ab	33.3	48.77ab	-0.8	364.0a	3.8
N2W2	193.8ab	33.5	564.1ab	31.8	73.03ab	48.5	508.6ab	45.0
N2W3	198.1ab	36.4	577.3ab	34.9	68.67ab	39.7	457.2ab	30.3
N3W1	195.7ab	34.8	632.4ab	47.8	54.87ab	11.6	450.5ab	28.4
N3W2	175.6ab	20.9	587.2ab	37.2	80.63b	63.9	614.7b	75.2
N3W3	215.8b	48.6	677.6b	58.2	67.77ab	27.7	532.6ab	51.8

Levels not connected by the same letter are significantly different ($p \geq 0.05$). Application treatments: N1 is 30, N2 is 60, and N3 is 90 kg ha^{-1} N; irrigation treatments: W1 is zero irrigation or rain-fed, W2 is deficit supplementary irrigation, and W3 is full supplementary irrigation; G is grain yield; G_INUE is irrigation-nitrogen use efficiency for grain yield; BM is dry biomass yield; BM_INUE is irrigation-nitrogen use efficiency for dry biomass yield; G_INUE and BM_INUE are expressed in percent relative to the control treatment (N1W1).

Table 4.4 Effect of supplemental irrigation on yield and yield components and irrigation water-use efficiencies of teff grown on Cambisols in 2009 and 2010.

	2009							2010			
W levels	NDVI	G (gm^{-2})	G_IWUE (gmm^{-1})	BM (gm^{-2})	BM_IWUE (gmm^{-1})	HI	Lodge (%)	G (gm^{-2})	G_IWUE (gmm^{-1})	BM (gm^{-2})	BM_IWUE (gmm^{-1})
W1	0.7a	93.3a	-	451.3ab	-	0.20a	45.6a	71.7b	-	536.2a	-
W2	0.7a	83.8a	-0.17	416.1b	-0.59	0.21a	42.2a	88.6b	0.69	567.7a	0.53
W3	0.6b	102.7a	0.09	486.6a	0.35	0.20a	48.9a	125.2a	0.63	599.4a	0.63

Levels not connected by the same letter are significantly different. G is grain yield; BM is dry biomass yield; NDVI is normalized difference vegetation index; HI is harvest index; G_IWUE is irrigation water-use efficiencies for grain and BM_IWUE is water-use efficiencies for dry biomass; W1 is zero irrigation or rain-fed, W2 is deficit supplementary irrigation, W3 is full supplementary irrigation.

differences. The reason for the inconsistent results is not clearly understood. Similar to the effects observed in teff grown in Vertisols, water levels had no effect on water lodging in Cambisols.

In 2009, relatively higher irrigation-nitrogen use efficiency for grain (G_INUE) and dry biomass (BM_INUE) were recorded in W3 as compared to W2. In contrast to the results obtained in 2009, in 2010, G_IWUE was higher in W2 than in W3 (Table 4.4) and BM_IWUE was relatively higher in W3 than in W2. Although these results show some inconsistencies, they indicate that full supplementary irrigation may be more advantageous than deficit irrigation for teff grown on Cambisols, under similar climate conditions.

During the 2009 and 2010 growing seasons, the response of teff to various levels of N on Cambisols indicated that grain and dry biomass yield increased significantly ($p < 0.05$) when teff was treated with N3, as compared to N2 and N1 (Table 4.5). In Cambisols, teff did not respond to N for lodging, although it did respond to N for NDVI. The NDVI values were higher in treatments N2 and N3 as compared to N1.

In both 2009 and 2010, the irrigation-nitrogen use efficiencies for grain (G_INUE) and for dry biomass (BM_INUE) were generally higher in N3 than in N2 (Table 4.6). This indicates that teff producing similar yield levels responded to relatively higher N levels when grown on Cambisols than on Vertisols. This could be attributed to low initial soil N content or to higher loss of N in Cambisols.

The highest irrigation-nitrogen use efficiency for grain (G_INUE) was recorded in treatment N3W3 (in both years) whereas the lowest G_INUE was observed in N1W2 and N2W1 in 2009 and 2010, respectively (Table 4.6). In 2009, the highest irrigation-nitrogen use efficiency for dry biomass (BM_INUE) was observed in treatment with N3W2 and the lowest (BM_INUE) was observed in treatments N2W1 and N1W2.

Table 4.5 Response of teff yield and yield components to various levels of nitrogen in Cambisols during the 2009 and 2010 cropping seasons.

	2009							2010			
N levels	NDVI	G (gm^{-2})	G_NUE ( )	BM (gm^{-2})	BM_NUE ( )	HI	Lodge (%)	G (gm^{-2})	G_NUE ( )	BM (gm^{-2})	BM_NUE ( )
N1	0.6b	60.5b	-	371.8c	-	0.16b	38.6a	77.3b	-	588.4a	-
N2	0.7a	102.0b	2.5	447.7b	12.7	0.23a	57.5a	92.7b	2.6	561.0a	-4.5
N3	0.7a	117.3a	3.7	534.5a	18.1	0.22a	40.6a	115.4a	4.2	554.0a	-3.8

Levels not connected by the same letter are significantly different. G is grain yield; BM is dry biomass yield; Nitrogen application treatments: N1 is 30, N2 is 60, and N3 is 90 kg ha^{-1} N; HI is harvest index; NUE_G is nitrogen use efficiencies for grain and NUE_BM is nitrogen use efficiencies for dry biomass; NDVI is normalized deviation vegetative index.

Table 4.6 Combined irrigation - nitrogen use efficiency of teff in Cambisols during the cropping season in 2009 and 2010.

	2009				2010			
N and W levels	G (gm^{-2})	G_INUE (%)	BM (gm^{-2})	BM_INUE (%)	G (gm^{-2})	G_INUE (%)	BM (gm^{-2})	BM_INUE (%)
N1W1	67.3a	-	390.4bc	-	50.4c	-	563.1a	-
N1W2	50.6a	-24.8	335.1c	-14.16	60.5c	20.0	585.1a	3.9
N1W3	63.6a	-5.5	389.9bc	-0.13	121.1ab	140.3	616.9a	9.6
N2W1	100a	48.6	447abc	14.50	63.9c	26.8	485.6a	-13.8
N2W2	86.4a	28.4	397bc	1.69	99.6b	97.6	615.6a	9.3
N2W3	119.6a	77.7	499ab	27.82	114.7ab	127.6	581.8a	3.3
N3W1	112.5a	67.2	516.5ab	32.30	100.8b	100.0	560a	-0.6
N3W2	114.5a	70.1	516.2ab	32.22	105.7b	109.7	502.4a	-10.8
N3W3	125.1a	85.9	570.8a	46.21	139.7a	177.2	599.6a	6.5

Levels not connected by the same letter/s are significantly different. G is grain yield; G_INUE is irrigation-nitrogen use efficiency for grain yield; BM is dry biomass yield; BM_INUE is irrigation-nitrogen use efficiency for dry biomass yield; G_INUE and BM_INUE are expressed in percent relative to the control treatment (N1W1); Nitrogen application treatments: N1 is 30, N2 is 60, and N3 is 90 kg ha^{-1} N; irrigation treatments: W1 is zero irrigation or rain-fed, W2 is deficit supplementary irrigation, and W3 is full supplementary irrigation.

4.4 Discussion

4.4.1 NDVI

In our studies, significantly higher NDVI values were observed in treatments with a higher rate of N than for those with a lower rate of N, which confirms that treatments with a lower rate of N were nitrogen deficient. However, it was not clear to us why NDVI values did not respond to water application levels.

4.4.2 Yield and yield components

Relatively higher dry biomass and grain yield were obtained when the crop was supplemented with a higher (W3) level of water. Increased yields may be attributed to increased uptake of nutrients and water from the soil. Prior studies have indicated that irrigation could improve grain yield (Araya et al. 2010b). Similarly, Habtegebrial and Singh (2006) reported that increased uptake of nutrients was observed in good growing seasons during which adequate soil moisture was available. In this study, the application of N3 in combination with W3 improved teff yield and dry biomass. As the rainfall in the study area was torrential in nature (i.e., high rainfall over a short time), nitrogen leaching, lodging, and drainage problems could occur during some of the growing season if not managed properly. For these reasons, N3 may not significantly improve yield and dry biomass of teff (local *keyh*) as compared to N2 under farmers' field management conditions. Habtegebrial et al. (2007) also documented relatively higher N leaching in treatments with higher N levels. Vertisols were also reported to have certain characteristics (such as poor drainage) that may limit the uptake of nutrients (Tulema et al. 2005).

Several studies showed that higher rates of N enhanced lodging (Tekalign et al. 2001, Habtegebrial and Singh 2006, Habtegebrial et al. 2007). Likewise, this study also indicated that lodging was enhanced by higher N levels. Under severe lodging, the panicles, as well as other parts of the teff plant, can stick to the soil and, the plant either may not form grain or it may not be possible to harvest the grain. Hence, based on our findings, considering the insignificant yield gains from the application of N3 over N2, and yield loss that could occur due to lodging as a result of excess N. Addition of an extra 30 kg ha^{-1} N on top of N2 is not recommended. In addition, farmers may not be able to accept this rate due to uncertain water supply, which is the case in most semi-arid regions where rain is the primary source of water. The N application requirements for teff in Vertisols were reported to vary between 60 and 80 kg ha^{-1} (Tekalign et al. 2001). Some of the experimental plots with full supplementary irrigation and higher N in our study resulted in about 2500 kg ha^{-1} of grain yield, which agrees with Tulema et al. (2005).

4.4.3 Nitrogen-use efficiency

Habtegebrial and Singh (2006) reported that nitrogen-use efficiency of teff could be limited by the time of application and the deficiency of other essential elements in the soil, such as sulfur. In some studies, phosphorus deficiency was also reported to reduce the nitrogen uptake and nitrogen-use efficiency (Delve et al. 2009). However, the judicious use of mineral fertilizers, coupled with optimum water supply, can help improve the grain and dry biomass yield. In this study, one of the reasons for a relatively higher grain nitrogen-use efficiency with a moderate nitrogen fertilizer application (N2) on Vertisols could be relatively better soil water availability. Lower N leaching and denitrification and relatively higher initial organic matter and total nitrogen content of Vertisols could also have helped when compared with the result for Cambisols.

4.4.4 Combined irrigation-nitrogen-use efficiency

Combined response of irrigation-nitrogen-use efficiency (G_INUE) on teff was found to increase with increasing water and nitrogen levels. However, increasing water level alone without also increasing the nitrogen level may not significantly improve teff yield. In this study, the interaction effect of both nitrogen and water levels has shown a considerable difference among the treatment combinations. Thus, the interaction effect must be well understood as it is more important for better decision making than are the effects of either nitrogen or water level alone. However, the increase in INUE with increasing nitrogen and water levels may slightly vary with genotypes (Araya, unpublished data) and soil characteristics. Balcha et al. (2006) also suggested the selection of genotypes that have a better N use efficiency at a lower supply of nitrogen.

If teff is fully supplemented with irrigation, the G_INUE could be doubled, provided that the nitrogen level is also increased (e.g., N3). However, it cannot be guaranteed that this condition will always hold true, due to the possible occurrence of unforeseen events, such as flooding, hail, and windy conditions, which usually increase the chance of teff lodging. This research revealed that when N3 was combined with full supplementary irrigation (W3) on Cambisols, it can result in a relatively higher teff yield. In contrast, lower N, when combined with higher water (or vice versa) can result in low teff yield. This is consistent with Araya et al. (2010b and 2011), who reported that teff under high N levels, in combination with low water availability conditions, could result in low yield. Therefore, increasing water without nitrogen has little significance in teff productivity. Hence, optimizing the water level in accordance with rate of nitrogenous fertilizer, as presented in this study, can improve teff yield in the drylands. Therefore, agronomic decisions need to be made based on the most effective interactions between supplemental irrigation and nutrient levels for improved yield and water use efficiencies (Howell 2001; Mandal et al. 2005).

4.5 Conclusions

Production and productivity of teff crops in northern Ethiopia increase when rainfall is complemented with an adequate supply of nitrogen. Combined supplemental irrigation water and nitrogen use efficiency increases with increasing water and nitrogen levels. However, increased use of water alone does not guarantee a higher teff yield. Similarly, increasing the amount of nitrogen would not increase yield if the water supply does not adequately support physiological functions. Due to lodging (when there is adequate water) or to unsuitable interdependence interaction effects (when moisture is limited), applying the N rates beyond 60 kg ha^{-1} is unlikely to result in a significant increase in yield. Hence, the optimum nitrogen rate recommended to increase teff yield, in the study, area is 60 kg N ha^{-1} when teff is grown under adequate moisture availability condition.

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5. Climate-Smart Integrated Soil Fertility Management (CS-ISFM)

Gebreyohannes Girmay[a]* and Gebretsadik Reda[b]

Summary

Agricultural production systems and associated livelihoods in northern Ethiopia are threatened by declining soil fertility due to degrading and dwindling natural resources under high population density, while climate change is adding further pressure to the already stressed systems. To restore soil fertility, the application of mineral fertilizers has been recommended for farms in the region. However, northern Ethiopia has significant spatial variability of soils within farms, making the recommendation to apply blanket rates of fertilizer to farms less effective and also more expensive. Knowledge gaps about the appropriate levels of nutrients to apply to different crops under various soils of northern Ethiopia have prevented resource-poor farmers from adopting appropriate integrated soil fertility management. This chapter presents some evidence of the positive impacts of climate-smart integrated soil fertility management (CS-ISFM), which is defined as practices that increase and stabilize yields through any, or a combination of, the following: (1) application of critical nutrient levels optimized for different soil types; (2) enhancement of nutrient use efficiency by adopting proper soil moisture management; and (3) integration of legumes in cropping systems to ensure improved livelihoods of smallholder farmers in the dryland areas. CS-ISFM approaches have the potential to sustainably enhance agricultural productivity, while improving ecosystem health and societal resilience to climate shocks and contributing to the reduction of greenhouse gas (GHG) emissions in Ethiopia and beyond. Further research on the spatial variability of soils, establishing critical nutrition levels, optimizing fertilization, and developing optimal CS-ISFM are needed to have evidence-based proper planning and the implementation and scaling-up of CS-ISFM adapted to specific and local contexts.

Keywords: agriculture, soil nutrient, smallholder farmers, leguminous crops, cropping system, faba bean, CS-ISFM, Ethiopia

5.1 Introduction

Agriculture has been the mainstay of the Ethiopian economy (Alexandratos 1995, Gebreegziabher 2007), which has been engaged in subsistence farming, and also where a mixed crop-livestock farming system has been in use for centuries. At the same time, Ethiopia has been facing serious food shortages since the 1970s, as the production of food has not kept pace with increases in human population (Belay et al. 1998, Elias 2002). According to the Food and Agriculture Organization of the United Nations (FAO 1984 and 1986), accelerated soil erosion, nutrient mining, and declining soil fertility are among the main causes that have contributed to declining agricultural productivity in Ethiopia. Stoorvogel and Smaling (1990) estimated that Ethiopia could face severe soil nutrient depletion (e.g., -47 kg N ha^{-1}, -15 kg P_2O_5 ha^{-1} and -38 kg K_2O ha^{-1}), with values that were twice the average values estimated for Sub-Saharan Africa. Although estimated soil erosion data have triggered a national debate, the average soil loss from cultivated land in the highlands was estimated to be 130 t ha^{-1} yr^{-1} (FAO 1984). More recent studies reported estimated soil loss ranging from 9.63 t ha^{-1} yr^{-1} (Gebreyesus and Mekonen 2009); 11.89 t ha^{-1} yr^{-1} for a catchment in the highlands of Tigray (Gebreyohannes 2013); to 18 t ha^{-1} yr^{-1} for cultivated areas (Nyssen et al. 2007). Food and nutrition security in Ethiopia under the projected population growth and climate change impacts cannot be achieved without efforts to enhance soil fertility management.

The awareness of declining soil fertility problems in Africa grew after FAO (1984) nutrient balance studies (Stoorvogel and Smaling 1990). However, initial efforts to understand

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[a] Mekelle University, Department of Land Resources Management and Environmental Protection, Mekelle, Ethiopia designated

[b] Bureau of Agriculture and Rural Development, Tigray Region, designated

* *Correspondence:* Gebreyohannes Girmay (email: gebreyohannes.girmay@gmail.com)

these problems were characterized by many polarities in concepts and approaches (FAO 1984), resulting in more attention given to physically controlling soil erosion than to managing soil fertility. The current efforts to solve low soil fertility in tropical soils are shifting their paradigms towards reframing and redefining the integrated soil fertility management (ISFM) approach. According to Vanlauwe et al. (2004), ISFM promotes a combined application of locally available organic resources and mineral fertilizers. Vanlauwe et al. (2010) defined ISFM as "a set of soil fertility management practices that necessarily include the use of mineral fertilizers, organic inputs, and improved germplasm combined with the knowledge on how to adapt these practices to local conditions, aiming at maximizing agronomic use of the applied nutrients and improving crop productivity."

This study further advances the concept of ISFM to be scaled up in an Ethiopian context and beyond by integrating it with climate-smart agriculture (CSA), which has three pillars—adaptation, mitigation, and enhancing productivity—as the basis for addressing and responding to climate change. We define climate-smart ISFM (CS-ISFM) as practices that increase and stabilize yields through any or a combination of the following: (1) application of critical nutrient levels optimized for different soil types; (2) enhancement of nutrient use efficiency by adopting proper soil moisture management; and (3) integration of legumes in cropping systems to ensure improved livelihoods of smallholder farmers in the dryland areas. CS-ISFM approaches have the potential to sustainably enhance agricultural productivity, while improving ecosystem health and societal resilience to climate shocks, as well as to contribute to the reductions of greenhouse gas (GHG) emissions in Ethiopia and beyond.

CS-ISFM is especially needed in the Ethiopian Highlands, where over half of the cultivated areas are in an advanced stage of land degradation due to the rugged topography and steep slopes, removal of the vegetation cover, and high rainfall erosivity, all leading to massive soil erosion (Elias 2002, Nyssen et al. 2004, Gebreegziabher 2007). The severe nutrient deficiencies of the agricultural soils call for the addition of nutrients at optimum rates and at optimal times, and specific for different soil types. Additionally, these issues necessitate conserving soil moisture, growing nitrogen-fixing species, retaining crop residue, and converting degraded lands to perennial vegetation. Application of mineral fertilizers has been recommended to restore the low soil fertility of farms, along with *in situ* soil conservation during the growing period to increase the amount of available soil moisture, which enhances nutrient uptake and crop yield. However, northern Ethiopia has significant spatial variability of soils within farms, making the recommendation to apply blanket rates of fertilizer (e.g., 100 kg ha^{-1} urea and diammonium phosphate (DAP) each) to farms less effective and more expensive. Lack of knowledge of the appropriate levels of nutrients to apply to different crops under various soils of northern Ethiopia has prevented resource-poor farmers from adopting appropriate integrated soil fertility management practices.

This chapter aims at elucidating some evidence and potential benefits of the application of CS-ISFM in northern Ethiopia through (1) applying critical nutrient levels optimized for different soil types, (2) integrating soil moisture management, and (3) integrating legumes into the cropping systems. The next sections review (1) the importance of correct knowledge of critical nutrient levels for different soil types, (2) proper soil moisture management technologies, and (3) the role of legumes in the cropping patterns in northern Ethiopia to reverse soil nutrient depletion and improve crop productivity. It then discusses the potential opportunities to scale-up CS-ISFM in Ethiopia and beyond.

5.2 The Need to Integrate the Information on Spatial Variability of Soil Type for Fertilizer Use

In Ethiopia, stakeholders and decision makers recognized soil nutrient depletion as a major constraint that challenges agriculture and rural development (Smaling et al. 1993, 1996). One of the difficulties in reversing the declining soil fertility trend is the limited access farmers have to fertilizers and the subsequent vicious cycle of soil fertility depletion and poverty this causes (Sanginga et al. 2003). Although many efforts for improving soil fertility do not consider farmers' knowledge of fertility management for local soils, smallholders recognize spatial soil variability within farms and adjust land management accordingly (Westphall et al. 1981, Buttner and Hauser 2003). Soil qualities at the farm scale also depend on nutrient management by farmers: the manipulation of nutrient stocks and flows, nutrient inputs in the system through organic and mineral amendments, nutrient export via crop harvest and crop residue removal, and conversion within the production systems (Bationo et al. 1998, Duegd et al. 1998).

The different soil types in the northern parts of Ethiopia include Leptosols, Vertisols, Cambisols, Arenosols, Regosols, Calcisols, Phaeozems, and Solenchacks (to a limited extent)

(FAO 1984). The spatial variability of soils and nutrient contents is high (Gebreyohannes 2001), and so demands the establishment of site-specific fertilizer application rates.

Despite this need, critical nutrient levels of soils have not yet been established. The critical nutrient level indicates a point beyond which increased application of mineral fertilizer is less likely to result in any increase of crop growth and yield (Cate and Nelson 1965). The critical nutrient level value is often determined from soil tests of scattered plots, which relate nutrient levels to a corresponding relative grain yield of a given crop. Beyond this critical level, the cost of additional fertilizer to produce extra crop yield would likely be greater than the value of the extra yield. A study by Gebreyohannes (2013) in northern Ethiopia reported that the critical concentrations of phosphorus (P) for different soil types were about 6 mg kg^{-1} for Vertic Cambisols, 4.32 mg kg^{-1} for Arenic Cambisols, 5.89 mg kg^{-1} for Pellic Vertisols, and 6.62 mg kg^{-1} for Calcaric Regosols. Likewise, Kidanemariam and Assen (2008) reported that the critical phosphorus level on teff fields in northwestern part of Ethiopia is 6 mg kg^{-1}. The phosphorus contents of the soils that received 23, 46, and 69 kg P ha^{-1} were 5.55, 8.38, and 8.59 ppm for Vertic Cambisols; 3.06, 5.57, and 4.46 ppm for Arenic Cambisols; 4.01, 6.71, and 7.48 ppm for Pellic Vertisols; and 3.49, 4.63, and 5.08 ppm for Calcaric Regosols, respectively. In addition, Gebreyohannes (2013) also recommended optimum rates of phosphate fertilizers based on the critical phosphorus levels for different soil types (e.g., 7 kg P ha^{-1} for Vertic Cambisols; 37 kg P ha^{-1} for Arenic Cambisols; 60 kg P ha^{-1} for Pellic Vertisols; and 62 kg P ha^{-1} for Calcaric Regosols (Table 5.1)).

Soil specific mineral nutrient application enhances crop nutrient use efficiency, which increases crop yield and adds soil organic matter important to achieving climate smart soil fertility management.

5.3 Conserving Soil Moisture for Improved Fertilizer Use

Water shortages are one of the major constraints that limit agricultural production in arid and semi-arid regions (Haibu et al. 2006). According to Haibu et al. (2006), erratic rainfall affects crop yield in arid and semi-arid regions in east Africa. In these areas, efficient rainwater harvesting and conservation may be seen as alternative options for smallholder producers looking to adopt inputs, such as fertilizers and improved varieties. Li (1998) reported that the more efficient utilization of rains could increase the availability of water for crops and thus would increase and stabilize crop yields.

Because rainfall erosivity, soil erodibility, and changes in land forms (coupled with improper soil management) lead to alarming annual soil loss rates, there is a need for improvements in control of soil erosion and runoff water as well as for better crop management practices (Lal 1977a, Hudson 1977). Because of erratic rainfall in semi-arid regions, it is, thus, important not to focus only on erosion control, but also on harvesting and storing the limited rainwater that is used in the crop root zone, which enhances crop productivity (Wiyo et al. 2000). For example, tied-ridge plots, as an *in situ* soil and water conservation technique, improve soil moisture and increase crop yields (Belay et al.

Table 5.1 Amount of P fertilizer required as determined based on the Critical P levels and P requirement factors for the different soil types.

Soil type	P_0 (mg kg^{-1})	P_c	P_c-P_0 (mg kg^{-1})	P_f [(kg P ha^{-1})/(mg kg^{-1})]	P required (kg P ha^{-1})
Vertic Cambisol	3.13	6.00	2.87	8.59	25
Arenic Cambisol	0.28	4.32	4.04	4.03	16
Pellic Vertisol	1.66	5.89	4.23	6.07	26
Calcaric Regosol	0.51	6.62	6.11	4.40	27

Source: Gebreyohannes (2013)

1998, Motsi et al. 2000, Gebrekidan 2003). Gebretsadikan (2008) also reported that grain yield of sorghum was significantly higher in plots with tied-ridges than in plots with flat-beds. On Vertisols, maximum sorghum grain yield (2827 kg ha^{-1} for tied-ridge plots vs. 1472 kg ha^{-1} for flat-bed plots) was found where both plots received 20–23 N-P kg ha^{-1} (Table 5.2), whereas the maximum sorghum grain yields on Calcisols were 1494 kg ha^{-1} for tied-ridge plots that received 10–23 N-P kg ha^{-1} and 279 kg ha^{-1} for flat-bed plots that received 20–23 N-P kg ha^{-1}.

Similarly, planting in the furrows of the tied-ridge plots without fertilizer was found to produce a reasonable sorghum grain yield as compared to the fertilized treatments on flat-bed plots (Gebretsadikan 2008). This indicates that an increase in soil moisture in a plot with tied-ridges would improve the efficient use of nutrients and, consequently, improve the yield. House (1979) indicated that the stage between flowering and grain formation in sorghum coincides with the maximum evapotranspiration per day, and, thus, it is very important to provide adequate moisture at this stage.

Table 5.2 Effects of *in situ* soil moisture conservation and N and P fertilizer application on sorghum grain yield in the southwestern lowlands of Tigray, northern Ethiopia.

Treatment	Vertisol			Calcisol			Cambisol		
	Yield (kg ha^{-1})	Diff.	%	Yield (kg ha^{-1})	Diff.	%	Yield (kg ha^{-1})	Diff.	%
Tied ridge									
Fertilized	2827	803	40	1494	677	83	1745	570	49
Unfertilized	2924			817			1175		
Flat-bed									
Fertilized	1472	366	33	279	154	123	318	214	206
Unfertilized	1106			125			104		
Tied-ridge fertilized vs. flat-bed fertilized									
Tie ridge fertilized	2827	1355	92	1494	1215	435	1745	1427	449
Flat land fertilized	1472			279			318		
Tied-ridge unfertilized vs. flat-bed unfertilized									
Tie ridge unfertilized	2024	918	83	817	692	534	1175	1071	1030
Flat land unfertilized	1106			125			104		
Tied-ridge unfertilized vs. flat-bed fertilized									
Tie ridge unfertilized	2024	552	38	817	538	193	1175	857	269
Flat land fertilized	1472			279			318		

Source: Gebretsadkan (2008). ‘Diff.’ on the column titles refers to ‘Difference’.

Studies that compared the benefits of closed-end tied-ridges and furrow planting methods on improving the crop growth and yield indicated that there is a significantly higher crop growth and yield during the rainy season with a low total rainfall distribution (Macartney et al. 1971, Moldenhauer and Onstand 1977, Gebrekidan 1989, Belay et al. 1998, Gebrekidan and Uloro 2002). Similarly, several researchers (Kowal 1970ab, Macartney et al. 1971, Moldenhauer and Onstand 1977, Gebrekidan 1989, Belay et al. 1998, Gebrekidan and Uloro 2002) also reported that tied-ridge plots increased the crop yield by increasing the time for the water to infiltrate into the soil. More water is harvested and retained in furrows than in the tied-ridge and flat-bed plots (Kowal 1970ab; Belay et al. 1998, Gebrekidan and Uloro 2002). Additionally, sorghum plants supplied with enough available moisture throughout the growing period produced a higher grain yield than sorghum plants that were planted in the furrows. Likewise, Belay et al. (1998) found the water harvested and retained by the furrows of tied-ridges could ease the water deficit periods that are mainly observed in the drylands of Ethiopia. Moreover, the study revealed that sorghum planted on tied-ridges without NP fertilization produced a lower yield than sorghum planted on tied-ridge with NP fertilization (Belay et al. 1998, Gebrekidan and Uloro 2002). Climate smart practices such as *in situ* rain water harvesting improve crop responses to applied mineral nutrients, resulting in higher crop yields.

5.4 Restoring Soil Fertility through Integrating Improved Legumes

Ethiopia is the largest producer of grain legumes in Africa (Yemane and Skjelvåg 2003), and the faba bean, which occupies 34% of the total cultivated areas for legumes, is the most important (CSA 2007). Despite this, legume yield is very low (often less than 0.5 t ha^{-1}) (Tsigie and Woldeab 1994) because legumes are mostly grown in inherently poor soils. For instance, legumes are cultivated in Calcareous soils, which are common, and represent some of the poorest soils in arid and semi-arid areas (Marschner 1995, Brady and Weil 1999). Calcareous soils are also characterized by large concentrations (>15%) of free carbonates (CO_3^{2-}) of calcium (Ca) and magnesium (Mg) (Hagin and Tucker 1982, Leoppert and Suarez 1996). The excess $CaCO_3$ buffers the soil pH between 7.5 and 8.5, a condition that reduces availability of N, P, Zn, Mn, and Fe (Marschner 1995, Brady and Weil 1999).

Most soils in the Ethiopian Highlands are low in soil organic matter (SOM) and deficient in N (Pulschen 1987), and P (Beyene 1988, Mamo et al. 1988). Improving fertility of the soils through applying optimum rates of mineral fertilizers is becoming unaffordable (Haregeweyn et al. 2008). Moreover, in the highlands, due to land shortages, farmers no longer practice the fallowing tradition, nor do they apply manure on their cropland, due to its limited availability. Instead, cultivating leguminous crops such as beans, chickpeas, and lentils, following the cultivation of cereals, is considered a form of soil fertility maintenance.

In terms of its affordability, and because it is already a local practice, growing legumes can be considered an alternative means of improving food production while restoring soil fertility (Carlos and Minguez 2001). To optimize grain yields and symbiotic N_2 fixation, legumes also require an adequate supply of nutrients (Jakobsen 1985, Henry et al. 1995, Leidi and Rodiguez-Navarro 2000, Santos et al. 2006). Except the reports on the effect of P on improving yields of legume crops (Tsigie and Woldeab 1994, Yemane and Skjelvåg 2003) and nodulation and symbiotic N_2 fixation of grain legumes (Amanuel and Tanner 1991, Habtegebrial et al. 2007), there is generally limited information on applying mineral fertilizers to grain legumes, especially those cultivated in poor soils in Ethiopia.

Therefore, it is important to provide the necessary information on the effects of mineral fertilizer on legume crops grown alone and for those intercropped/rotated with cereal crops; it must also be noted, however, that legumes already improve soil fertility and crop yield by fixing nitrogen (N). Among the grain legumes, faba bean is reported to fix the most N from the atmosphere. A study by Amanuel et al. (2000) in sub-humid conditions of southern Ethiopia reported that the percentage of N derived from the atmosphere by faba bean varies from 62% to 74%, with the corresponding N_2 fixed ranging from 152 to 189 kg N ha^{-1}. Sulfur fertilization ranging from 97 to 200 kg N ha^{-1} applied to faba bean, in semi-arid regions of northern Ethiopia, also increases total N fixation by faba bean (Habtegebrial et al. (2007).

A study on the effect of mineral fertilizers on faba bean production was conducted on Calcaric Regosols in northern Ethiopia. The study revealed that the total number of initiated nodules per faba bean plant in response to mineral fertilizer application at rates of 25-23 kg Zn-P ha^{-1} and 15-23 kg Zn-P ha^{-1} was 225 and 362, respectively (Figure 5.1, Gebreyohannes 2013). This indicates that an increase in Zn application, without P, particularly on the Calcaric Regosols, did not result in high initiation and development of root nodules. Application of 15 kg Zn ha^{-1}, with increasing P rates, significantly increased the number of effective root nodules (i.e., >5 mm in diameter). The number of effective root nodules was significant at application rates of 15-23 kg Zn-P ha^{-1} and 25-23 kg Zn-P ha^{-1}, which resulted in 5 to 11 and 7 to 12 nodules/plant, respectively (i.e., many effective nodules) (Beck et al. 1993). The application rate of 15-46 kg Zn-P ha^{-1} resulted in 6 to 8 nodules/plant (i.e., few effective nodules) (Beck et al. 1993). Development rate of effective root nodules, on average, was higher. Specifically, development was 122% (at 15-23 kg Zn-P) and 167% (at 25-23 kg Zn-P ha^{-1}) higher than the control (Figure 5.1). Root nodulation of faba bean declined when the application rates of Zn and P rose to 25 kg Zn ha^{-1} and 46 kg P ha^{-1}, respectively.

In addition, the study demonstrated that application of P and Zn fertilizers boosted the yield of faba beans. For example, application of 15 kg Zn ha^{-1} alone resulted in a significantly higher grain yield (i.e., 1,362 kg ha^{-1} in 2009 and 1653 kg ha^{-1} in 2010; see Figure 5.2) as well as biomass yield (i.e., 3,822 kg ha^{-1} in year 2009 and 4,593 kg ha^{-1} in year 2010 in which amount of rainfall was better than that in 2009). The next highest yield was attained when only P was applied (see Figure 5.2). Faba bean responded better to applications of P (23 kg P ha^{-1}) and Zn (15 kg Zn ha^{-1}) than to both in combination. These application rates are found to be within the range of faba bean requirements for 20-30 kg P ha^{-1} and 10-25 kg Zn ha^{-1} (FAO 2000). The response of

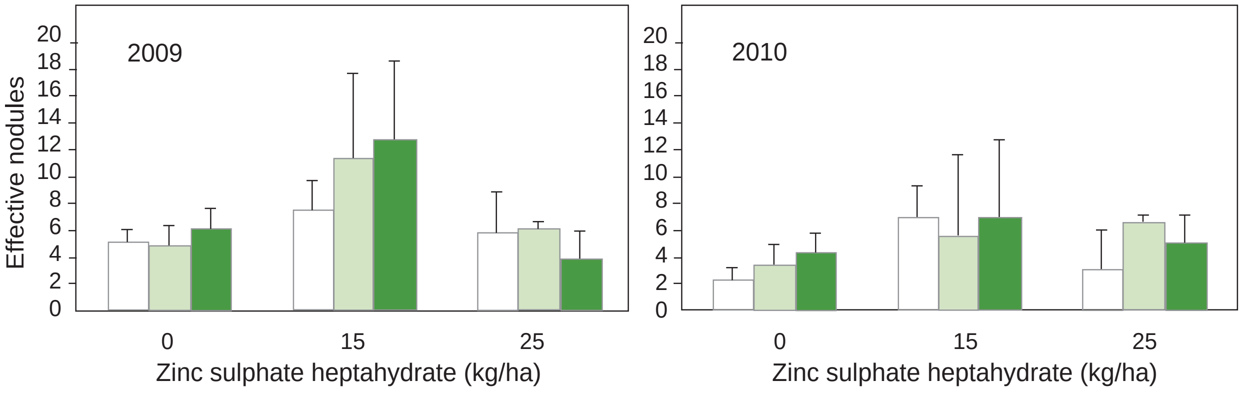

Figure 5.1 Effect of P and Zn application on nodulation of faba bean on Calcaric Regosol (source: Gebreyohannes 2013).

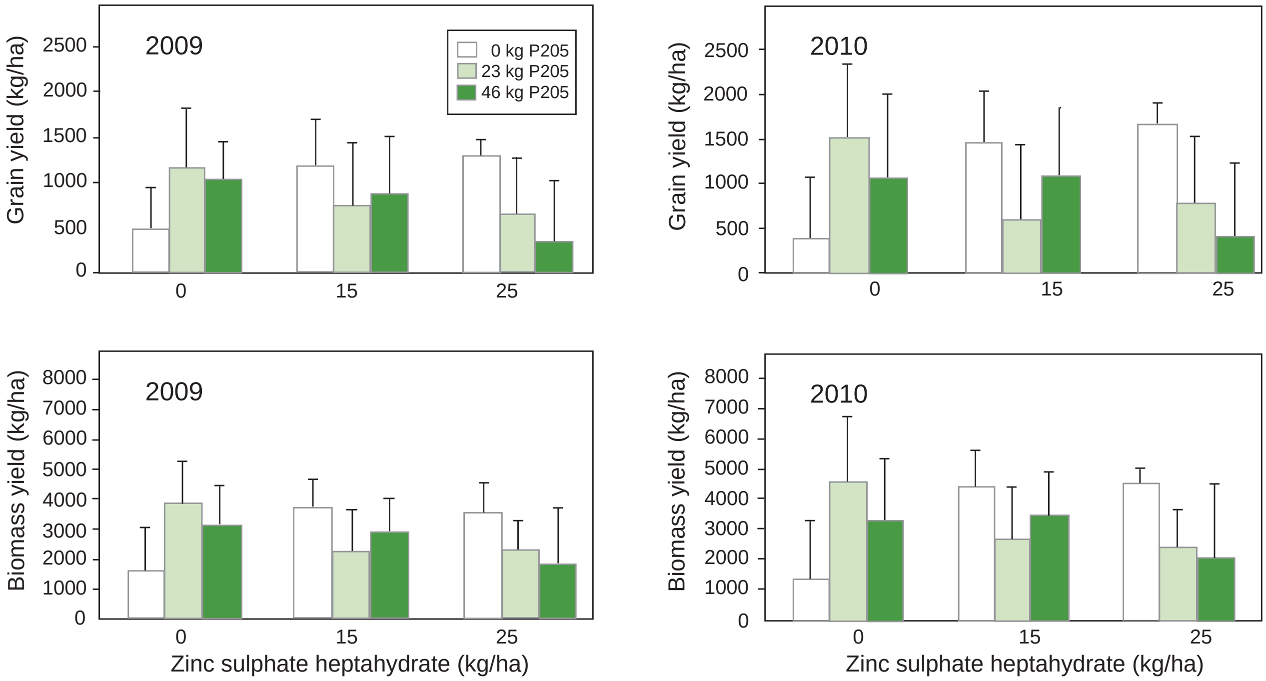

Figure 5.2 Effect of P and Zn application on yield and yield components of faba bean on Calcaric Regosol (source: Gebreyohannes 2013).

faba bean to Zn resulted in an increased grain yield, ranging from 121% to 242% of the control, and biomass yield from 124% to 188% of the control. Similarly, the production increase of faba bean in response to P ranged from 200% to 223% of the control, for the grain yield, and from 176% to 178% of the control, for the biomass. However, an increased rate of Zn-P to 25-46 kg ha^{-1} resulted in a reduced yield of faba bean. In soils marginally deficient in P and Zn, high P fertilization would induce Zn deficiency in plants by affecting the Zn solubility and mobility in plant cells and tissues (Marschner 1995).

In addition to their positive effect on soil fertility and crop yields, legumes intercropped and/or rotated with cereals also lowered the rhizosphere pH through enhanced nodulation and NH_4^+ uptake by plants, leading plant roots to release H^+. The total soil nitrogen (N_{tot}) content after harvest was 0.34 g N kg^{-1} for year 2009 and 0.36 g N kg^{-1} for year 2010 significantly increased when treatments received 25 kg Zn ha^{-1} alone as compared to treatments that received combined levels of Zn and P (Table 5.3, Gebreyohannes 2013). The application of Zn resulted in low soil N_{tot} (0.18 g N kg^{-1} for 2009 and 0.21 g N kg^{-1} for 2010) when it was combined with P, specifically at the rate of 25-46 kg Zn-P ha^{-1}. Gebreyohannes (2013) reported that application rates of 15 to 23 kg Zn-P ha^{-1} and 25 to 23 kg Zn-P ha^{-1} did not show a significant improvement in available P (P_{av}) in the soil, probably due to enhanced P_{av} uptake. Available P in the soil increased, compared to the control, by 173%, at a rate of 15-23 kg Zn-P ha^{-1}. However, increases in P_{av} were also associated with an increasing rate of P (46 kg ha^{-1}).

5.5 Discussion and Conclusions

CS-ISFM refers to practices that increase and stabilize yields through application of critical nutrient levels optimized for different soil types wherein nutrient use efficiency is also enhanced by adopting proper soil moisture management, as well as by integrating legumes in cropping systems in order to improve the livelihoods of smallholder farmers in dryland areas. Blanket recommendations of mineral fertilizers have often been implemented in the Sub-Saharan African countries. Studies in northern Ethiopia show significant response of wheat to urea and diammonium phosphate (DAP), each applied at rates of 100 kg ha^{-1} on all soils low in organic carbon, total N, and available P. However, the optimum rates of P fertilizers, based on the critical levels for different soil types, were 57 kg P ha^{-1} (i.e., equivalent to 124 kg DAP ha^{-1}) for Vertic Cambisols; 60 kg P ha^{-1} for Pellic Vertisols; and 62 kg P ha^{-1} for Calcaric Regosols.

The amount of available moisture in dryland soils determines nutrient uptake and crop yield. Thus, *in situ* soil conservation during the growing period increases crop response to applied fertilizers and crop yield. For instance, sorghum yield in northern Ethiopia almost doubled on Vertisols and increased by six-fold on Calcisols when tied-ridges were used, compared to flat-beds, when all received 20 to 23 N-P kg ha^{-1}.

Legumes, such as faba beans, can play an important role in improving the availability of N and P in calcareous soils because of their high N_2 fixing capacity. In addition to

Table 5.3 The effect of P and Zn, and their interactions on the soil's N_{tot} and P_{av} after faba bean.

		2009		2010	
Treatment (kg P-Zn/ha)	pH (H_2O)	N (g/kg)	P (ppm)	N (g/kg)	P (ppm)
0-0	8.16	0.16^{c}	1.94^{e}	0.19^{cd}	2.42^{cd}
0-15	8.17	0.18^{c}	2.17^{de}	0.22^{cd}	3.01^{cd}
0-25	7.95	0.34^{a}	3.07^{de}	0.36^{a}	3.48b^{c}
23-0	8.20	0.21^{b}	3.34^{de}	0.25^{c}	3.23^{c}
23-15	8.18	0.29^{ab}	3.22^{de}	0.36^{a}	4.36^{ab}
23-25	8.21	0.25^{b}	4.17^{cd}	0.28^{b}	3.17^{cd}
46-0	7.81	0.23^{b}	8.12^{ab}	0.34^{a}	3.76^{bc}
46-15	8.21	0.32^{a}	9.74^{a}	0.29^{b}	4.97^{ab}
46-25	8.49	0.18^{c}	6.33^{bc}	0.21^{cd}	7.81^{a}
LSD	*1.06*	*0.55*	*2.49*	0.41	0.62

Source: Gebreyohannes (2013); Difference among figures with the same letter in a column are non-significant.

macronutrients, applying optimum rates of micronutrients to legumes grown for food on poor soils synergistically improves the N and P status of soils, which in turn helps to enable sustained farming on marginal soils.

Substantial increases in grain food production and income can be achieved on soils of declining fertility by following climate-smart soil management approaches, such as the proper addition of nutrients, *in situ* moisture conservation, and the growth of legumes and cover crops, which are rotated with cereals. Further research on the spatial variability of soils, establishing critical nutrition levels, optimizing fertilization, and developing optimal CS-ISFM are needed in order to conduct evidence-based planning, implementation, and scale-up of CS-ISFM adapted to specific and local contexts.

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PART III. Enhancing Ecosystem Resilience at the Landscape Scale

Photos (clockwise, from top left): Eastern Tigray landscape, with rainwater harvesting pond used for irrigation purposes during the dry season; the Afromontane forest of Northern Ethiopia, Tigray and Afar border; East Wollega, Oromia region; and North Shoa, Amhara region, Central Ethiopia (all photos by Aklilu Negussie).

6. Restoration of Degraded Landscapes: Lessons from Northern Ethiopia

Niguse Hagazi[a]*, Aklilu Negussie[b], Kiros Meles Hadgu[a], Emiru Birhane[c], and Zelalem Hadush[c]

Summary

Addressing the root causes of poverty and environmental degradation through restoring degraded areas using proper soil and water conservation, reforestation, afforestation, grazing land management practices, etc., has been one of the development priorities in Ethiopia. To this end, community-led watershed-based land restoration and natural resource management (NRM) programs have been implemented and have brought some desired changes in the landscapes of Tigray, northern Ethiopia. However, the land restoration successes have not been studied for scaling up. The aim of this chapter is to review the participatory and integrated watershed-based land restoration efforts and practices in northern Ethiopia and to draw lessons for better understanding so as to scale out to similar agroecologies. This chapter reviews the historical process of landscape restoration in Tigray and discusses key factors, especially, direct and indirect benefits of land restoration, which contributed to sustainable adoption and scale-up. Comparing the land restoration approaches before and after the 2000s, this chapter highlights the importance of enabling institutions including coordinating programs and policies for extension approaches among key stakeholders on watershed restoration, as well as establishing and enacting local bylaws for the mobilization of community members, including women, the elderly, and youth.

Keywords: land degradation, restoration, participation, watershed management, Tigray

6.1 Introduction

Land degradation in Ethiopia has been one of the major factors to negatively affect food production and economic growth in Ethiopia (Hurni 1993, Kebrom 1999, Girma 2001, Amare et al. 2005). Much of the degraded land has been found in the highlands of Ethiopia, which cover around 45% of the country's total area (FAO 1986). The landscape degradation due to deforestation, degradation of natural vegetation, overgrazing and over-cultivation leads to soil and water erosion (El-Swaify and Hurni 1996). The consequences of land degradation are manifold and are also expressed in terms of decreasing soil organic matter (Mulugeta et al. 2005), soil nutrient depletion (Haregeweyn et al. 2008), deteriorating soil quality (Solomon et al. 2000), and shrinking size of farmlands due to population pressure (Nyssen et al. 2006). Land degradation has also contributed to siltation of downstream reservoirs (Haregeweyn et al. 2006, Haregeweyn et al. 2012). Land degradation adversely affects the economic importance of soil and water resources and causes severe economic consequences including, but not limited to, declining agricultural production, chronic food shortages, and reduced farm income (Sonneveld and Keyzer 2002). Hence, land degradation is considered a major challenge for the Ethiopian agriculture sector and should be halted or reversed through the adoption of integrated approaches and policies.

The Ethiopian Highlands, especially the northern Highlands, have been reported as some of the most degraded land areas in Africa (El-Swaify and Hurni 1996, Nyssen et al. 2004). The landscapes of the northern Ethiopian Highlands are characterized by steep topography and inadequate and erratic rainfall distribution (Nyssen et al. 2004, German et

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[a] World Agroforestry (ICRAF) - Ethiopia, c/o ILRI Ethiopia, P. O. Box 5689, Addis Ababa, Ethiopia

[b] WeForest, Ogentroostlaan 15, B-3090 Overijse, Belgium

[c] Mekelle University, Mekelle, Ethiopia

* *Correspondence:* Niguse Hagazi (email: nigusehagazi@gmail.com)

al. 2012, TANGO International and Institute of Development Studies 2012). In these areas, particularly Tigray, land fragmentation, small-size landholdings, and lack of diversification in economic activities are constraining agricultural production (German et al. 2012; TANGO International and Institute of Development Studies 2012). The landscape degradation there is driven mainly by human and livestock pressures coupled with the limited adoption of appropriate conservation technologies and inefficient extension systems (Sonneveld and Keyzer 2002). Consequently, the region has been significantly affected by landscape degradation.

Since the early 1980s, some efforts have been made to mitigate land degradation problems in the highlands of Ethiopia, mainly in North Wello, Tigray, Eastern Hararge, and North Shoa (Hurni 1990, Mitiku et al. 2006). Massive campaigns have been carried out since the early 1980s in an effort to build terraces on farmlands and hillsides to tackle soil erosion (Figure 6.1; Hurni 1990, Gebremichael 2002). Currently, a significant portion of the northern Ethiopian Highlands has been restructured with millions of hectares of terraces. What has contributed to this successful scale-up? Initially, in most cases, these interventions were neither participatory nor evidence-based, but instead were introduced without prior assessment of the problems of land degradation or the conservation needs of the local environment (Mitiku et al. 2006). The greater emphasis of land restoration programs was given to physical soil conservation activities rather than biological and socioeconomic measures (Mitiku et al. 2006). Since around the year 2000, however, landscape restoration has been practiced mainly through collective action and community-based watershed management activities, with the active participation and decision making of local communities (Haileselassie 2013). Millions of workers in Tigray have joined together to participate in massive interventions such as soil and water conservation (SWC), integrated watershed management and development, afforestation and reforestation of degraded lands, gully reclamation, farmland management, and more (Figure 6.2). The landscape restoration effort in Tigray is now recognized as a “degraded land restoration model” by the international community. For example, the farming community of Abreha we Atsbeha in Tigray, northern Ethiopia, received an “Equator Prize Award” in 2012 from the United Nations Development Programme (UNDP) “in recognition of their outstanding success in promoting local sustainable development solutions for people, nature, and resilient communities” (see Case Study 6.1).

Figure 6.1 Exclosure landscape reshaping for farming by integrating soil and water conservation structures in Eastern Tigray. Photo by Aklilu Negussie.

Landscape restoration activity, which is now recognized by the Government of Ethiopia as a major tool to address the root causes of land degradation and poverty, should be implemented widely via appropriate extension programs. It is critically useful to draw lessons from evidence on successful cases—both indigenous practices and innovative approaches—for wider application. This chapter attempts to identify successful landscape restoration efforts that can be scaled up in the rest of Ethiopia and other parts of Africa. Information on landscape restoration and extension systems in northern Ethiopia, especially Tigray, were gathered from recent studies and reports, including grey literature, along with anecdotal evidence and informal studies for the preparation of this book chapter. In addition, comprehensive discussions and dialogues were conducted with experts during a writeshop organized by World Agroforestry (ICRAF). The next section reviews the historical process of landscape restoration in Tigray. The following section, especially referring to the case of Abreha we Atsbeha village, discusses key factors, i.e., direct and indirect benefits of land restoration, which contributed to sustainable adoption and scale-up.

Figure 6.2 (a) Encroachment on natural forests in northern Ethiopia (photo by Aklilu Negussie); and (b) production of fodder grasses on reclaimed gullies by individual farmers at Gergera watershed, March 2017 (photo by Niguse Hagazi).

6.2 Historical Review of Restoration Activities in Tigray: Before and After 2000

Before 2000, the northern Ethiopian Highlands, especially the highlands of Tigray, were known for their severe land degradation (Mitiku et al. 2006, Gebremichael 2002, Birhane et al. 2006). The farming community in Tigray was predominantly engaged in crop and livestock production (Gebremichael 2002, Birhane et al. 2006); hence, the extension system was biased towards a crop production system. However, severe environmental degradation, driven by a multitude of environmental as well as land use factors—including unreliable rainfall, deforestation, and overgrazing—prompted the people and government of Tigray to kick off a new type of intervention: landscape restoration (Mengsteab et al. 2010, Haileselassie 2013), taking the watershed as a working unit (Table 6.1; Figure 6.3).

Although activities such as soil and water conservation and tree planting were implemented in the pre–1990 period, using the food for work program, livelihood improvement and landscape restoration goals were not attained as expected. This was mainly due to a top-down extension approach and the lack of participatory and community-based planning, implementation, monitoring, and evaluation systems (Mengsteab et al. 2010). In many cases, local communities were not involved in the planning process; instead, they only implemented the activities ordered from the top. Moreover, communities were only looking toward receiving payments and were not concerned with the effectiveness, sustainability, and contextual-appropriateness of the work. For this and other reasons, this top-down approach eventually failed.

For reversing the severe land degradation and improving production systems and livelihoods, massive participatory and community-led landscape restoration approaches have been implemented, mainly since 2000 (Gebremichael 2002).

Case Study 6.1 Case Study in Abreha we Atsbeha

Winner of Equator Prize 2012 from UNDP "in recognition of outstanding success in promoting local sustainable development solutions for people, nature, and resilient communities."

Figure CS 6.1 Fruit trees planted on rehabilitated land in Abreha we Atsbeha. Photo by Niguse Hagazi, October 2018.

Farmers' incomes have improved from vegetable production (e.g., tomato, pepper, onion, cabbage, lettuce, and potato), increasing from 29,070 USD in 2004 to 574,417.5 USD in 2011 (Haileselassie 2013), in addition to rainfed cereals produced during the rainy season. The synthesized data from the Haileselassie (2013) findings, as depicted in the two graphs, also revealed that the irrigable area has increased nine fold (from 32 ha in 2004 to 285 ha in 2011) and production has increased by twelve fold (from 328 tons in 2004 to 3,965 tons in 2011), which plays a significant role in the improvement of livelihoods in the community (Figure CS 6.2).

Of the 90 household head farmers interviewed by Haileselassie (2013), 100% of them have changed their dietary style from mono- or traditional feeding to a diversified diet, either through their own produce or through market purchase. Haileselassie indicates that the farming community in Abreha we Atsbeha currently uses 15% for home consumption, 31.9% for sale and income generation, and 52.7% for both consumption and sale of what they produce. Considering the availability of corrugated iron sheet housing as an indicator, Haileselassie (2013) found that 89 out of 90 respondents have owned houses in the village, and 70 (79%) of the sample households had corrugated iron sheets for roofing.

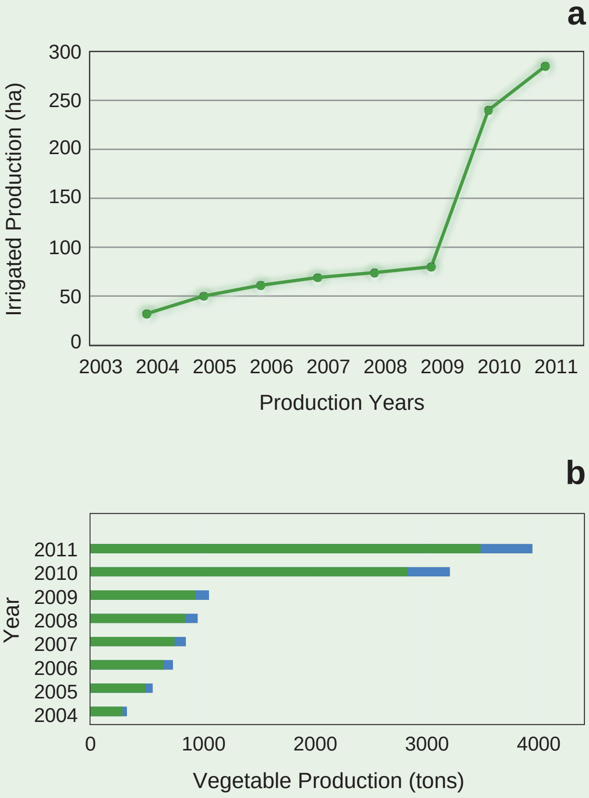

Figure CS 6.2 (a) Increasing trend of irrigated production area (ha) and (b) vegetable production (tons) trends by year after integrated soil and water conservation practices in Abreha we Atsbeha.

Table 6.1 Summary of natural resources management activities performed in the region between 1992 and 2013.

Activity / intervention	Coverage (ha)	Regional land mass share (%)
Treated cultivated area	960,000	
Community based integrated watershed management	1,078,335	
Subtotal	2,038,335	37.4
New plantation	764,765	
State forest	266,240	
Wildlife park	217,643	
Area exclosure management	1288445	
Subtotal	253,7093	46.6
Grand total	4,575,428	84

Sources: Mulugeta Gebreselassie (2013), from the report presented at the Regional Agriculture & Rural Development Partners Linkage Advisory Council (ARDPLAC) annual meeting, Axum Hotel, Mekelle, Tigray, Ethiopia.

This has occurred largely as a result of several factors: learning from the experiences gained from other countries, like India, regarding watershed development approaches; the Tigray regional government's conservation-based development approach; and some donor-led initiatives, such as the Irish Aid integrated watershed development approach in the Gergera watershed (Taha et al. 2006).

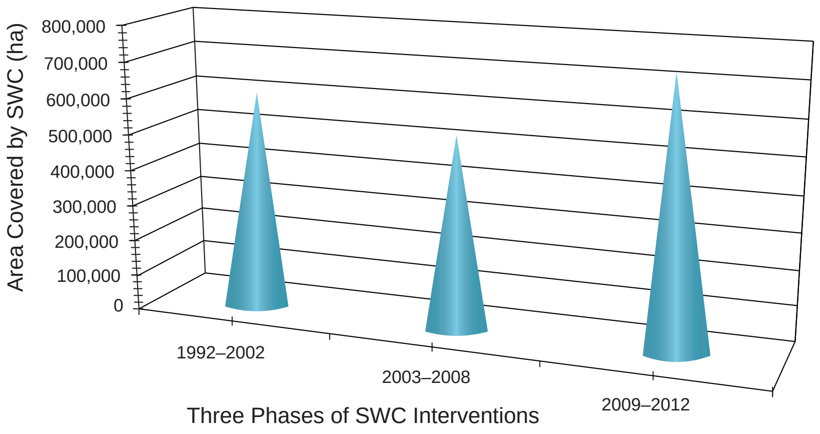

Figure 6.3 Area covered (ha) by watershed based SWC activities in three different periods in Tigray.

The government and other stakeholders have recognized the role and approach of an extension system in land restoration through the coordination of programs and policies. For example, an extension department within the Tigray Regional Bureau of Agriculture and Rural Development emphasized conservation-based agriculture and natural resources protection and management. Since the establishment of the extension system and the selection of the watershed approach as a strategy, both governmental organizations (mainly, the Bureau of Agriculture and Rural Development) and non-governmental organizations (specifically, the WFP-MERET national programme, the Irish Aid Watershed program, REST, the GIZ-SUN (Sustainable Utilization of Natural Resources for Food Security) program, and World Vision) have agreed to coordinate their efforts to contribute to the landscape restoration activities. Moreover, the stakeholders have been strengthening the landscape restoration extension system as a holistic approach for improving the landscape level production and protection system, rather than focusing only on crops and livestock production, as practiced in the past.

The community bylaw has also made clear that equity in participation and benefit sharing among the members of the community, regardless of their wealth status, gender, age, creed, education status, etc., is a binding principle (Mengsteab et al. 2010). Additionally, the community bylaw accommodates concerns regarding how the poor, women, and other disadvantaged groups access the resources of the rehabilitated landscapes. The grassroots level community has played a key role in restoring degraded landscapes through donating their labor and crafting a community bylaw for protecting the rehabilitated landscapes. It has also packaged and disseminated successful restoration practices by considering inputs obtained from its members, other stakeholders, and lessons learnt from past practices. The extension approach has generally brought desirable and significant landscapes restoration. The changes in landscape restoration have had an indispensable impact on creating improved and resilient livelihoods, as described in the next section.

6.3 Restoration Activities and their Benefits, with Special Reference to Abreha we Atsbeha

This section reviews the land restoration activities implemented under the participatory and integrated watershed management, with reference to the historical experience of the Abreha we Atsbeha community of Tigray. Before the landscape restoration activities began, agricultural production in the community had been seriously threatened by land degradation, to the degree that the community had been asked to resettle in other potential places (Haileselassie 2013). However, the residents of the Abreha we Atsbeha community refused to resettle, preferring to rehabilitate the degraded landscape of the village instead. The community agreed collectively to implement community-led physical and biological conservation activities, along with exclosure practices (Haileselassie 2013). Establishing enabling institutional mechanisms was critical. The bylaw in Abreha we Atsbeha demonstrated villagers' concerns regarding equity, and, accordingly, it gave priority to the poor, to landless youth groups, and to marginal farmers (e.g., the disabled and returnees from migration to access resources in rehabilitated sites). These groups were permitted to use the rehabilitated landscape mainly for income-generating activities such as beekeeping, collection of animal feeds by the cut-and-carry system, and others (Figures 6.4 and 6.5). Conflicts arising between individuals, groups, and adjacent villages in using the resources were resolved as stipulated in the bylaw. Through the support of local institutions and local administrative bodies (i.e., *Baito)*, the community has accomplished most of the landscape restoration activities, including soil and water conservation, hillside plantation, exclosures, and afforestation (Birhane 2006, Haileselassie 2013). The Abreha we Atsbeha community is now enjoying the benefits of landscape restoration, including production and livelihood benefits (Gebremariam 2009, Niguse et al. 2011, Haileselassie 2013), as documented below.

6.3.1 Area exclosures for restored vegetation

Area exclosures have been adopted as a land management method/tool for more than two decades in the Tigray Region and in the nation as a whole (Figure 6.6). Area

Figure 6.4 Beekeeping as an emerging and expanding enterprise in Tigray region on rehabilitated or restored landscapes. Photos by (a) Aklilu Negussie, Central Tigray; and (b) Niguse Hagazi, Atsbi district, December 2017.

Figure 6.5 Rural youths collecting fodder grasses from reclaimed gullies. Photo by Niguse Hagazi at Gergera watershed, March 2017.

Figure 6.6 Well-managed exclosure in eastern Tigray. Photo by Aklilu Negussie.

exclosures prohibit people and livestock interference to hillsides and mountainous areas through established local bylaws by involving women, elderly people, youth farmers, community and religious leaders, and local administrators. This has been a common practice and has brought significant increases in vegetation cover to many parts of Tigray. Almost every district (and, probably, village) has at least one exclosure that has been restored and is managed by the local community. In areas like Abreha we Atsbeha, communities within and around the watersheds are getting direct and indirect benefits (Haileselassie 2013) from existing exclosures. Some of the benefits from the exclosures include increased species composition and diversity of herbaceous and woody plants, as well as higher aboveground biomass, compared to adjacent grazed areas (Yayneshet 2009, Haileselassie 2013). Moreover, exclosures have had a pronounced role in fostering native flora and enhancing biodiversity. For better restoration of degraded lands, exclosure practices were supported by enrichment planting focusing on some economically important tree and/or shrub species (Figure 6.7; Wolde et al. 2010, Tafere 2009). For example, in Abreha we Atsbeha, about 37 woody plant species and 872 individual plants were identified and recorded in area exclosures, compared to only 2 woody species and 4 individuals on open access land (on hectare bases). Moreover, Haileselassie (2013) indicated in his household survey in Abreha we Atsbeha, which was complemented with a focused group discussion (FGD), that about 98.9% of respondents agreed on the socioeconomic benefits of exclosure.

6.3.2 Soil and ground water management for improved crop productivity

Soil loss and moisture stress are among the most common and prominent challenges in Tigray, including Abreha we Atsbeha, contributing to low agricultural productivity and

Figure 6.7 (a) Enrichment planting and FMNR practices to increase farm productivity at Hawzien district, November 2018; (b) Balanites aegyptiaca and Ziziphus spina-christi trees in integrated farming system at Koraro, Hawzien, November 2018. Photos by Niguse Hagazi.

poverty (Mitiku et al. 2006, Nata 2003). The landscape restoration activities included rehabilitation of gullies, hillsides, eroded farmlands, deep trenches, micro-ponds, surface and underground water tankers, spring developments, check dam construction, river diversions, and, in some places, community built micro-dams (Nata 2003, WFP 2004, Nyssen et al. 2004, Mulugeta 2013). Combining the physical and biological soil and water conservation activities with indigenous soil fertility management practices (e.g., composting, manuring, crop rotation, and terracing) and water harvesting (Figure 6.8) has improved farmland soil fertility, ground water recharge, and agricultural productivity in general (Hailu 2006). Farmers who have combined indigenous soil and water fertility management with landscape restoration have benefited significantly; these processes have increased production, conserved moisture, reduced soil loss, and enabled sustainable and resilient production systems (Hailu 2006, Gebremariam 2009, Nyssen et al. 2006). Furthermore, landscape restoration activities have recharged the groundwater and raised the water table. Because of the mounting water table, the number of shallow wells has increased significantly, so that farmers can easily develop hand-dug wells and check dams for growing vegetables (e.g., tomatoes, onion, and cabbage) through small-scale irrigation practices. This opportunity enables farmers to cultivate their farmlands twice during the off-season, and in some cases, even three times per year (Haileselassie 2013). Landscape restoration and restoration-focused policies and strategies have improved the yield of some main crops (i.e., average increases of 25% to 40%, compared to post 2000), which has improved food security and the livelihood of the communities, as well as the resilience of the landscapes (TBoARD 2013).

6.3.3 Income and assets building

In Abreha we Atsbeha, due to the impacts of land restoration, including agroforestry practices and use of improved technologies and extension systems, agricultural productivity has increased. Subsequently, the per-capita income of many farmers has improved from less than a dollar to more than two US dollars per day (Haileselassie 2013). As a result, farmers are saving money in lending institutions from which they were previously accessing credit. Generally, many farmers, especially those farmers who own hand-dug wells, are food-secure and have better living conditions (Haileselassie 2013). In addition, these farmers are becoming healthier, as they frequently consume nutritious food, such as vegetables and animal products (Figure 6.9). Moreover, farm households have also started saving new assets (Niguse et al. 2011, Haileselassie 2013). For example, farmers have modernized their houses with corrugated iron roofs and improved furnishings. Additionally, farmers are now able to own private motor pumps for irrigation purposes and have generated additional income that enables them to buy school materials and send their children to school (TANGO International and Institute of

Figure 6.8 Naturally regenerated indigenous trees around Adigrat area with moisture-harvesting physical structures. Photo by Niguse Hagazi, February 2018.

Figure 6.9 (a) A farmer planting an avocado sapling on his farm in Gergera watershed, July 2018; (b) a female farmer growing high value and nutritious vegetables in her small garden at Wukro, February 2019; and (c) farmers integrating high value fruit trees in their farmlands in Gergera watershed, June 2018. Photos by Niguse Hagazi.

Development Studies 2012, Gebremariam 2009, Niguse et al. 2011, Haileselassie 2013). Thanks to the positive impact of land restoration, social capital has allowed the adoption of even more promising technologies and management systems, including agroforestry, irrigation water allocation, grazing, and the use of reclaimed gullies.

6.3.4 Further opportunities and challenges

Before the land restoration activities, farmers were not motivated either to practice agroforestry and irrigation or to maintain naturally grown trees and shrubs or plant seedlings on their individual farms and communal lands. With the absence of rules to prohibit tree cutting, indigenous trees were cut down to meet demands for fuelwood, construction, and charcoal production, and the practice of free grazing enabled unrestrained and unregulated access to the forest and communal watershed. Thus, when farmers began to practice agroforestry, free grazing of livestock was one of the challenges for maintaining naturally grown trees and shrubs, as well as for planting seedlings. The free grazing problem was solved via collective action, however, and by creating bylaws to prohibit free grazing and tree cutting (Niguse and Kinfe 2012) in areas like Abreha we Atsbeha. Now, there are opportunities to scale up these practices, which depend on further community empowerment. Still, grazing management continues to be a challenge in many villages and watersheds of the region and requires some reinforcement of bylaws, as well as consultation with communities and policymakers. The competition for water is also increasing over time, and in some cases, may evolve into conflict (Nata 2003; TBoARD 2013). Thus, careful planning and regular monitoring is very important to avoid conflict between water users. Fortunately, this concern is well recognized by the local community and by the extension and administrative bodies of the region. Empowered via bylaws, and organizing training for the extension system and other relevant stakeholders, the Abreha we Atsbeha community has been successfully using the conserved water sustainability approach at a household level.

6.4 Discussion and Conclusions

Land degradation (primarily, land and vegetation degradation), loss of biodiversity, acute soil erosion, nutrient depletion, scarcity of water resources, and harsh weather conditions are severe in the northern mid- and highland parts of Ethiopia, particularly in Tigray. The problems of land degradation have been addressed through implementing community-led, participatory, and bottom-up restoration approaches, which have brought positive changes in the restoration of degraded lands, as well as livelihood improvement. Moreover, local innovations, coupled with indigenous knowledge, have also helped enormously in rehabilitating the degraded landscape. The productive, resilient, and sustainable landscape restoration efforts in Tigray should, therefore, be scaled out to other areas with similar agroecologies and socioeconomic settings in Ethiopia and other parts of Africa. Although landscape restoration efforts have provided multiple benefits to farming communities, the benefits from these efforts should be maximized by integrating evidence-based and value-adding technologies, practices, and approaches, and by ensuring the rights to these benefits through sustainable benefit-sharing mechanisms.

This chapter reviews the historical process of landscape restoration in Tigray and discusses key factors, i.e., direct and indirect benefits of the restoration efforts that contributed to the sustainable adoption and scale-up and compares land restoration approaches before and after the year 2000. It also highlights the importance of enabling institutions—including coordinating programs and policies for extension systems among key stakeholders on watershed restoration—as well as establishing and enacting local bylaws for the mobilization of communities members, especially those who are marginalized, who are direct contributors, as well as beneficiaries of direct and indirect benefits of soil and water conservation activities (see, e.g., Figures 6.10 and 6.11). Landscape restoration activities in Tigray have brought significant changes in livelihoods as well as in landscape improvement. For example, landscape

Figure 6.10 Rural youths planting high value trees, 2018. Photo by Niguse Hagazi.

Figure 6.11 Women planting tree seedlings in Central Tigray. Photo by Aklilu Negussie.

Figure 6.12 Landscape rehabilitated by local communities using enrichment planting and FMNR practices in Saese-Tsaeda Emba district. Photo by Niguse Hagazi, November 2018.

restoration, with the active participation of local communities in planning, implementation, and joint monitoring and evaluation, has transformed the livelihoods and the landscape of Abreha we Atsbeha village. This village once had very degraded landscapes and had been known for food insecurity, due to severe soil erosion, poor soil fertility, and low agricultural productivity (WFP 2004, Birhane et al. 2006, Gebremariam 2009). Landscape restoration efforts contributed to direct and indirect benefits, which were key factors for sustainable adoption and scale-up. Some of the direct benefits include animal fodders, through cut-and-carry systems; increased honey production; increased density and diversity of vegetation; increased crop yield, as a result of soil fertility enhancement and increased water productivity (Tulu 2002, Vancampenhout 2006); and increased and diversified livelihood opportunities. The indirect benefits include soil loss reduction, long-term water resource availability with an increased discharge rate, improvement of micro climate, reduction of flooding hazard, and improved amenities such as landscape beauty (Haileselassie 2013, Wolde et al. 2010).

Many lessons can be learned from the landscape restoration efforts in the Tigray Region, in northern Ethiopia, generally (Figure 6.12), and Abreha we Atsbeha, in particular, to support the Ethiopian government's policies and strategies, such as the Rural Development Strategy and Agriculture-Led Industrialization (ADLI), Climate-Resilient Green Economy (CRGE), and an initiative on restoration of 15 million ha by 2030 (FDRE 2011). Key messages for scaling up land restoration efforts are summarized below:

1. Design bottom-up, coordinated extension approaches focused on natural resources conservation and rehabilitation.
2. Commit local policymakers and extension to engaging with farmers.
3. Consider farmers to be the key and central players in the process of planning, designing, implementing, monitoring, and evaluating landscape restoration activities.
4. Promote the culture of social mobilization for public works like the free labour contribution, both for individuals and group benefits and goals.
5. Establish continuous learning processes through exposure and experience-sharing visits, thereby deriving benefits from some model sites that urge farmers and/or communities to work hard.

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7. Restoring Degraded Landscapes for Improved Ecosystem Services

Wolde Mekuria*

Summary

There is a consensus that major improvement in agricultural systems is necessary to meet the food demand of the growing global population. Restoring degraded lands could play multiple roles in meeting the growing demand for food, ensuring food security, improving rural livelihoods, and adapting to and mitigating the effects of climate change. Restoration of degraded landscapes, which is one of the climate-smart approaches, is critical for conserving water, increasing yields, sequestering carbon, and reducing risks in rainfed agriculture through improving water availability and reducing soil erosion. Restoration of degraded landscapes can generate both private and public benefits, and thus constitutes a potentially important means for generating "win-win" options. In connection with the aforementioned, case studies from the highlands of Tigray, northern Ethiopia, have demonstrated that exclosures are effective for restoring degraded landscapes, thereby improving provisioning, regulating, supporting, and cultural ecosystem services. Upon protecting communal grazing lands via exclosures, the soil carbon, total soil N, and available P contents increased from 29 (±4.9) to 61 (±6.7) Mg C ha^{-1}, 2.4 (±0.6) to 6.9 (±1.8) Mg ha^{-1}, and 17 (±3) to 39 (±7) Kg ha^{-1}, respectively. The case studies also indicated that exclosures are important in reducing soil erosion (47% decrease following establishing exclosures), sustaining perennial habitat, restoring vegetation composition, and improving indigenous plant species diversity and richness. Further, over a period of 30 years, the NPV of the exclosure ecosystem services under consideration was about 28% (USD 837), which is higher than alternative wheat production, justifying that exclosures have economic and livelihood benefits. Restoration of degraded landscapes is, thus, essential for achieving improved, resilient, and sustainable production systems, livelihoods, and ecosystems.

Keywords: ecosystem, exclosure, landscape restoration, resilience, sustainability

7.1 Introduction

According to the Food and Agriculture Organization of the United Nations (Branca et al. 2011), close to one billion people went hungry in 2010. When the global population reaches 9 billion by 2050, food needs are projected to increase by 70% (World Bank 2010). In contrast, climate change is projected to reduce global average yields (World Bank 2010, Zhao et al. 2017). For instance, Zhao et al. (2017) indicated that each degree Celsius increase in global mean temperature is estimated to reduce average global yields of wheat by 6%. This same study indicated that rice yields would cut by 3.2%, and maize by 7.4% for each degree of Celsius warming. Indeed, in 2011 the Horn of Africa was hit by the worst drought in 60 years and was consequently plagued by hunger (Branca et al. 2011).

Climate change is also adding pressure to the already stressed ecosystems of smallholder farms (Grainger-Jones 2012). Studies (Cline 2007, World Bank 2010) predict that without strong adaptation measures, severe crop yield reductions can be expected in the coming decades, particularly in Sub-Saharan Africa and South Asia, where farming systems are highly sensitive to climate change or variability although rural households are highly dependent on agriculture. An assessment by Cline (2007), based on a pessimistic assumption about global warming, estimated a decline in worldwide agricultural productivity by 3% to 16% by the 2080s; this loss could be even worse in Africa, i.e., 17% to 28% (Cline 2007). Therefore, there is a consensus that major changes in agricultural systems will be required to meet the food demand of an increasing global population under a changing climatic condition (Branca et al. 2011, Grainger-Jones 2012).

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* International Water Management Institute, P.O. Box 5689, Addis Ababa, Ethiopia
Correspondence email: w.bori@cgiar.org

Over the past 45 years, about 1.2 billion hectares (11% of the Earth's vegetated surface) have been degraded by human activity (Grainger-Jones 2012). In developing countries alone, an estimated 5 million to 12 million hectares of land become infertile for use in agriculture due to severe degradation (Scherr 1999 cited in Grainger-Jones 2012). The Global Partnership on Forest Landscape Restoration estimates that there are over 700 million hectares of degraded forest landscapes in Africa, which offer opportunities for restoring or enhancing the functionality of "mosaic" landscapes that mix forestry, agriculture, and other land uses (Minnemeyer et al. 2011). Sub-Saharan Africa is one of the regions worst affected by land degradation, where per-capita food production continues to decline, and hunger affects about a third of the region's population (Scherr 1999 cited in Grainger-Jones 2012). The continued cultivation of marginal areas (without adequate management), deforestation, wind and water erosion, and overgrazing, are all major drivers of widespread land degradation.

Degraded landscapes such as communal grazing lands, woodlands, and agricultural lands can be restored to provide ecological connectivity for improved water and nutrient flows, as well as improved habitat conditions for indigenous tree species (World Bank 2010, Mekuria and Veldkamp 2012). As climate change intensifies, nutrient flow and hydrological resources improvements become increasingly important as adaptation strategies (Millar et al. 2007). Along these lines, the climate-smart agriculture-landscape restoration approach could provide options for meeting the growing food demand while providing climate change adaptation and mitigation benefits, as it simultaneously improves food availability and rural livelihoods, as well as restores degraded landscapes (World Bank 2010, Scherr et al. 2012).

The landscape restoration approach, which aims to restore degraded ecosystems, has played an important role in mitigating human pressure on natural ecosystems (Holl et al. 2003), improving ecosystem services (Doren et al. 2009, Scherr and Sthapit 2009, Bullock et al. 2011), reversing biodiversity losses (Bullock et al. 2011, Bernazzani et al. 2012), and improving agricultural productivity and food security (Mekuria et al. 2009, Milder et al. 2011). The restoration of degraded ecosystems can also generate both private and public benefits and, thus, may constitute a potentially important means of providing "win-win" options for addressing poverty, food insecurity, and environmental problems (Scherr et al. 2012).

In Ethiopia, land resources are facing severe degradation. This is largely a consequence of deforestation, over-cultivation, and overgrazing, which together result in significant environmental degradation and reductions in provisioning, regulating, supporting, and cultural services derived from ecosystems (Mekuria et al. 2015). For example, the rate of deforestation in the Ethiopian highlands was estimated at 160,000–200,000 ha yr^{-1} (Bishaw 2001), the average rate of soil erosion for all kind of land use was estimated at 35 Mg ha^{-1} yr^{-1} (Keyser and Sonneveld 2001), and nutrient depletion was reported as 30 kg ha^{-1} yr^{-1} of nitrogen and 15–20 kg ha^{-1} yr^{-1} of phosphorous (UNDP 2002). Consequently, the restoration of degraded watersheds through the establishment of exclosures has become increasingly important in the highlands of Ethiopia (Mekuria et al. 2011b). Exclosures (Figure 7.1) are common land areas, which are traditionally "open access," where wood cutting, grazing, and other agricultural activities are forbidden or strictly limited as a means to promote the restoration and natural regeneration of degraded lands (Mekuria et al. 2011a,b).

This chapter briefly discusses (1) the effects of exclosures on restoring degraded landscapes and improving ecosystem services; (2) the importance of the restoration of degraded landscapes for achieving improved, resilient, and sustainable production systems, livelihoods, and ecosystem health; and (3) the impacts of exclosures on the livelihoods of smallholder farmers.

7.2 Methods

7.2.1 Study area

This chapter presents the results of five case studies on the changes in ecosystem carbon stock, vegetation composition, soil erosion, soil properties, and income and livelihoods following the establishment of exclosures. The studies were conducted in the highlands of Tigray at lat. 12°–15° N, long. 36°30′–40°30′ E, northern Ethiopia. The altitude of the study sites ranged from 2,232 to 2,937 m above sea level. The exclosures in the study area were established three to four decades ago. All of the sites had semiarid climate conditions. From 2000 to 2006, the mean annual rainfall varied between 578 and 671 mm yr^{-1}, with an average of 609 mm yr^{-1} (Ethiopian Meteorological Service Agency 2007). The rainy season usually starts at the end of June and ends in September. The growing season stretches from 90 to 120 days. The mean minimum temperature ranges from 7.8 to 11.6°C, and the mean maximum temperature ranges from 22.2° to 28.2°C (Ethiopian Meteorological Service Agency 2007). Landscape composition in the study districts where exclosures were located

Figure 7.1 Examples of exclosures at ages (a) 5 years, (b) 15 years, and (c) 20 years, established on communal grazing lands in the Douga-Tembien District, Tigray, in northern Ethiopia (photos by Wolde Mekuria).

includes cultivated lands (9%–33%), forest lands (3%–58%), exclosures (3%–16%), communal grazing lands (6%–39%), and other uses (20%–41%). Mixed crop-livestock farming is the backbone of household livelihoods in all of the study sites. The major cultivated crops include barley (*Hordeum vulgare* L.), wheat (*Triticum aestivum* L.), tef (*Eragrostis tef* [Zucc.] Trotter), common bean (*Phaseolus vulgaris* L.), and sorghum (*Sorghum bicolor* [L.] Moench). Soils of the study sites are classified into four major groups: Luvisols (Alfisols), Regosols (Entisols), Cambisols (Inceptisols), and Calcisols (Aridisols) (Soil Survey Staff 1996, IUSS Working Group WRB 2006).

7.2.2 Exclosure management

Three to four decades ago, in an effort to restore degraded landscapes and improve the services that they provide, communities in the northern highlands of Ethiopia embarked on exclosure schemes to protect and regenerate degraded communal grazing lands (Mekuria et al. 2011b). Exclosures are usually established in steep, eroded, and degraded areas that have been used for grazing, wood collection, and other purposes in the past. Priority areas for establishing exclosures are normally identified through a joint committee, which is composed of local communities and governmental and non-governmental organizations (Descheemaeker et al. 2006, Mekuria et al. 2011b). Final decisions are made at a general meeting of the community (Yami et al. 2013). Exclosure management and protection have proven to be an effective sustainable landscape management option because these lands are owned and managed by the local community (Descheemaeker et al. 2006). The coverage of a given exclosure ranges from 1 ha to 700 ha (Nedessa et al. 2005).

7.2.3 Data collection and analysis

A space-for-time substitution approach (Mekuria et al. 2011b) was used to detect changes in ecosystem services following the establishment of exclosures with ages of 5, 10, 15, and 20 years. In five separate studies undertaken, changes in regulating (e.g., carbon sequestration and soil erosion control) and supporting ecosystem services (e.g., soil fertility improvement and vegetation restoration), economic viability, and the perception of local communities following the establishment of exclosures on communal grazing lands were investigated (Mekuria et al. 2009, Mekuria et al. 2011ab, Mekuria and Veldkamp 2012, Mekuria and Aynekulu 2013). Exclosures with ages of 5, 10, 15, and 20 years were selected and replicated three times, and each exclosure was paired with a plot of adjacent grazing land during statistical analysis.

To investigate the changes in vegetation composition, richness, and diversity, vegetation inventory was undertaken with the method used by Mekuria and Veldkamap (2012). To investigate the changes in soil properties and nutrient contents, soil samples were collected and analyzed (Mekuria and Aynekulu 2013). Dominant woody species were identified based on relative importance values (i.e., the sum of relative basal area, relative frequency, and relative density) (Mekuria et al. 2011b). The methods of Hoff et al. (2002) and Snowdon et al. (2002) were used for measuring the aboveground biomasses of the dominant woody species. Selected individual plant species in exclosures and the communal grazing lands were harvested and weighed. Measured fresh biomass of the aboveground vegetation was adjusted to dry biomass using a correcting factor after oven drying at 65°C for 72-78 hours until a constant weight was attained. Carbon fractions in the aboveground biomass were estimated by multiplying the oven-dried biomass by a factor of 0.5 (Snowdon et al. 2002).

The enhancement of aboveground carbon is considered to be an indirect benefit of exclosures on communal grazing land. The necessary input factors are land and labor. As certified emission reductions (CER) are traded as CO_2 units (UNFCCC 2003), carbon storage in this study was converted into CO_2-e quantities (Mg CO_2 ha^{-1}) by multiplying the carbon storage (Mg C ha^{-1}) by a molar conversion factor of 3.67 (Olschewski and Benitez 2005). Additionally, for determining the carbon revenues, permanent carbon prices were transformed into prices for temporary credits, in accordance with Olschewski et al. (2005) and Mekuria et al. (2011a). Assuming a tCER (temporary certified emission reduction) expiring time of 5 years, an average price of USD 25 per permanent credit, and a discount rate for Annex I countries of 3% results in a price of USD 3.43 per temporary certified emission reduction (Mekuria et al. 2011a). Labor cost for the guards protecting the exclosures was calculated as a wage per hectare, which is based on a guard's monthly salary and the coverage of the exclosure to which they are assigned. Costs and benefits analysis was conducted based on market prices for valuing the project impacts. Given the long-term project horizon, costs and benefits occurring at different points in time were discounted to make them comparable. Net present value (NPV) was used as a decision criterion and was calculated using the equation described in Mekuria et al. (2015).

Using a revised universal soil loss equation (RUSLE), Mekuria et al. (2009) investigated the effectiveness of exclosures in combating soil erosion. The RUSLE was used to estimate potential soil losses. In addition, data on local community perceptions on exclosures was obtained from a survey of 62 farm households and five local experts. In-depth interviews, group discussions, and non-participant field observations were also carried out to obtain additional information.

7.3 Major Highlights

Restoration of degraded landscapes is important for achieving improved, resilient and sustainable production systems, livelihoods, and ecosystems. This case study has demonstrated that exclosures provided higher levels of ecosystem services than did non-closed lands. Differences in ecosystem carbon stock (ECS), total soil N stock and available P stock between exclosures and grazing lands varied between 29 (±4.9) and 61 (±6.7) Mg C ha^{-1}, 2.4 (±0.6) and 6.9 (±1.8) Mg ha^{-1}, and 17 (±3) and 39 (±7) Kg ha^{-1}, respectively. All differences in ecosystem services increased with exclosure duration. Differences in plant species richness and biomass between exclosures and communal grazing lands were higher than differences between older and younger exclosures. Over a period of 30 years, sequestered carbon dioxide was 246 Mg ha^{-1}, total soil nitrogen increased by 7.9 Mg ha^{-1}, and additional available phosphorous stocks amounted to 40 kg ha^{-1}. The NPV of the exclosure ecosystem services under consideration was about 28% (USD 837), which is higher than for alternative wheat production, demonstrating that exclosures have a comparative advantage to alternative agricultural practices. Given that more than 75% of the respondents had a positive view on exclosure effectiveness for restoring degraded landscapes, there are substantial opportunities to mobilize local communities in an effort to establish more exclosures. Establishing exclosures on communal grazing lands can be effective for restoring degraded landscapes and thereby increasing the services that they provide.

The estimated soil loss from the free grazing lands was higher than soil loss in exclosures by 47%, which indicates that exclosures are effective for controlling soil erosion. The RUSLE results agreed with the opinions of the majority of respondents, 67% of whom said that soil erosion in the study area was severe and affected the quality of residents' lives. The majority of respondents (70%) also rated the effectiveness of exclosures in controlling soil erosion as "high". Local communities were optimistic that the remaining degraded lands could be rehabilitated and converted to productive land through exclosure land management. The local community's optimistic perspective can be considered an asset for future planning and rehabilitation of degraded landscapes at the national level.

Soil and vegetation C stocks, soil nutrient contents, and species diversity and richness were higher in all exclosures than in communal grazing lands. This indicates that exclosures have a significant positive effect on the restoration of ecosystem services. Similar studies conducted in Ethiopia also demonstrated that the establishment of exclosures on degraded communal grazing lands contributes to the provisioning function of ecosystem services through improved animal feed and human food products, such as honey (Haile 2012); regulating services through sequestering below- and aboveground carbon (Descheemaeker et al. 2006, Girmay et al. 2009, Verdoodt et al. 2009); supporting services through improving soil formation and soil fertility (Mamo 2008, Tsetargachew 2008, Mekuria 2013); enhancing nutrient cycling and biomass production (Birhane et al. 2007); and facilitating cultural services through generating aesthetic value and use for educational purposes. Exclosures are also important for sustaining habitat and restoring vegetation composition, as well as improving indigenous plant species diversity and richness (Mengistu et al. 2005a, Abebe et al. 2006, Yami et al. 2006, Birhane et al. 2007, Muchiru et al. 2009, Hosseinzadeh et al. 2010, Verdoodt et al. 2010).

7.4 Conclusions

Restoration of degraded landscapes through establishing exclosures contributes toward a more resilient community and environment. Achieving landscape restoration objectives involving the use and management of exclosures requires institutional mechanisms such as the participation of local communities, establishment of village bylaws, support of governance systems, and joint monitoring and evaluation systems for accounting for the impacts generated from the restoration of degraded landscapes. Case studies from northern Ethiopia substantiated the importance of exclosures in restoring degraded landscapes. However, for the best use of exclosures as an means for landscape restoration, due attention should be given to the following issues: (a) identification of the best community organization to effectively manage exclosures, whether at the level of a few individuals to an entire village, hamlet, or district; (b) redefining rehabilitation objectives; (c) crafting strategies to move from conservation to enhancing economic benefits; and (d) ensuring gender equity in management and benefit sharing. Such concerns indicate the need for clarity of objectives and responsibilities in the management of exclosures, as well as the need to increase short-term benefits to attain the sustainability of exclosures.

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8. Restoring Degraded Landscapes with Farmers' Managed Natural Regeneration (FMNR) Approach

Niguse Hagazi[a]*, Emiru Birhane[b], and Tony Rinaudo[c]

Summary

Farmer managed natural regeneration (FMNR) is a rapid and effective method of landscape restoration that involves the selection and pruning of regrowth from tree stumps, roots, or seeds. FMNR is highly replicable and is believed to be an appropriate and climate-smart option for restoring and rehabilitating degraded landscapes in Ethiopia and other areas where there are similar problems. The FMNR approach enhances the systematic regeneration and management of underground forest from tree stumps, live roots and seeds within the soil (underground) which have potential to sprout stems under favorable conditions. Evidence of the effectiveness of FMNR for landscape restoration and its positive economic, social, and environmental impacts can be seen in Ethiopia, with examples including Zongui and Abreha we Atsbeha, of northern Ethiopia (the Equator Prize Winner of 2012, in recognition of outstanding success in promoting local, sustainable development solutions for people, nature, and resilient communities), and Humbo, of southern Ethiopia (the first showcase for clean carbon trading initiatives in Ethiopia). Through restoring degraded landscapes, providing important products and services, and improving livelihoods, FMNR enhances the productivity and resilience of both ecosystems and societies. The practice of FMNR should, therefore, be scaled-up in Ethiopia and beyond by integrating it into existing strategies, programs, and initiatives supported by science-informed policies.

Keywords: FMNR, degraded land restoration, climate smart agriculture, agroforestry, scaling-up, Humbo, Abreha we Atsbeha

8.1 Introduction

Historical sources indicate that 35% of the Ethiopian land mass was once covered with high forest (Gill et al. 2010). The heterogeneous forests of Ethiopia are composed of 6,500–7000 vascular plants, about 12% of which are endemic (EFAP 1994). Forests and their products have played a great role in economic development. Tens of millions of people in Ethiopia still rely on forests for a whole range of products and services (EFAP 1994), while the forest area has been gradually dwindling, for example, from 13.7% to 12.5% of the total land area from 2000 to 2015 (World Bank World Development Indicators 2018, FAO 2010). Thus, the restoration of degraded forests and the adoption of agroforestry techniques are important interventions for Ethiopia in order to meet future demands for forest products and services, as well as to combat climate change.

The Ethiopian Government, in its Growth and Transformation Plan (GTP), which was implemented in 2011, declared the vision to make Ethiopia a middle-income country by 2025. The first phase of GTP ran from 2011 to 2015 and the second phase runs from 2015 to 2020. The Government also announced the Climate Resilient Green Economy (CRGE) strategy, which presented a plan to create 50% abatement potential in the forestry sector by 2030 in order to sequester carbon emissions while significantly reducing deforestation (Yigremachew et al. 2015, FDRE 2011). The CRGE targets sequestration of more than 40 million tons of CO2e through the afforestation and reforestation of 3 million ha of land and the sustainable management of 4 million ha of forests and woodlands by 2030. Agroforestry has been greatly emphasized in the CRGE strategy as a potential climate-smart agriculture (CSA) practice. The development

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[a] World Agroforestry (ICRAF), Addis Ababa, Ethiopia

[b] Mekelle University, Mekelle, Ethiopia; Email: emiru.birhane@gmail.com

[c] World Vision Australia, Australia, Email: tony.rinaudo@worldvision.com.au

* *Correspondence:* Niguse Hagazi (email: nigusehagazi@gmail.com)

Figure 8.1 Landscape restoration through FMNR practices in Humbo district. Photo by Niguse Hagazi, December 2017.

of appropriate agroforestry systems is officially recognized as a means of adapting to climate change, while continuing to sustain agricultural production and productivity for improving livelihoods and land management.

In Ethiopia, agroforestry practices can be found in different forms. These include dispersed trees in croplands as a parkland system, trees on soil conservation and reclamation structures, shelterbelts/wind breaks, fuelwood production/woodlot plantations, trees on rangelands, fodder banks, multi-purpose trees, exclosures, and hillside distributions (Jama and Zeila 2005, Iiyama et al. 2017). Tree-based landscape restoration through agroforestry adoption at scale in Ethiopia has the potential to mitigate and reverse land degradation through trees' services and production functions, which include erosion control and soil fertility maintenance, the protection of watersheds and maintenance of ecological stability, conservation of biodiversity, and the delivery of various products for home consumption and income generation (World Vision Australia 2017). To achieve the multiple services and benefits of agroforestry, technologies or tools that promote tree/forest development in farmlands, rangelands, degraded hillsides, and exclosures are fundamental. Farmer managed natural resource regeneration (FMNR) is one of the techniques/tools that plays a useful role in addressing the aforementioned issues and demands.

This chapter aims to present principles, practices, merits, advantages, and implementation modalities of FMNR as a technique/tool for enhancing agroforestry. It also aims to synthesize the experiences and lessons of FMNR in restoring degraded lands in Ethiopia (Figure 8.1).

8.2 What is FMNR?

8.2.1 Principles

FMNR is a rapid and sustainable method of reforestation that involves the selection and pruning of regrowth from stumps, roots, or seeds (Rinaudo 2010). It involves the culling of excess shoots and the pruning of remaining shoots, allowing the vigorous ones to grow to maturity. FMNR, as a technique, is highly replicable for the reforestation and intensification of agroforestry technologies at both household and landscape levels. It involves the systematic regeneration and management of the "underground forest" in order to attain important forest products and other environmental services. "Underground forest" is a term coined for the "unseen" but present latent forest that is largely buried in the ground, in the form of living tree stumps, roots, and seeds that have the capacity to regenerate under the right conditions (Danjuma et al. 2016). Through regular pruning and thinning of any unwanted new stems and side branches, shading and excessive competition with crops is reduced, making it possible to grow annual crops between and around the trees. The practice of FMNR is not confined to croplands. It has also been practiced on grazing land and degraded communal forestland.

8.2.2 Implementation steps

Initially, knowing and determining the purpose of the FMNR practice is indispensable. Once the intended objective is defined, there are three important steps to be considered during the implementation of FMNR (Rinaudo and Cunningham 2009).

Step 1: Do not slash all tree growth, but first, survey your farm to determine how many and what species of trees are present.

Step 2: Select the naturally regenerated seedlings/sprouts or stumps that will be used for regeneration.

Step 3: Select the best seedlings/sprouts or stems that will be singled out/pruned, and remove the others (Figure 8.2).

Based on personal experiences and observations while working with farmers and extension officers and providing training, as well as on the findings of Mekonnen et al. (2009), the authors determine that decisions on the type and number of plants to maintain in a farm should be given to individual farmers or community groups. The decision criteria mainly include what species to leave (if there are different species); when and how to cull excess shoots and prune remaining shoots; what spacing is required; and how to share the benefits in the case of communal activities. The frequency and intensity of the culling of excess shoots and the pruning of remaining shoots also depend on the intended objective of individuals or groups. Some farmers may be interested in producing more leaves and pods as livestock feed, especially in grazing areas, and therefore may want to leave more branches. In contrast, farmers interested in producing timber/poles for construction purposes may apply intensive and high pruning to produce poles/posts quickly for harvest. The species selection generally depends on three important things: (1) the ability of the species to resprout after cutting, (2) the value that local people place on those species, and (3) farmers' objectives in practicing FMNR for one or more benefits. On farmland, these benefits may include producing fruit, firewood, and poles for farm implements, and improving the yields of annual crops. On grazing lands, benefits include producing fodder trees. On degraded forestland, benefits may include biodiversity enrichment and environmental restoration.

Figure 8.2 Forest management practices (thinning and pruning) to reduce competition and enhance the growth of indigenous tree species in Humbo, South Ethiopia.

8.2.3 Advantages

The practice of FMNR is flexible, and it is farmer managed. In the case of communal lands, it can also be community managed. It has many potential advantages as a tool for restoring degraded lands, whether private farmland or communal land. The major advantages of this practice, as found both by the authors and according to some indigenous experiences in Tigray, northern Ethiopia, are as follows:

- It is a rapid, low cost, and easily replicable approach to rehabilitating degraded lands and establishing agroforestry.
- It is an empowering form of social forestry that gives individuals and communities the responsibility to sustainably manage communal land and farmland at their disposal.
- It gives farmers and communities an opportunity to harvest wood and non-wood forest products from their holdings.

- It eliminates the costs and time required for tree nurseries and seedling establishment.
- It enhances biodiversity and in-situ conservation of important tree/shrub species with high survival and growth performance.
- It can be practiced with locally available tools, such as sickles, axes, machetes, harvesting knives, and saws. The tools should be sharp, and the cuts should be made in an upward direction wherever possible, in order to make a clean cut and minimize damage such as stem splitting or bark stripping.
- The practice is farmer managed and can be spread by farmers themselves.
- It benefits all community members, including members of vulnerable groups.
- FMNR is normally practiced in the dry season when labor is more readily available, but it does not have to be restricted to a particular season.

8.3 Experiences of FMNR in Ethiopia

8.3.1 FMNR in community-managed land at Humbo, southern Ethiopia

Humbo is located in the southern part of Ethiopia. It has been one of the areas targeted for development programs or as an intervention district for World Vision Ethiopia and Australia. A joint forestry-based carbon sequestration project was initiated in 2004 at Humbo, which covered about 2,728 ha (Asrat 2010). The Humbo FMNR objectives were to improve carbon sequestration through the regeneration of native forests; improve environmental benefits (biodiversity, groundwater, and reducing soil erosion); generate income for local communities through forest products (wood and non-wood) and carbon credits; and create a pilot for Clean Development Mechanism (CDM) in Ethiopia. To achieve these objectives and ensure community participation, seven cooperatives were established, and the communal area was divided for FMNR practice. A series of awareness-creation meetings and trainings, supported with practical demonstrations, were given to farmers and local experts in order to adopt and practice FMNR. Farmers then agreed to close their watershed from sources of interference, such as charcoal making and free-range grazing. Through discussion with local administrations and the district (*Woreda*) agriculture and rural development office, a user right was granted to each cooperative, supported with user right certificates and bylaws (Asrat 2010). Humbo community-managed FMNR is now a learning center for many farmers and development practitioners.

The most encouraging benefits obtained due to the FMNR and enrichment planting practices at Humbo were social, economic, and ecological benefits to the community (Figure 8.3). According to Assefa (2009), an estimated 880,000 tons of CO_2 will be sequestered over 30 years. Humbo is also described as the first project site in the Carbon Finance in Africa Portfolio to receive payment and become a learning site for community-based carbon financing. Because of the FMNR practices, the Humbo area has successfully transformed from a barren to a green landscape and has shown a dramatic increase in annual carbon sequestration of aboveground woody biomass, from 6.1 t CO_2/ha to 30.9 t CO_2/ha (Landscapes for People, Food and Nature 2019). Moreover, Shirko (2014) found an average harvest of 222 man loads of fodder,[1] 236 man/women loads of firewood, and 70 kg of honey per household per year based on the survey made of sampled households. According to Assefa (2009), Asrat (2010), and Shirko (2014), the direct positive impacts of the Humbo FMNR practice include the following:

- Strong community cohesion and engagement
- Flooding cessation and decreased soil erosion
- Increased production of forest and non-forest products, such as honey and fruit
- Habitat restoration, resulting in the return of flora and fauna, and increased bio-diversity
- Tree trimmings that provide a sustainable source of fuelwood
- Sustainable sources of fodder for livestock, via the cut-and-carry system
- Improved ecotourism and micro-environment.

8.3.2 FMNR practices on farmlands in Tigray, northern Ethiopia

The government of Tigray has been pursuing conservation-based agriculture development efforts in all agroecologies of the region for over two decades (Debessay ADPTC, PLC 2013). Accordingly, intensive conservation and plantation of trees have been carried out to reclaim degraded and moisture-stressed areas, where more than 85% of the total landmass of the region is classified as dryland (Debessay ADPTC, PLC 2013). In such a situation, the rehabilitation

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[1] For a definition of "man load" as a unit, see Adhikary (1994, p. xv), where 1 man load = 20–30 kg for fodder (dry and green).

Figure 8.3 Humbo district: (a) natural regeneration and high biomass production of grasses; and (b) natural regeneration in a very degraded area. Photos by Niguse Hagazi, December 2017.

and restoration of degraded lands might not be attained solely through plantation/enrichment planting. Raising seedlings in nurseries is costly compared to assisting natural regeneration (Rinaudo and Cunningham 2009). The existing practice and approach of the restoration of degraded lands through area exclosures is fundamental and encouraging. Moreover, there are diverse species growing naturally, either from stumps, roots, or seeds, when the land is exclosed.

Between September and January, once harvest begins for annual crops (including grasses in grazing areas), many regrowths of indigenous tree/shrub species were observed in farm and grazing lands in areas like Abreha we Atsbeha. The farmers of Abreha we Atsbeha and Zongui are experienced in managing the regrowth and have begun to receive the benefits thereof (Figure 8.4).

According to Tafere (2009), traditional agroforestry has been practiced for centuries in the central zone of Tigray, particularly in the Zongui area in the Weree Leke district. The dominant species maintained in the farmers' fields included *Faidherbia albida*, among others. Farmers have maintained newly regenerated *F. albida in* scattered patterns on their farmlands for soil fertility maintenance and other direct and indirect benefits (Figure 8.5). The farmers of Abreha we Atsbeha, located in the eastern zone, have

Figure 8.4 Naturally regenerated indigenous Acacia species on farmlands in Saese-Tsaeda Emba district. Photo by Niguse Hagazi, November 2018.

also maintained *F. albida* on their farmland and communal lands to enhance soil fertility, provide feed for livestock, and provide shade for both people and livestock (Niguse et al. 2011). Hailu (2006) indicated that about 86% of the community in Abreha we Atsbeha maintained naturally regenerated *F. albida* in their farmlands. Currently, the percentage exceeds 95% (Haileselassie 2013; and personal communication, D. Haileselassie, June 2014), and in the same village, more than 2 million *F. albida* regenerates have been established, mainly through FMNR (personal communication with Gebremikael Gedy, February 2017). Moreover, there were also other multipurpose agroforestry tree species, such as *Balanites aegyptiaca* and *Ziziphus spina-christi,* in different parts of the region (Niguse and Kinfe 2012). The dominant agroforestry farming systems in the region using indigenous species were identified as follows:

Faidherbia albida-based farming system: this system exists predominantly in the eastern and central zones of the region.

Balanites aegyptiaca-based farming system: the farmers of western Tigray have been involved in a sesame and sorghum farming system. The farmers maintain *Balanites aegyptiaca* on their farm in a scattered spatial arrangement to providethe benefits of food, fuelwood, shade, fodder, medicine, and construction materials (Hailemariam 2009).

Ziziphus spina-christi-based farming system: farmers living in the moist lowlands of the northwestern, western, central, and southern zones of the region maintain *Ziziphus* trees, primarily on the border of their farmlands, mainly for feed, fencing, soil fertility, and food.

Figure 8.5 Community leader at Abreha we Atsbeha looking at naturally regenerated Faidherbia Albida trees. Photo by Niguse Hagazi, October 2018.

Rhamnus prinoides based woodlots: *Rhamnus prinoides* is an indigenous shrub species mainly found in irrigable lands, river valleys, and to some extent, around homesteads in most parts of the region.

8.3.3 Enabling factors of FMNR with special reference from Tigray and Humbo areas

The experiences of and lesson learned from FMNR as a tool for restoring degraded lands and scaling up agroforestry practices are mentioned below. This list is not all-inclusive, and there may be other factors not mentioned here.

- The application of FMNR has been exercised and adopted largely in the Tigray and Humbo areas. This has been a good lesson (and enabling factor) for scaling out/adopting FMNR to restore and transform degraded landscapes, as well as to create CSA practices and farming systems in order to ensure economic, social, and ecological benefits, as well as enable farmers to adapt to and mitigate the effects of climate change.
- Exclosures, hillsides, gullies, rangelands and other communal lands are being distributed to rural unemployed people and to landless youth groups. Thus, by supporting the FMNR practices with enforced bylaws, like in the Humbo and Abreha we Atsbeha areas, the livelihoods of local communities, including rural peoples and youths, can improve, while keeping the environment healthy.
- Continuous technical support and guidance to restore degraded areas and manage them sustainably while obtaining short-, mid-, and long-term benefits and services has been the lesson learnt from the Humbo and Abreha we Atsbeha areas as an enabling factor for the scaling up of FMNR in the country.
- The Sustainable Land Management national program, the Forest Restoration National Program, the African Restoration Initiative (where Ethiopia committed to restore 15 million ha), and many other similar government and non-government (as well as private sector-led) restoration-related programs and projects have been learning from the Humbo and Abreha we Atsbeha areas about FMNR and other restoration techniques. Thus, we have learned that many of these programs and projects, including the government-led mega programs and projects, are incorporating FMNR as a tool/method of restoration and agroforestry practice in their program and/or project annual plans. This makes mainstreaming FMNR feasible as a tool of restoration and agroforestry scale-up in the country and beyond.
- A number of factors enabled the success of FMNR in Tigray. Firstly, the involvement of policymakers and model farmers during training and experience-sharing events was found to be important in the mainstreaming and institutionalization of FMNR as a tool for the

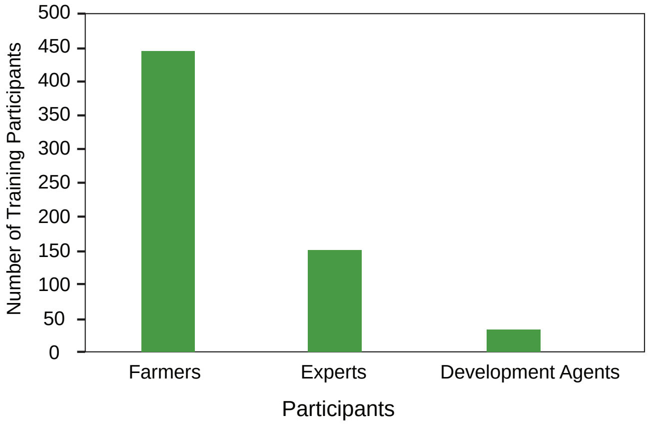

Figure 8.6 FMNR training participants as Training of Trainers in Tigray region as of June 2013.

Figure 8.7 FMNR training and joint planning at Medebay Zana, 2012, Tigray Region, Ethiopia. Photos by Niguse Hagazi.

rehabilitation and restoration of degraded lands (Figures 8.6 and 8.7). The experience has also shown us that FMNR has become helpful in the promotion of agroforestry. The practical guidelines manual—produced in the local language and distributed to experts, development agents, and other practitioners in the Tigray region to use as extension materials—was also found to be useful for the appropriate application of FMNR techniques and principles.

- The lessons learned from the Humbo area on enrichment planting, along with FMNR practice, have been helpful in filling some gaps regarding economically important tree/shrub species. Once the naturally regenerated seedlings have grown large enough, some silvicultural practices like pruning and thinning should be initiated with care and good management, followed by enrichment planting on the open spaces available.

8.4 Conclusion and Way Forward

FMNR is already accepted as a technique and best practice to restore degraded lands and promote agroforestry practices in some parts of Ethiopia, mainly in the Tigray and Humbo areas. Abreha we Atsbeha, "the Equator Prize Winner of 2012," from the Tigray Region, and the Humbo area, which earns an income from the carbon market, are thus far serving as examples for the nation, and they provide evidence of the effectiveness of FMNR when adopted by farmers and communities alike.

The existing endeavors/movement related to FMNR in Ethiopia should be strengthened and receive government recognition at all levels, including national, regional, zonal, district, and village. In areas where this practice is new, massive awareness creation, consultation, and involvement of different stakeholders, and planning are important.

In addition, the authors also recommend the use of FMNR as a tool for creating tree-based landscape restoration and for the Ethiopian Climate Resilient Green Economy (CRGE) strategy in order to achieve the targets settled in the document to increase carbon sequestration through afforestation, reforestation, and forest management. By doing so, the country can achieve its target of 50% of the total domestic abatement potential of carbon sequestration in order to build a carbon neutral economy by 2030 and achieve its pledge, at the New York 2014 Climate Summit, to restore 22 million hectares of forests, as part of the Bonn Challenge.

However, research organizations should also engage in robust evidence generation within the context of different agroecologies, social, and cultural contexts of Ethiopia. Action-research needs to be conducted concurrently with FMNR-oriented development interventions to ensure that the interventions are the most appropriate and are applied in the best way. The robust evidence-generation process and action-research activities should be framed so as to compare results with those of existing FMNR interventions, in terms of economic, social, cultural, and environmental issues and values.

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9. Constructability Criteria for Reclaiming Farmland by Using Reservoir Sediments

Kazuhisa Koda[a]*, Gebrayohannes Girmay[b], and Tesfay Berihu[b]

Summary

In efforts to produce more crops to feed the growing population, the Ethiopian government has implemented a massive campaign to construct water-harvesting technologies, including reservoirs/micro-dams, during the last few decades. However, such benefits are often short-lived due to severe soil erosion, which supplies sediments and siltation to downstream reservoirs, leading to the loss of water storage capacity and decreased lifespan, while sediment-fixed nutrient export due to soil erosion remains a serious nutrient loss process. There is an urgent need for improved sediment management strategies to solve both the water and soil nutrition challenges facing Ethiopian smallholder farmers. One such potential strategy is the reclamation of farmland using reservoir sediment, which would be periodically harvested and used to rehabilitate degraded soil. The success or failure of designing and implementing effective farmland reclamation strategies by using reservoir sediment depends on sound planning with an understanding of the factors that can affect interventions. An appropriate project concept prior to planning can significantly reduce the risks or at least minimize problematic factors. This chapter introduces constructability concepts as an organized way of guiding farmland reclamation using reservoir sediment and presents its application in Tigray, northern Ethiopia. The chapter also discusses areas of further research.

Keywords: farmland reclamation, reservoir sediment, constructability, Ethiopia

9.1 introduction

The Ethiopian economy is dominated by smallholder farming systems. Most agricultural areas of the country are rain-fed and characterized by a highly variable rainfall distribution. At the same time, the Ethiopian smallholder agriculture sector has chronically suffered from low levels of soil nutrients caused by continuous cultivation and consequent soil losses in the form of sheet, rill, and gully erosion (Hurni et al. 2016). Soil erosion in the highlands of Ethiopia is especially severe due to rugged landscapes and degraded vegetation. It has been estimated that the region loses nutrient-rich top soil at the rate over 130-ton ha^{-1} year^{-1} (Woldearegay et al. 2018), resulting in reduced crop yields (Tamene et al. 2006). While there is a growing demand for food for the ever-increasing population, Ethiopia's food security is severely hampered by soil nutrient loss. Compounding this problem are both the scarcity of water and the increasingly unpredictable supply under the influence of climate change. Climate change affects resource-constrained smallholder farmers directly by increasing the risk of crop failures and indirectly by impairing their coping ability, which is already constrained by stagnant yields under poor soil conditions (Lipper et al. 2014).

To alleviate water scarcity in efforts to produce more crops to feed the growing population, the Ethiopian government has, over the last few decades, introduced a massive campaign to construct water-harvesting technologies, including reservoirs/micro-dams (Tamene et al. 2006, Girmay et al. 2012, Berhane et al. 2016). The construction of reservoirs is expected to produce various economic, hydrologic, and ecological benefits, including increased food production,

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[a] Japan International Research Center for Agricultural Sciences (JIRCAS), Tsukuba, Ibaraki
[b] Department of Land Resources Management and Environmental Protection, Mekelle University, Ethiopia
* *Correspondence:* Kazuhisa KODA (email: kodakazu@affrc.go.jp)

easy access to drinking water for people and livestock, a rise in the groundwater level, and issuance of new springs (Tamene et al. 2006). However, such benefits are often short-lived due to severe soil erosion, which supplies sediments and siltation to downstream reservoirs, leading to decreases in the water storage capacity and lifespan of the reservoirs (Tamene et al. 2006, Woldearegay et al. 2018). While reservoirs accumulate sediment, catchments sending sediment into reservoirs lose a significant quantity of soil nutrients. Sediment-fixed nutrient export due to soil erosion is a serious nutrient loss process that aggravates soil degradation (Girmay et al. 2012). For example, some scholars have estimated that 50% of the reservoirs in northern Ethiopia have had their life expectancy reduced from 26 to 13 years because of sedimentation (Haregeweyn et al. 2008, Girmay et al. 2012). Such a process resulted in lower soil nutrients, such as organic carbon (OC), total nitrogen (N), available phosphorus (P), and exchangeable cations in the soils of the catchment than those in reservoir sediments (Girmay et al. 2012). As a result, the silted-up reservoirs with high nutrient accumulation were left unused, while degraded areas, which used to be farmlands, were abandoned—despite the increasing demand for higher-yield farmland to produce food for the growing population (Girmay et al. 2012).

In view of these problems, there is an urgent need for improved sediment management strategies to solve both the water availability and soil nutrition challenges facing Ethiopian smallholder farmers (Tamene et al. 2006). One such potential strategy is the reclamation of farmland by using sediments periodically harvested from reservoirs to rehabilitate degraded soils. Reservoir sediments contain high quantities of nutrient-rich clay and silt with low to medium OC and total N and high available P and exchangeable cations (Girmay 2012). Accumulated sediments deposited in reservoirs can therefore play a significant role in improving the nutrient status of degraded soils by enhancing the physical-chemical soil properties of the cultivated fields while also maintaining reservoir water-storage capacity. The use of reservoir sediment can be economically viable through creating new land for farming, rehabilitating gullies and riverbanks; providing potting media for seedling production; and amending degraded soils (Girmay 2012). Farmland reclamation by using reservoir sediments will be of great value to administrative officers, land owners, and farmers in Ethiopia because of its potential to (1) create new reclaimed farmland among young landless farmers, (2) achieve reservoir conservation by removing reservoir sediments, and (3) improve agricultural productivity by enabling farmers to cultivate vegetables in soils amended with fertile sediments.

Failure to maintain the expected lifespan of the reservoirs is mostly associated with the lack of sufficient site-specific biophysical and socioeconomic databases (Tamene et al. 2006). Similarly, the success or failure of designing and implementing effective farmland reclamation strategies by using reservoir sediments depends on sound planning with reliable data and understanding of the factors that can affect interventions (Tamene et al. 2006, Berhane et al. 2016). The selection of optimum approaches to reclaim farmland systems is indeed not a simple task and requires good planning and strong commitment among all parties—researchers, administrative officers, land owners, and farmers—involved in the reclamation. The design and construction process of reservoirs also needs adequate engineering, including geological investigations of the location and type of reservoirs that are built, especially (1) the safety of the reservoir on its foundations; (2) the water tightness of the foundation and reservoir area created by the impoundment; and (3) the availability of construction materials and economic considerations (Berhane et al. 2016). An appropriate project concept prior to planning followed by in-depth technical studies can significantly reduce the risks or at least keep problematic factors to acceptable levels (Berhane et al. 2016).

This chapter introduces constructability concepts as an organized way of guiding farmland reclamation using reservoir sediments, and then presents the application of these concepts in Tigray, northern Ethiopia. Constructability will be further defined and its concepts will be discussed in detail through the chapter (CII 1986). The following section reviews the significance of soil erosion, reservoir sediment problems, and the demand for farmland reclamation in Tigray. Then, it elaborates on the definition and concepts of constructability. Next is a section describing how constructability concepts are technically applied, in practice, in the process of reclaiming formerly degraded farmland using reservoir sediments. The chapter concludes with discussion on areas of further research.

9.2 Soil Erosion and Reservoir Sedimentation in Tigray

Tigray is located in the northern Ethiopian highlands. The climate is characterized as tropical semi-arid, with an annual rainfall ranging from 450 mm in the north, east, and central zones to 980 mm in the southern and western parts of the region. The topography of the region mainly consists of highland plateaus up to 3900 m.a.s.l., which are dissected by gorges (Haregeweyn et al. 2008). In terms of geohydrology, the region is dominated by rocks/soils with variable hydraulic properties (Woldearegay et al. 2018). This rugged topography with rocky geohydrology is very sensitive to erosion, making effective utilization and management difficult. The highland climates have supported a high population density with a long cultivation history, which is estimated to date back to 3000 BC (Haregeweyn et al. 2008). The long-term unlimited use of farmlands for crop production, combined with steep topography, erosive rains, and the unwise use of vegetation, has caused severe land degradation. As a result, the region is considered one of the most degraded (and still degrading) regions in Ethiopia (Tamene et al. 2006, Woldearegay et al. 2018). The land degradation, coupled with erratic distribution of rainfall in Tigray, has caused recurring drought and famine, which was historically demonstrated during 1888–1892, 1973–1974, and 1984–1985 (Gebremeskel et al. 2018).

In response to these human crises, the government of Ethiopia, in collaboration with international organizations, launched a massive soil-water conservation scheme through the construction of reservoirs and micro-dams in Tigray: from 1996 to 2001, over 50 micro-dams were built in the region (Tamene et al. 2006, Gebremeskel et al. 2018). Due to a lack of good planning, however, including the selection of appropriate dam sites and technologies, these reservoirs suffered from serious sedimentation, resulting in the reduction of expected services (Haregeweyn et al. 2008). Based on a study conducted in Tigray on reservoir sedimentation in relation to catchment soil erosion, Tamene et al. (2006) reported that most of the reservoirs constructed to harvest rain water lost 50% of their storage capacity less than 5 years after entering service. Haregeweyn et al. (2008) showed that 50% of the 13 studied reservoirs had lost half their life expectancy, while only 3 reservoirs were projected to serve their entire expected lifespan (cited in Girmay et al. 2009). Furthermore, based on an analysis of the inventory of the 92 reservoirs, Berhane et al. (2016) found that 61% had sedimentation/siltation problems, 53% suffered from leakage, 22% experienced insufficient inflow, 25% had structural damage, and 21% had spillway erosion problems.

The rapid sedimentation is mainly attributed to poor planning of the reservoirs (Haregeweyn et al. 2008). It is crucial to determine which technologies will be the most efficient and economical for reservoir conservation and farmland reclamation in locally specific contexts before reservoirs are built.

9.3 Constructability Definition and Concepts

9.3.1 Definition

The Construction Industry Institute (CII) Constructability Task Force defines constructability as the "optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives" (CII 1986).

Vanegas (1987) provided a general framework for constructability research. Research conducted by the CII was the main catalyst for the formal organization of the field of constructability. Research from the CII identified 17 constructability concepts, and the CII also developed a Constructability Concepts File (1987) that provided helpful examples related to the application of each concept. These concepts were classified into three major project delivery phases: (1) conceptual planning; (2) design and procurement; and (3) field operations. The CII also published a Constructability Implementation Guide (1993) which organized a system of methods for carrying out constructability in the form of a roadmap.

9.3.2 Concepts

The CII groups 16 high-level concepts by their roles in each phase of conceptual planning, design and procurement, and field operation. Each concept is described as follows (CII 1993).

In the conceptual planning phase, there are seven concepts:

Concept 1-A: The constructability program should be made an integral part of the project execution plan.

Concept 1-B: Special emphasis should be placed on maintaining an effective project team.

Concept 1-C: Early project planning should actively involve individuals with current construction knowledge and experience.

Concept 1-D: This early construction involvement should be a consideration in developing the contracting strategy.

Concept 1-E: The master project schedule should be startup and construction-sensitive.

Concept 1-F: Major construction methods should be analyzed in-depth early on and should be facilitated through proper facility design.

Concept 1-G: Site layouts should promote efficient construction, operation, and maintenance.

In the design and procurement phase, there are eight concepts:

Concept 2-A: Design and procurement schedules should be construction-driven.

Concept 2-B: The capabilities and benefits of advanced information technology should be exploited.

Concept 2-C: Designs should be configured to enable efficient construction.

Concept 2-D: Design elements should be standardized.

Concept 2-E: Technical specifications should promote construction efficiency.

Concept 2-F: Detailed designs of modules and preassemblies should be prepared to facilitate efficient fabrication, transport, and installation.

Concept 2-G: Project designs should promote accessibility to materials and equipment by construction personnel.

Concept 2-H: Designs should allow for and enable construction under adverse weather conditions.

In the field operation phase, there is one concept:

Concept 3-A: Special effort should be applied toward developing innovative construction methods.

The next section provides a case study from Tigray to demonstrate how to apply these concepts in each of the planning, designing, and operation phases of the actual farmland reclamation. Adizaboy reservoir conservation has been a joint project of Japan International Research Center for Agricultural Sciences (JIRCAS) and Mekelle University, which have been experimenting with small-scale water-conserving irrigation technology to grow garlic and onions on reclaimed farmland (an area measuring 23 m x 14 m) (Koda et al. 2018). The following section presents the authors' experiences with using the CII constructability criteria to guide the implementation of the farmland reclamation exercises.

9.4 Constructability Criteria in Practice

Each criterion is examined in the sections below, followed by bullet points summarizing key considerations for each section.

9.4.1 Conceptual planning phase

Concept 1-A: Selecting optimal potential farmland for reclamation in view of the entire execution plan—The selection of optimal sites for farmland to be reclaimed is the first step of planning an entire execution plan (Figure 9.1). Engineering consideration considering biophysical factors is especially critical for the sustainability of farmland reclamation projects. For example, reclaimed farmland size must be compatible with farmers' capacity. Distance, as well as height difference, between reservoirs and reclaimed farms should be kept modest, since the greater each becomes, the more difficult it is to transport sediment and to pump up/allocate irrigation water from reservoirs to farms (Figure 9.2). Farmland slopes should not be steep enough to cause soil erosion, and thus fail to maintain the thickness of sediments for the reclaimed farmland.

- Compatibility of reclaimed farmland size with farmer's operability and maintainability
- Distance between reservoir and reclaimed farmland
- Height difference between reservoir and farmland
- Slope of farmland and thickness of sediments
- Clearing and leveling of land for reclamation
- Fencing the compatible farmland size

Logistical considerations are equally important for optimal site selection, given the fact that farmland reclamation projects are often implemented in rural remote sites. Efficient use of site conditions must be maximized and exploited. For example, the availability of construction materials (i.e., stones, gravel, sand, poles) and sediment to be harvested in surrounding areas facilitates mobilizing local resources for operation. In turn, procuring external construction materials and tools (i.e., iron bars and sheets, barbed wire, poles) as well as inputs (such as extra chemical fertilizer to complement the fertility of sediments) requires good accessibility to farms for easy delivery of supplies. The project staging area should be large enough to allow on-site work such as assembly and concrete mixing for the construction of fences, along with space for the construction of the warehouse to store equipment and a guardhouse for protection against wild animals. After the farmland is reclaimed, accessibility is still critical for the farmers who will be commuting to the land to grow crops and deliver outputs to markets. There should also be sufficient space to expand reclaimed farmland in the future. The following site attributes should be taken into consideration:

- Site accessibility for material delivery, as well as for farmers
- Adequate laydown area availability for requisite working space, as well as a warehouse in which to keep necessary heavy equipment and tools
- Extra space for future site expansion

Figure 9.1 Selection of optimal sites for farmland to be reclaimed.

Figure 9.2 Consideration on distance between reservoir and reclaimed farmland.

Figure 9.3 Concrete mixing training.

Figure 9.4 On-site communication.

Figure 9.5 Farmland reclamation permit process.

Concepts 1-B, 1-C, 1-D: Building an effective project team—The success of a farmland reclamation project also depends on the capacity of project team members in designing, procurement, and field operation through relevant training, incentives, and communication (Figures 9.3 and 9.4). The needed attributes are as follows:

- A training program for specific crafts
- Daily allowances for on-site jobs
- On-site communication with persons who have construction expertise
- On-site teamwork under the leadership of those with construction expertise

Concepts 1-E, 1-F, 1-G: Facilitating proper designs and layouts—Decisions on appropriate construction methods, facility designs, and site-layouts must be based on in-depth analyses to promote efficient construction, operation, and maintenance, utilizing information and survey data, such as below.

- Amount of storage water in the reservoir to be used for irrigation
- Availability of standard designs of sand/silt basin and drip irrigation

9.4.2 Designing and procurement phase

Concept 2-A: Planning design and procurement schedules and flexibility—In planning design and procurement schedules, the interaction and interface of activities must be well managed. Applications for farmland reclamation permits should be made early. Schedules should have room for flexibility and should consider potential factors which can delay field operation and procurement processes, such as the following (Figures 9.5–9.8):

- Land permit processes for obtaining the land for reclamation
- Adaptability to unexpected field conditions, such as extremely low

or high run-off volume, dropping or rising groundwater level, and water consumption by the people in the vicinity

- Potential delays due to the unavailability of an accounting officer
- Potential delays due to the unavailability of specialized equipment, material, and labor

9.5 Farmland reclamation permit process

Concepts 2-B, 2-C, 2-D, 2-E: Designing efficient construction elements—Designing farmland reclamation requires considerations for minimizing costs, including procurement costs and costs for labor, materials, equipment, and guards. In doing so, the following points must be considered in designing and procuring schedules (Figure 9.9):

- Maximize the use of advanced and innovative survey technologies, including level survey equipment and GPS, note PCs, and echo-sounders.
- Minimize the complexity of design details and reduce the need for overly detailed specifications.
- Use survey results from past studies and water balance analysis results.
- Use standard dimensions and sizes for the reclaimed farmland system.

Concepts 2-F, 2-G: Preparing for preassemblies and logistics—In order to facilitate efficient field operations, detailed designs of modules, including fabrication, transport, and installation of materials and equipment should be prepared by construction personnel in advance. Procurement schedules must be planned and designed to minimize potential factors that can delay field operations, such as delays in equipment delivery, custom clearance, and permission processes. Inventory of construction

Figure 9.6 Water use restriction from a dried-up reservoir.

Figure 9.7 Material procurement (nails).

Figure 9.8 Material procurement (wood poles).

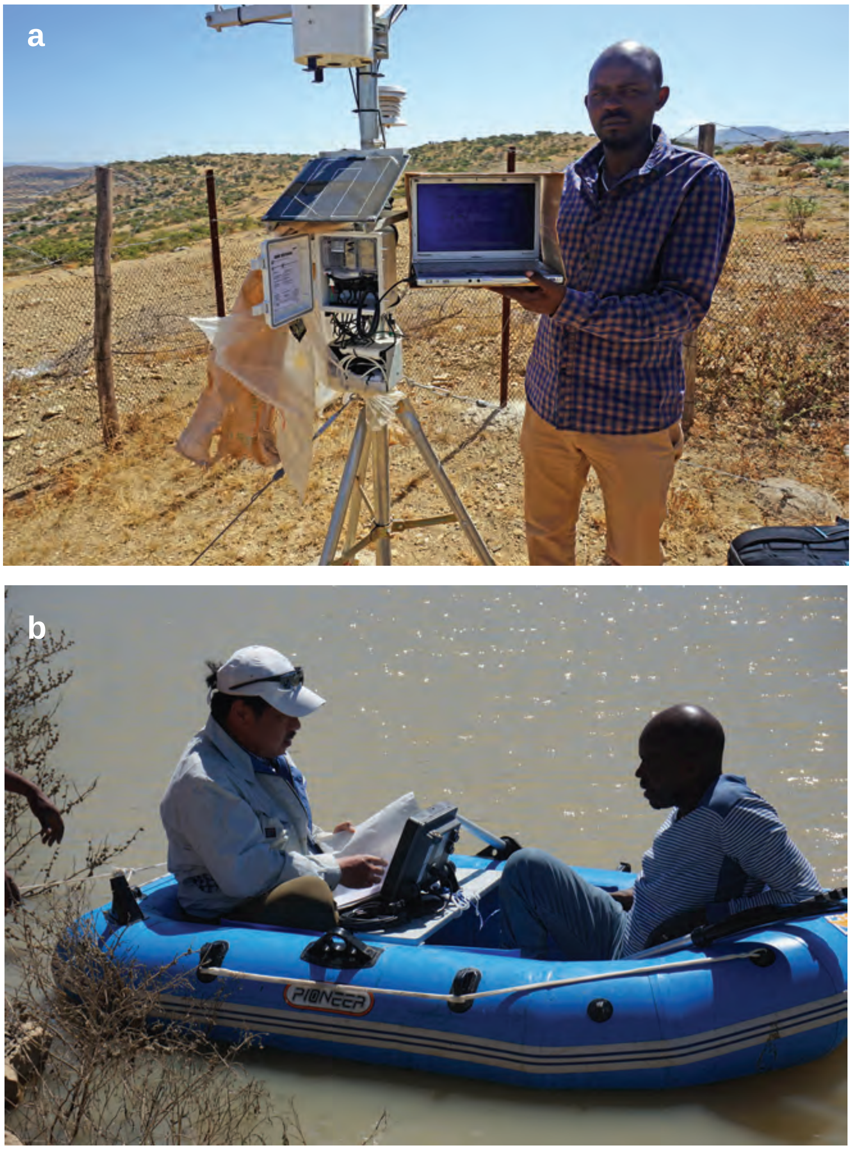

Figure 9.9 Use of advanced and innovative survey technologies, including (a) level survey equipment, GPS, and note PCs and (b) echo-sounders.

Figure 9.10 L-type metal column preassembled by cutting and welding.

and delivery components can help minimize costs and time involved in on-site and off-site field operations, thus maximizing efficiency (Figures 9.10 and 9.11).

- Construction processes involving maximum use of on-site equipment and minimum labor
- Off-site preassembly of some materials involving prefabrication (i.e., weather observation devices) and cutting/welding (i.e., construction components, such as L-type metal columns, etc.) by skilled labor
- Plan for maximizing the use of the same transportation system for material and equipment delivery.
- Facilitate custom inspection for equipment made abroad.

Concept 2-H: Preparing for adverse weather conditions—Negative effects due to bad weather must be minimized (Figures 9.12 and 9.13).

- Reclamation work, such as sediment transportation in reservoirs and concrete work for sand/silt basins, should be limited under rainy conditions.
- Restrict site access through submerged farms and roads under rainy conditions.
- Provide temporary storage of weather sensitive equipment or materials in warehouses.

9.4.3 Field operation phase

Farmland reclamation processes usually consist of the construction of (1) a stone bund; (2) sediment layers; (3) a drainage canal; (4) a weather observation device; (5) irrigation facilities such as a pump, a hose, and a water tank; (6) a warehouse to store equipment, as well as a guard; and (7) a fence with barbed wire attached to metal columns to protect agricultural products against attacks by wild animals when deemed necessary, given local conditions.

In practice, once a farmland site is defined, weeding, shrub-clearing, and the removal of large stones can begin. Stones are utilized for constructing stone bunds along the boundaries of farmland. Reservoir sentiments are collected by shovels and then transported by donkeys to farmland. Transferred sediments are layered and leveled on the reclamation farmland, from which small stones and weeds are removed, so that the farmland surface is made flat and conductive to farming. Before seeding on the farmland, fences are established to keep away domestic animals such as goats, sheep, and cattle, which can intrude into and graze on the farmland, destroying planted crops. A warehouse is built to accommodate a guard to watch the crops and prevent theft or damage by wild animals, as well as to store equipment such as water pumps and drip irrigation. After water flow from upstream catchments to the reclaimed farmland is observed during rains, a drainage system can be established so that the water eventually flows into the reservoir without causing erosion problems to the reclaimed farmland.

9.5 Discussion and Conclusions

Existing reservoirs in Tigray and beyond have been built in Ethiopia to address constraints to increased crop production. However, many of these reservoirs have suffered from sedimentation and water leakage problems, which have reduced their expected performance (Berhane et al. 2016). One possible solution is the reclamation of farmland by using sediment harvested from reservoirs to rehabilitate degraded soil, while using the reservoir water for irrigation. The success or failure of designing and implementing effective farmland reclamation strategies by using reservoir sediment depends on sound planning with an understanding of the factors that can affect interventions. The constructability criteria provide a

Figure 9.11 Lumber cutting.

Figure 9.12 L-type metal fence with barbed wire surrounding the reclaimed farmland.

Figure 9.13 Temporary warehouse.

framework for the selection of the optimum reservoir conservation methodologies that maximize benefits while minimizing costs. In this paper, the authors have mapped CII constructability criteria to help guide planning, design, and implementation operations of farmland reclamation using reservoir sediment. Construction material recycling, based on methodological frameworks such as that developed by CII, would justify and formalize financing and scaling up of meaningful land reclamation programs for rural development in developing countries.

An appropriate project concept prior to planning can significantly reduce the risks, or at least minimize problematic factors, especially when supported by the availability of quality biophysical and socioeconomic data to guide decision making. Research to estimate the availability of reservoir sediment in Tigray/Ethiopia could be used to evaluate potential areas of farmland to be reclaimed, depending on assumptions of volume/thickness of sediments to be transferred per unit area (Koda et al. 2019). Aside from biophysical estimations, a socioeconomic feasibility assessment will also be critical to determine the capacity of the landless youth to venture into farming in the reclaimed farmland and to determine the types and levels of capacity development that would be necessary. Allocation of reclaimed lands for needy, landless rural farmers, and securing their tenure on the lands, would lead to sustainable rural development in Ethiopia and other Sub-Saharan Africa countries.

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PART IV. Making Livestock, Energy and Forestry Sectors Climate Smart

Photos (clockwise, from top left): livestock fattening for market, Northern Ethiopia (by Aklilu Negussie); livestock management: farmer feeding donkeys crop residues, Oromia region (by Miyuki Iiyama); fuelwood collection by women, Oromia region (by Miyuki Iiyama); and agroforestry landscape in East Wollega, Oromia region (by Aklilu Negussie).

10. Climate-Smart Livestock Production Systems in the Midlands and Highlands of Ethiopia

Solomon Kiros[a,b]*, Gebrehiwot Hailemariam[c],
Gebregziabher Gebreyohanes[d], Tessema Zewdu[e], Kiros Meles Hadgu[c],
Aklilu Negussie[f], Emiru Birhane[g], and Zelalem Hadush[g]

Summary

Livestock is an integral part of agriculture and has an important economic, social, and cultural significance in Ethiopia. Climate change affects livestock production by affecting feed and nutrition, water accessibility, and health. Although livestock production plays a huge role in Ethiopia's economy and food security, poor livestock management practices characterized by unsustainable free grazing and greenhouse gas emissions have had a negative impact on the environment. At the same time, climate change has had tremendous negative impacts on livestock production. In order to reduce the effects of climate change on livestock and enhance environmentally friendly livestock production, it is important to improve livestock management practices and introduce a sustainable grazing system, appropriate policies, and institutional set up. Applying cut-and-carry feeding and agroforestry, along with improved feed and better breeding practices offers major opportunities for reducing emissions and increasing the sequestration of greenhouse gases. Moreover, it is necessary to encourage and reward farmers, administrative bodies, and experts who practice the cut-and-carry feeding system successfully. This chapter elaborates on the application of integrated technical and non-technical "best fit" options for a livestock production system. The best fit technological options focus on modifying livestock diversity and number and improving management, breeding, and feed, while non-technical options include developing and implementing appropriate policies, local bylaws, and indigenous knowledge on livestock production systems. Integrating these approaches, together with effective surveillance and rapid response strategies, as well as use of better breeds with greater resistance to drought and disease vectors, could play a large role in developing adaptation and mitigation strategies and building resilient livestock agriculture in the face of a changing climate.

Keywords: climate change, livestock, policy, grazing, technological, non-technological

10.1 Introduction

Ethiopia's agriculture is dominated by smallholder farmers, and over 80% of the population is supported by and depends directly on climate-affected natural resources. The country is known for its diverse ecology and topography, where diverse resources and traditional skills and experience in livestock rearing are common (Tesfaye et al. 2010). Integrated crop and livestock production systems in the mid- and highland areas are age-old traditions. The Ethiopian livestock population is estimated to be the largest in Africa, constituting approximately 150 million head in 2009/2010 (ECSA 2010): over 50.9 million cattle, 25.9 million sheep, 21.9 million goats, 1.9 million horses, 5.7 million donkeys, about 400,000 mules, 800,000 camels, and 42 million poultry. Livestock production systems have significant importance in food production, and they enable communities to successfully inhabit arid and semi-arid regions (Duguma et al. 2012). The livestock sector produces multiple benefits, including sources of food, wool for clothing, fuel, fertilizer, and nutrient cycling for soils, as well as other functions such as draught power, income, and employment (Figure 10.1). Livestock are also attached to social and cultural identities and offer risk management functions.

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[a] School of Chemical and Bio-Engineering, Addis Ababa Institute of Technology, Addis Ababa University, P.O. Box 385, Addis Ababa, Ethiopia

[b] Department of Biology, Mekelle University, PO Box 231, Mekelle, Tigray, Ethiopia

[c] World Agroforestry (ICRAF) - Ethiopia, c/o ILRI Ethiopia, P. O. Box 5689, Addis Ababa, Ethiopia

[d] Ministry of Agriculture and Livestock Resources, Addis Ababa, Ethiopia

[e] School of Animal and Range Sciences, College of Agriculture and Environmental Sciences, Haramaya University, Dire Dawa, Ethiopia

[f] WeForest, Ogentroostlaan 15, B-3090 Overijse, Belgium

[g] Department of Land Resource Management and Environmental Protection, Mekelle University, P.O. Box 231, Mekelle, Ethiopia

* *Correspondence:* Solomon Kiros (email: selamawitsole@yahoo.com / solomun.kiros@aait.edu.et)

Figure 10.1 The majority of Ethiopian farmers use livestock power to thresh their crop harvests to separate the grain from the straw; photo taken in Central Tigray by Aklilu Negussie.

Despite this huge resource, the contributions of the livestock sector to the national economy are insignificant, due to poor livestock management, low productive traits, and limited access to markets and financial resources, coupled with the impact of climate change on animal physiology, feed availability, and the occurrence of several diseases (Addis 2015, MoA and ILRI 2013). At the same time, poorly managed livestock farming has been recognized as a major threat to natural resources. In particular the free-grazing system, in fragile landscapes with high livestock density, has been associated with extensive land degradation. Livestock productivity in Ethiopia is highly impacted by weather; climate change adds significant challenges to already-stressed ecosystems such as those in which smallholder farming takes place. Although smallholder farmers have developed the capacity to adapt to environmental change and climate variability through experience and by using indigenous knowledge, the speed and intensity of climate change is overtaking their ability to respond.

Given the reality, it is evident that the livestock production system in Ethiopia must be transformed into an effective, resilient, and "climate-smart" practice that will strengthen food security and result in sustainable natural resources management. There are however considerable knowledge gaps regarding how climate change affects crop-livestock production systems and their productivity in Ethiopia. To this end, climate-smart livestock production will require cutting-edge science and research, political commitment, adequate financing, robust governance, policies in support of land use and production practices, improved feed resources development activities, better functioning of grazing and rangeland management, and environments that foster long-term investments at all levels through the livestock value chain.

This chapter addresses the question of how livestock keepers can improve their livelihoods, while reducing negative impacts on the environment. It describes some of the likely impacts of climate change on livestock production and vice versa. Then, it highlights the importance, for Ethiopian livestock keepers, of mitigating and adapting to climate change in terms of livestock productivity and water and feed resources availability and elaborates on appropriate options, which include improved livestock and grazing management in order to enhance the contribution of the livestock sector to the national economy and to food security at all levels.

10.2 Climate Change and Livestock Production

The Intergovernmental Panel on Climate Change (IPCC) has predicted that by the year 2100, the average global surface temperature will have increased between 1.5 °C and 2.5 °C (IPCC 2001). As a result, approximately 20% to 30% of plant and animal species are expected to be at risk of extinction, leading to severe impacts on food security and the economies of developing countries (IPCC 2001, FAO 2007).

Figure 10.2 (a) Encroachment of natural forests and changes in land use to other types such as grazing land, farmland, and settlements in Eastern Tigray; (b) fast degradation of Rift Valley escarpment Afromontane forest in Tigray and Afar. Photos by Aklilu Negussie.

The negative impacts of climate change are felt more severely by rural people, who rely heavily on the natural resource base for their livelihoods (Kassa et al. 2012). The possible effects of climate change on food production are not limited to crop production, as climate change could also severely affect livestock production systems. Indeed, climate change impacts may be felt more heavily in the areas of livestock production and productivity than in crop production, as traditional livestock production systems often incorporate free grazing practices that require travelling long distances in search of feed and water, both of which are vulnerable to climate change (Kassa et al. 2012). Climate change has short- and long-term consequences for dairy, meat, and wool production, as well as for livestock growth and reproduction. These issues mainly arise from the limited availability of water and feed resources, leading to poor growth and reproduction of animals, and the high prevalence of various diseases due to rising temperatures and changing rainfall patterns (Rotter and Van de Geijn 1999).

Climate change can cause reduced availability of freshwater and increased scarcity of water resources. Since groundwater recharging capacity may decrease with the lowering of the water table as a result of climate change, a reduction in the production of borehole water points can be expected (IPCC 2001). A consequence of this may be conflict over water sources for livestock keepers, particularly in arid and semi-arid regions where groundwater is the main water source. Wetlands, which represent critical dry-season grazing areas for livestock, are projected to shrink drastically in size or disappear altogether across climate-change time scales (Kinyangi et al. 2009). Climate change can also cause shortages of and changes in feed resources linked to the fluctuation of livestock numbers on grazing lands, which can further lead to the loss of the buffering abilities of ecosystems, as well as to intensified desertification processes (Figure 10.2; Steinfeld et al. 2006).

Rising temperatures and changes in rainfall patterns and distribution may be translated into the increased spread of vector-borne diseases and macro parasites. In addition

Case Study 10.1 The Role of Community Bylaws in Enhancing Climate-Smart Grazing Land Management and Utilization in Tigray, Ethiopia

Figure CS 10.1 Communal pasturelands accommodating a huge number of livestock, which is always more than the carrying capacity of the pastureland. Photo taken in Eastern Gojam, Amhara region, by Aklilu Negussie.

Background

Livestock management in Ethiopia is mainly based on extensive and uncontrolled grazing on communal lands, degraded hillsides, roadside areas, crop stubble, and fallow lands. The free-grazing system has contributed to poor soil fertility, land degradation, and deforestation, and it aggravates climate change. Soil and water conservation practices implemented so far through the construction of terraces on arable lands have brought limited change, due to the free-grazing effect. To reduce the negative impacts while improving the productivity of livestock, the introduction of a restricted grazing system in Tigray is crucial to enhance food security and climate-smart agriculture activities.

Approaches

Districts that practice controlled grazing have used different approaches, such as creating awareness to convince communities and the development of different bylaws for the utilization of communal grazing lands. During the delineation process, the community, development agents, and local administrations together identified the sites for restriction and improvement based on criteria such as bare lands, shallow soil depth, stoniness, and coverage of unpalatable species. The final decision was made during a general meeting of the community members and was endorsed by traditional bylaws that helped to manage, restrict, and utilize the restricted grazing land. The community participated at no cost on the enrichment of grazing land implementation, including ploughing, sowing, planting, and weeding. The designated grazing lands are protected by guards who are assigned and paid by the community as the lands are not fenced. The community allowed for newly delivered cows and oxen to graze on the restricted grazing lands from June to August, when animal feed shortage is mainly observed. Finally, after the restricted grazing areas were well established, the communities allowed controlled use for cutting grass for feed or construction, fuelwood collection from dead trees, dung collection, and in a few areas, beekeeping.

Impacts

Grazing land enclosures and enrichment showed that reversing land degradation significantly increased biomass yield, improved the nutritive value of biomass, increased grain and straw harvest, substantially increased milk production, decreased the prevalence of disease, reduced the incidence of newborn calf deaths, and helped buffer the community from the adverse effects of drought. In addition, once indigenous trees were established, farmers were able to harvest green forage three times per year, as opposed to just once.

Policy implications/relevance

The community-based initiatives on communal grazing-land management influenced farmers in other places, as well as agricultural policy makers, to look for conservation-based agriculture and to contribute to the national strategy, “Climate Resilient Green Economy,” which enhances the expansion of agroforestry on grazing and farm lands. In addition, the success of restricted grazing is closely related to the issue of benefits and their equitable distribution in successful districts, which has helped to develop a sense of ownership security. In addition, the community-based bylaws related to the restriction and management of the enriched communal grazing areas may be identified as good practices to be scaled out to other places. Developing sustainable communal grazing-land management and utilization policies can be a helpful option as part of overall strategies for sustainable land management.

To find out more, see Gebregziabher Gebreyohannes and Gebrehiwot Hailemariam (2011). *Challenges, Opportunities and Available Good Practices related to Zero Grazing in Tigray and Hararghe, Ethiopia*. Drylands Coordination Group Report No. 66, Norway, ISSN: 1503-0601 to the higher prevalence of diseases, there may also be the emergence of new diseases and even new means of disease transmission (Rotter and Van de Geijn 1999). The behavioral, immunological, and physiological functions of animals are greatly affected by thermal stress associated with climate variability and change (Nienaber and Hahn 2007). Thermal stress also reduces the rate of feed intake and results in poor growth performance of animals (Rowlinson 2008). Mader (2003) described how metabolic activities of animals were impaired when they were exposed to heat stress. The degree of impact and the response depend on the type of animal and the genotype, body condition, physiological state, and age, as well as the management practices being used, which may include housing and shading to protect animals from heat stress (Figure 10.3). Some breeds of livestock may not cope well with extreme heat events, and they may suffer high mortality rates due to increased incidence of weather-related diseases. Longer, more frequent, and more intense droughts may also lead to increased mortality. The emergence and the re-emergence of vector-borne diseases in many regions of East Africa have already provided a clear message on the link between climate change and the effects on animal health (IPCC 2001).

While climate change affects livestock production by affecting water availability and animal nutrition and health, poor livestock management practices in turn have various negative impacts on the environment. Such impacts include overgrazing and land degradation, and they can become an important driver of deforestation. Livestock also produce methane and nitrous oxide emissions from ruminant digestion and manure management. The livestock sector is the largest global source of methane emissions, estimated to be 37%, and also contributes to total carbon dioxide and nitrous oxide emissions (9% and 65%, respectively) (FAO 2010b). Significant constraints that hinder sustainable livestock production include poor market infrastructure and capital; a lack of output-processing technologies; weak institutional linkages between research, extension, and

Figure 10.3 A farmer applying cut-and-carry feeding practice under tree shade for fattening purposes. Photo by Gebrehiwot Hailemariam.

farmers; resource degradation; and climate change and variability (Notenbaert et al. 2010).

10.3 The Need to Make Livestock Production Systems in Ethiopia Climate Smart

Climate change and food insecurity are two emerging issues facing people all over the world, particularly in developing countries, including Ethiopia. The impacts of climate change, coupled with environmental degradation, demographic pressures, and increasing poverty, may lead to a decrease in livestock production and productivity (McSweeney et al. 2008). The impact of climate change on the livestock sector is a matter of serious concern, as most of the livestock in the high- and midlands of Ethiopia are reared in disturbed ecosystems with degraded resources (Temesgen et al. 2014, Kassa et al. 2012; Gebregziabher and Gebrehiwot 2011). Similarly, in lowland regions of the country, climate change has increased the frequency of droughts and the occurrence of diseases and pests, resulting in a loss of livestock resources and leading to food insecurity, while also exacerbating conflicts over scarce resources (Demeke 2006). Losing livestock assets in rural communities of Ethiopia might trigger a collapse into chronic poverty because livestock serve rural households in providing income generation; a means of ploughing and crop thrashing; and sources of nutrition, saving assets, fuel (from dung), dowries for marriages, and cultural holidays.

Because livestock production is vitally important for myriad cultural and economic reasons, urgent adaptation and mitigation mechanisms are required to address the complex set of problems linked to climate change, such as extended hot seasons; changes in the quantities, intensities, and patterns of rainfall; and competition over land uses (e.g., for food, forage crops, fuelwood, and the allocation of land for restoration). So far, poor management practices, due to the lack of resources, knowledge, research facilities, and technologies, as well as poor veterinary and extension services, have exposed Ethiopia's livestock sector to the aforementioned problems resulting from climate change. However, there are some successful cases where communities have developed ways to cope with and adapt to climate variability. For example, farmers in Eastern Tigray, Ethiopia, whose livelihoods depend on crop and livestock production, have adopted climate-smart livestock production systems by modifying livestock diversity and numbers, protecting enriched grazing land until it is well established, collecting and preserving hay, purchasing crop residues, and selling unproductive livestock (K. Solomon and M. Kiros, unpublished data, 2013).

10.4 Integrated Options for Climate-Smart Livestock Production Approaches

The climate-change resilience mechanisms that could increase livestock productivity in Ethiopia may require the application of integrated technical and non-technical best fit options within the livestock production system. The best fit technological options should focus on genetics and reproduction, livestock feed and nutrition, and animal health control. The non-technical options include improved controlled grazing through cut-and-carry feeding and agroforestry (along with enabling policies), institutional arrangement, and indigenous knowledge. Integrating these approaches, together with improved surveillance systems, would play a great role in developing adaptation and mitigation strategies and in building livestock agriculture that is resilient to the changing climate.

10.4.1 Technological options

10.4.1.1 Modifying livestock composition (diversity and number)

The behavioral, immunological, and physiological functions of animals are greatly affected by the thermal stress associated with climate variability and change (Nienaber and Hahn 2007), although the type of livestock determines the degree of such impacts. Destocking of livestock might help to construct shelter for selected better breeds and modern husbandry. Extreme weathers such as drought and increasing temperatures may also increase the susceptibility of animals to parasites and diseases, particularly vector-borne diseases (Sutherst 2001, Tabachnick 2010). Genotypes/breeds with greater resistance to drought and disease vectors are pertinent issues in climate smart animal production systems. Depending on the agroecology of the area (e.g., highland and midland), low-producing animals should be replaced with fewer but highly productive, disease-resistant animals (either local or crossbreed). It is important to identify and strengthen local livestock breeds that have adapted to local climatic stresses and feed sources in order to improve genetics through crossbreeding with heat- and disease-tolerant breeds. However, in Ethiopia, little effort has been made to understand the potential impact of climate change on parasite types and the rate of occurrence of disease and the subsequent effects on animal production. More research is required in this field. Universities and research institutes should undertake functional genomic research to identify the gene expressed during heat stress in order to gain a better understanding of heat resistance mechanisms and consequently improve thermal tolerance via gene manipulation.

10.4.1.2 Modifying and improving management practices

Considering the great role of livestock in Ethiopia, assessing ways of improving livestock management for improved animal nutrition and health and decreasing pressure on natural resources and the environment is critical. Soussana et al. (2010) explain that in livestock production systems, the main problems are methane emissions and deforestation, and they note the uncertain role of carbon sequestration in grazing systems. The efficient treatment of manure for biogas can be promising. For example, the anaerobic digestion of manure stored as a liquid or slurry can lower methane emissions and produce useful energy, while composting solid manures can produce useful organic nutrients for soils and substitute for and/or reduce the use of inorganic fertilizers for improving soil conditions and productivity.

Furthermore, animal nutrition and health control is critically important while contributing to potentially mitigating emissions from livestock production. Balancing the energy-to-protein ratios in ruminant diets by introducing forages with high energy and protein content for grazing or by feeding via the cut-and-carry system will reduce methane emissions from the livestock due to metabolic activity. Feeding plant source lipids and other supplements, such as tannins and saponins may also reduce unwanted gases emissions. The ecological distribution and feeding habit of the livestock should be considered to determine the type of forage to be introduced, its favored climate and soil, a system of development, and its and utilization at the household or community level. Keeping the livestock in shade, feeding them through a cut-and-carry system (which will be discussed in the next subsection), and making changes in feeding frequencies and feeding times can have an impact in reducing thermal stress in the dry seasons (Figure 10.3). The use and planting of shade trees is highly recommended and will benefit livestock by providing fodder (leaves and pods) and reducing the effect of thermal stress on the animals. The extension system should be dynamic and supported with evidence to interject new techniques, skills, and technologies. Moreover, research should be done to identify bottlenecks in the extension system and on the low adoption rate of cut-and-carry feeding and the scale up of agroforestry and best fit technology across the scale.

10.4.2 Non-technical options

10.4.2.1 Developing and implementing policies to enhance cut-and-carry feeding and agroforestry along the scale

Cut-and-carry feeding systems should be supported with policies, regulations, and local bylaws. Destocking nonproductive livestock and limiting free grazing should be guaranteed. Policies on restricting free grazing and destocking need to be harmonized with local efforts. The enforcement of regulations can play a significant role in sustainable grazing management and enhance cut-and-carry feeding practices and the survival of established seedlings in the landscape. These practices can be supplemented with backyard forage development strategies, which involve multipurpose tree species planting as agroforestry systems. Forage growing in recommended arrangements on cropland boundaries, around gullies, on hillsides, and within exclosures can contribute towards increased livestock productivity and climate change resilience. For example, multipurpose fodder trees and shrubs include six tree species: lucerne (*Chamaecytisus palmensis*), Leucaena (*Leucaena leucocephala*), sesbania (*Sesbania sesban*), pigeon pea (*Cajanus cajan*), *Faidherbia albida*, and Moringa. Grass species include elephant grass (*Pennisetum purpureum*), Rhodes grass (*Chloris gayana*), Phalaris, and local grasses, such as desho grass (*Brachiaria brizantha*) and others. Legume species include oats, vetch, alfalfa, cowpea, and lablab. These trees, shrubs, legumes, and grasses should be planted and sown on different areas, including grazing lands, backyards, irrigation sites, hillsides, farmlands (as agroforestry), grass strips on gullies, and boundaries of farmlands and irrigation canals, as well as undersown with maize and sorghum where possible to provide good sources of animal fodder (Figure 10.4).

In addition to focusing on directly improving animal productivity and feed and manure management, there are also grazing-land management practices available that can address and improve climate change resilience. Reducing further degradation and increasing the restoration of degraded grazing lands through the use of a proper grazing management system, such as limiting the number of livestock based on the carrying capacity of the grazing land and its re-vegetation, are important in encouraging cut-and-carry feeding practices and climate change mitigation strategies. These practices can include traditional grazing exclosures, the use of cut-and-carry fodder, shifting grazing periods until pasture species are properly established, limiting the number of days that livestock are allowed to stay in grazing areas, limiting the number and type of species allowed to graze, and ensuring the even grazing of pasture species throughout the grazing area. Livestock keepers can stimulate diverse mixtures of pasture species, improve nutrient cycling, and increase plant productivity and biodiversity. Moreover, farmers who are interested may be encouraged and incentivized to destock livestock numbers and adjust production based on factors such as agroecology suitability and easy access to feed, inputs, and the market. Feed improvement interventions such as urea treatment, silage making, and urea molasses multi-nutrient block or UMMNB, which is a source of protein and energy supplements, should be applied. Policies and development interventions should strengthen the involvement of well-functioning informal institutions in decision-making so that cut-and-carry feeding practices can be achieved.

10.4.2.2 Integrating best and effective local bylaws and indigenous knowledge

Implementing controlled grazing requires enabling policies and institutional arrangements that strengthen the effectiveness of grazing management systems. First, however, it is useful to recognize the knowledge of local communities and indigenous peoples, who have both an in-depth understanding of their environment and vast experience in adapting to climate variability. In addition, community awareness should be raised on the negative impacts of livestock and on the mismanagement of natural resources. It is critical to build capacity through training and experience sharing among community members, development agents, and experts on grazing-land management on topics such as proper stocking, the proper season of grazing, duration of grazing, resting of grazing land, and diversity of livestock grazing. The adoption of best practices will be facilitated by strengthening applicable bylaws on how to use communal grazing lands and the rights to the use of grasses grown on these communal areas, in favor of zero grazing practices. Farmers, administrative bodies, and experts who practice the cut-and-carry feeding system successfully should be encouraged and rewarded.

Figure 10.4 Land cover of grazing land was dominated by unpalatable forage, and animals are freely grazed on (a) on open grazing lands and (b) on farmlands after crop harvest. Source: Gebregziabher and Gebrehiwot (2011). Photo by Gebrehiwot Hailemariam.

10.4.3 Improved surveillance, diagnosis and response strategies

An improved ability to forecast the risks and determine the effects of climate change and the early detection and control of disease outbreaks are fundamental to enable prompt responses to climate change and build resilience. Improved detection of climate-related risks and the provision of climate risk-management services, which comprise early-warning services by responsible sectors at federal and regional levels, can enable professionals, donors, and the government to react appropriately and rapidly. With such improvements, farmers will be able to get information in advance that can help them better prepare. The responsible national and regional sectors should be required to have better climate-prediction abilities, more reliable and accessible information, and greater capacity to interpret information and understand the implications of a given threat. At the local level, improved early detection will require awareness creation and training, as well as improved understanding between farmers and extension workers. At the national level, greater investment may be required to improve seasonal climate forecasts and meteorological data collection and dissemination so that information is available regularly and reliably as well as to provide appropriate contingency planning and training. Selected adaptation measures should contribute to improvements in sustainable grazing lands and their management and to the availability and quality of feed, all while increasing carbon sequestration and reducing deforestation.

10.5 Conclusions and Recommendations

The livestock production sector is clearly a very important and dynamic part of the Ethiopian agricultural economy, and this sector must change rapidly in response to population growth, urbanization, and the growing demand for meat and milk. The increasing demand for livestock products in the country presents opportunities for this sector, but these changes also present many challenges for the improvement of productivity. Some of the challenges include finding a balance between the potential negative contribution of livestock to climate change and the environment against the positive benefit in terms of food security, meeting protein demands, and improving rural livelihoods.

Climate change affects Ethiopia's livestock production sector through changing the weather patterns and causing extreme variability in rainfall. This in turn causes inadequate feed supply, water shortages, and increased incidences of diseases and pests. The direct and indirect effects of climate change on animal production necessitate urgent solutions. It is therefore essential to focus on the destocking of livestock and replacing them with better breeds, implementing a cut-and-carry feeding system, and reducing free grazing. Free grazing should be restricted on farmlands, irrigable lands, uplands, and sloped areas vis-à-vis feed availability; farmers should be encouraged through incentives to practice controlled grazing and develop grazing land-use policies suited to local/agroecology and socioeconomic conditions; indigenous knowledge on grazing land utilization in order to control the free grazing should be strengthened; and selection of better breeds that will have the ability to resist thermal stress, diseases, and drought while maintaining traits considered good for production should be encouraged. It is essential that livestock farmers should apply cost-effective adaptation and mitigation options as well as engage closely with policy makers and other stakeholders to ensure that the adaptation and mitigation measures put into practice also emphasize the multiple roles of the livestock sector in maintaining landscape and biodiversity and improving food security and rural livelihoods.

Policy makers should give serious attention to the need to develop policies linked to reducing the use of free-grazing systems, combined with reducing livestock density on sensitive ecosystem zones in order to demonstrate more environmentally friendly and sustainable livestock production. Farmers should be provided incentives or offset payments for adopting controlled livestock grazing systems that reduce environmental degradation while allowing them to maintain their livelihoods.

Research is needed in the fields of breeding, understanding the mechanisms by which climate change affects livestock, housing and health of livestock, and feed supply and systems. There are also some key issues that still need to be answered through research, including policy issues on grazing land use; controlling free grazing; land and tree tenure and usage rights; and identifying forage species that are nutritious, reduce livestock nitrogen and carbon excretion, resist grazing and drought, and effectively sequester carbon. Other critical steps include encouraging and expanding effective agroforestry practices (e.g., Abraha Atsibaha watershed management in the Tigray region) on grazing and croplands to rehabilitate the environment and improve both livestock productivity and carbon sequestration. In addition, farmers' indigenous adaptation mechanisms should be supported by scientific research. Also still necessary are the documentation of effective indigenous knowledge and practices on grazing land management and the utilization, dissemination, and sharing of such innovative approaches, as well as their integration with research.

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11. Climate-Smart Pastoral and Agro-Pastoral Development in Ethiopia

Tessema Zewdu*

Summary

With rising concerns about climate change and the rapidly increasing human population, the sustainable utilization of arid and semi-arid rangelands in Ethiopia and other countries in Sub-Saharan Africa becomes greatly important. Moreover, deforestation, overgrazing, and the conversion of rangelands to other land use types puts east African rangelands under threat. Recurrent droughts have also been major issues throughout history in the pastoral areas in eastern Africa, and strategies to cope with and adapt to these droughts are embedded in the traditional social structures and resource management systems of the pastoral communities. It is crucial to develop participatory rangeland management tools through relevant policies, legislation, and other decision-making processes that can enhance the future productivity, sustainability, and resilience of rangelands. Through strengthening inclusiveness and leadership capacity of local communities, participatory rangeland management facilitates the preparation of efficient and locally fit rangeland plans, policies, and strategies. It increases the participation of pastoral communities and their inclusiveness in decision making during the use of communally owned grazing lands by considering the complex nature of the pastoral systems. Similarly, drought cycle management is an important tool to mainstream disaster risk reductions in the livelihoods of pastoral communities since it reduces the prominence of relief activities and emphasizes the need for disaster mitigation and preparedness activities under the ever-changing climate. In addition, understanding the concept of rangeland carrying capacity is also very useful in pastoral systems because it tell us the maximum number of herbivores that the rangelands can support within a given time without degradation. Thus, to achieve climate -smart pastoral and agro-pastoral development in Ethiopia under the ever-changing climate, this chapter briefly discusses the concepts of participatory rangeland management, drought cycle management, and rangeland carrying capacity within the pastoral context in Ethiopia.

Keywords: carrying capacity, communal grazing land, drought, rangeland, pastoralism

11.1 Introduction

Rangelands are defined as indigenous vegetation or uncultivated land (Pratt and Gwynne 1977). Globally, there are more than 5 billion ha of rangelands that make up between 40% and 70% of the landmass, depending on the continent, and accommodate 120 million pastoralists as their custodians (Derner et al. 2006, Tennigkeit and Wilkes 2008). Over 50% of rangelands are in the arid and semi-arid lands, while they provide about 70% of the global forage for both domestic and wild ungulates (Derner et al. 2006) in the form of grazing and browsing (Holechek et al. 2005). In Africa, rangelands are the major sources of feed for ruminants and constitute about 65% of the total land area (Friedel et al. 2000), which supports 59% of all ruminant livestock in Africa. The East African rangelands account for about 86% of the total area, hold 57% of the total biomass of domestic ruminants in the region (Sandford 1995, Rutherford et al. 2006), and accommodate small ruminants, 73% of the cattle, and 45% of the camels (Kassahun et al. 2008a). Similarly, in Ethiopia, the dryland areas around the periphery of the country, which cover about 62% of the total land area, are used as rangelands (Tessema and Oustalet 2007, Kassahun et al. 2008a) and support about 9.8 million people (Desta and Coppock 2004, PADS 2004) (Table 11.1 and Figure 11.1).

Rangelands in East Africa, including those in Ethiopia, are known for their traditional pastoral livestock production systems (Prins 1989, Abule et al. 2005), which are characterized by extensive livestock keeping that has been developed and refined over many centuries to enable pastoral households to survive and thrive in semi-arid and arid rangelands (Coppock 1994, Derner et al. 2006,

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* School of Animal and Range Sciences, College of Agriculture and Environmental Sciences, Haramaya University, Dire Dawa, Ethiopia
Correspondence email: tessemaz@yahoo.com

Derner and Shuman 2007). In semi-arid Africa, herds of different livestock species on extensive rangelands are a common and effective means of satisfying the needs of the people who mainly depend on livestock production for their livelihoods (Richardson et al. 2010). Communal rangelands not only provide the major feed resources for free-ranging animals (Prins 1989, Tessema et al. 2011c) but also provide important ecosystem services, such as biological diversity, wildlife habitat, soil protection, and sequestration of greenhouse gas (GHG) emissions (Derner and Schuman 2007, Brown and Thorpe 2008). Livestock production not only constitutes the main livelihood of the pastoralists (Harris 2010, Ho and Azadi 2010, Tessema et al. 2011ab), but also represents the main component of the gross domestic product (GDP) of the economy in East Africa (Kassahun et al. 2008ab). The direct financial value of pastoralism in Ethiopia in 2008 was estimated to be 1.22 billion USD, whereas the indirect economic value of pastoralism, which included livestock used as a source of draught power and manure, as well as tourism, gums, and resins, was estimated to exceed 458 million USD—together amounting to at least 1.68 billion USD of the total annual economic value (SOS Sahel Ethiopia 2008).

While the economic contributions of pastoral production systems remain significant in most African countries, a recent trend indicates a gradual decline in their economic importance that is mainly due to rangeland degradation (Prins 1992, Coppock et al. 2011). This degradation poses an increasing threat to rangeland-based lifestyles, associated industries, and the rangeland environment (Terefe et al. 2010ab, Gemedo et al. 2006, Harris 2010, Ho and Azadi 2010). Land degradation is driven by population growth, which can lead to deforestation, overgrazing, and increased land use, while contributing to climate change (Dodd 1994, Kassahun et al. 2008b, Harris 2010, Fratkin 1997, Snyman 1998, Vetter 2005). Such land degradation is characterized by a reduction of total vegetation cover, an increase in bare land coverage, and deterioration in soil quality, as well as the replacement of palatable grass species with unpalatable ones (Zimmermann et al. 2010, Tefera et al. 2010, Tessema et al. 2011a). The loss of herbaceous biomass and plant biodiversity are serious challenges for rangeland ecosystems (Kassahun et al. 2008a) and cause negative impacts on livestock production and on the livelihoods of pastoral communities (Hardin 1968, IFAD 1995, Briske et al. 2003).

With increasing concerns over the rapidly increasing human population, as well as climate change, the sustainable utilization of arid and semi-arid rangeland areas becomes more and more important (Zimmermann et al. 2010). The management of rangelands plays an important role in mitigating rising atmospheric carbon dioxide concentrations, as the soils and vegetation serve as large carbon sinks through the process of carbon sequestration (Derner and Shuman 2007). While globally, more than 5 billion ha of rangelands store up to 30% of the world's soil carbon (Tennigkeit and Wilkes 2008), the available estimates suggest that improved rangeland management has the biophysical potential for sequestering 1,300 –2,000 Mt CO_2 worldwide by the year 2030 (Tennigkeit and Wilkes 2008). This indicates that rangelands play an important role in reducing GHG emissions released into the atmosphere. It has been found that pastoralists are rational land managers whose experience with variable climates has equipped them with the skills needed for adaptation. Pastoralists follow several identifiable adaptation paths, including the diversification and modification of their herds and herding strategies, adoption of livelihood activities that did not previously play a permanent role, and making the deliberate decision to train the next generation for non-pastoral livelihoods.

In response to anthropogenic and natural challenges, approaches to climate-smart pastoral and agro-pastoral development can use both the best- and locally-fit option for improving food security and pastoral livelihoods, while contributing to climate-change adaptation and mitigation (World Bank 2010, Scherr et al. 2012). Therefore, understanding the responses of arid and semi-arid rangelands to climate change is crucial for improving the management of rangelands through both biological conservation and sustainable use, while meeting the climate-smart development objectives in the pastoral and agro-pastoral systems of Ethiopia (Grainger-Jones 2012). The focus of this chapter is to highlight knowledge regarding participatory rangeland and drought cycle management as well as rangeland carrying capacity and the role of each in achieving climate-smart pastoral and agro-pastoral development objectives in Ethiopia. This is because participatory rangeland management supports the leadership of pastoral communities and their inclusion in land-use planning and decision making that considers the complexity of pastoral systems.

11.2 Participatory Rangeland Management as a Tool for Climate-Smart Pastoral Development

Historically, rangelands in the pastoral systems of Ethiopia have been managed according to a customary governance system, which has worked well until recent times. The rangelands include diverse ecological zones; within these

Figure 11.1 Location of rangelands in Ethiopia (in green).

Table 11.1 Area coverage of major rangelands in various parts of Ethiopia.

Region	Area in km^2	References
Somali region	301,484	EASP 2008
Oromia region	150,070	Desta and Coppock 1994
Afar region	97,970	CSA 2010
Southern Nations, Nationalities and Peoples region	30,307	Terefe et al. 2010ab
Benishangul Gumez region	8,410	—
Dire Dawa administration	1,200	—
Gambella regions	17,300	—

are the extensive livestock production systems that form the mainstay of pastoralists, who depend on and provide access to these “key grazing resources” for their livestock, which they need to survive during drought periods.

Today, competition over resources and land in pastoral areas of Ethiopia has grown, mainly because of population increases, as well as an influx of settlers and commercial enterprises into pastoral areas. These parties are keen to acquire land in pastoral areas because agricultural production there is perceived to be viable. Moreover, pastoral areas are challenged by the conversion of pocket rangeland productivity hotspots into higher agricultural productivity areas; these areas could otherwise provide essential grazing in times of drought, and they play a central role in the health of pastoral production systems. As evidenced in most rangeland areas of Ethiopia, the availability of water in grazing areas during the “wet seasons,” for example, has resulted in spontaneous settlement and year-round grazing by pastoralists (Terefe et al. 2010ab, Angassa and Oba 2010). Unless grazing is better managed in the rangelands and grasslands and these areas are given the opportunity to recover, highly palatable species (e.g., *Panicum coloratum, Chloris gayana, Cenchrus ciliaris, Cynodon dactylon*) will be selectively overgrazed, and the species mix will potentially be irrevocably changed under climate variability (Abule et al. 2005, Tessema et al. 2011a).

There is a growing concern in the Horn of Africa that land degradation due to anthropogenic factors and climate change is undermining the livelihoods of people in rangelands. While the increasing incidence of droughts does seem evident, it is also clear that a lack of coherent decision-making in the rangelands has undermined rangeland productivity more than what cyclic droughts could have ever done (Grainger-Jones 2012). Unless these key grazing resources can be demarcated and protected for future generations, coupled with pastoralists' indigenous knowledge, extensive livestock keeping will become increasingly challenging and may result in no or limited availability of alternative livelihood options. This may consequently increase the number of households who will depend on food aid. By recognizing the challenges in Ethiopia, pastoral leaders, local government, and other stakeholders should come up with a more comprehensive approach which may include appropriate land-use planning, policy, and strategies that consider the interests, positions, and needs of all rangeland users in pastoral areas.

To address these challenges, there is a need for integrating participatory rangeland management (PRM) with the traditional system of pastoralists, which depends on key resources such as rangeland "hotspots," particularly dry-season grazing areas and watering points at certain times of the year (Figure 11.2). Participatory rangeland management, coupled with relevant policies, future legislation, and other guiding or decision-making processes, is a key tool for providing alternative and sustainable options in pastoral systems. The process of PRM is a series of sequential steps in which elements are put in place to produce a participatory rangeland management agreement. PRM supports the community leadership and their inclusion in land-use planning and decision making that considers the complexity of pastoral systems. It also considers the interests, positions, and needs of all rangeland users and offers opportunities for negotiations to be carried out among different stakeholders to allow them to come to an agreement over the future of pastoral land use. It also provides a suitable and legitimizing process of communal land and resource tenure that fits with both the priorities of pastoralists and government bodies. The ultimate objective is to have a legally binding agreement, endorsed by relevant stakeholders, which can be used effectively for monitoring purposes.

The PRM process can be divided into three distinct stages (Flintan and Cullis 2010) (Figure 11.3), which are summarized here:

1. Investigating PRM: The first stage in the PRM process is to gather information about the different resources found in the rangelands, their uses (including at different times of the year), and the stakeholders and users (including their institutions and groups that have a role in rangeland resource management). This is achieved by using different tools, including resource mapping and stakeholder analysis.

2. Negotiating PRM: The second stage is focused on negotiation. The initial task is to identify the most appropriate community-led group or institution (i.e., the rangeland management institution) to manage the process. In most pastoral areas of Ethiopia, customary institutions still play a central role in the management of and access to rangeland resources that allows their utilization for the benefit of all stakeholders. Although adjustments to new challenges and developments may need to be made, PRM can be based upon these long-standing indigenous knowledge systems and institutions. The second task is to fully negotiate with the rangeland management unit or area for which an institution will be responsible. This is done first via a participatory rangeland resource assessment, and then by facilitating a negotiation process between the different stakeholders to clarify the boundaries of the rangeland management unit. The outcome of the negotiation should be a consensus between

Figure 11.2 As part of participatory rangeland management, Borana pastoral community members work together to clear the bush that has encroached on the rangeland. Photo by Tessema Zewdu.

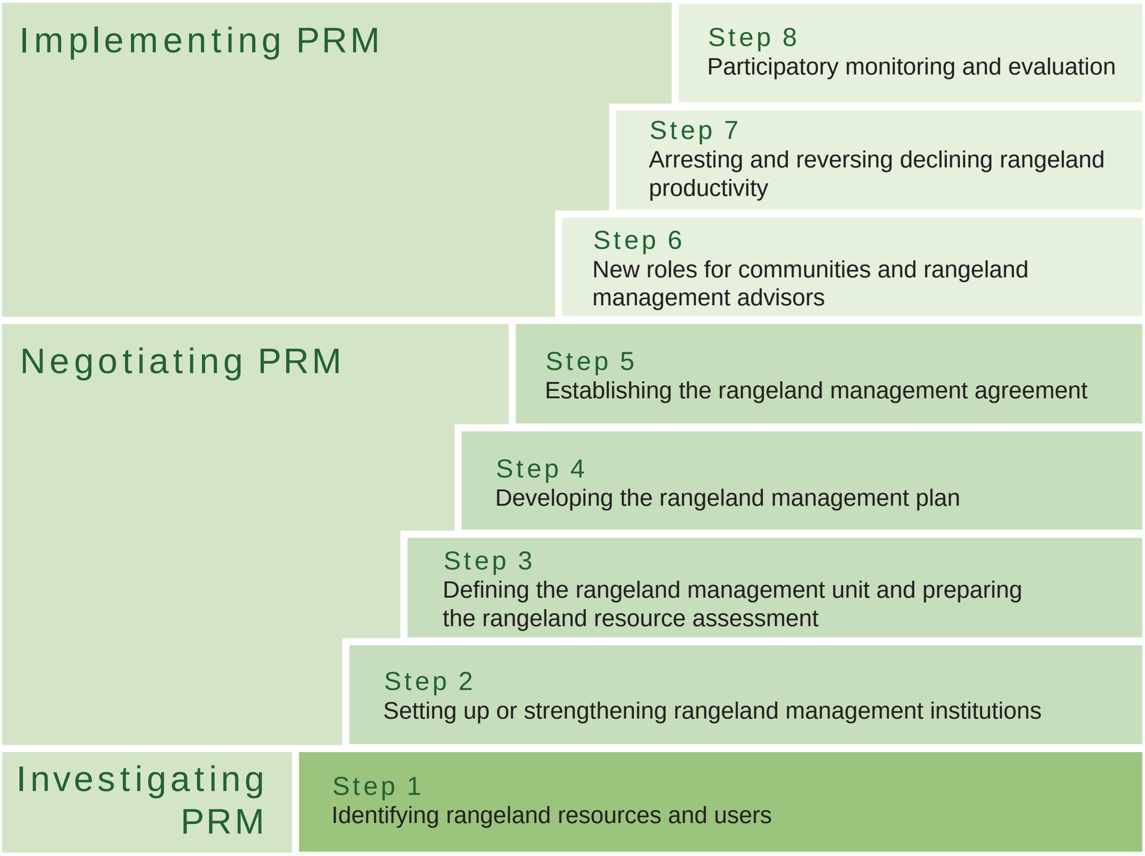

Figure 11.3 Stages of PRM process (adapted from Flintan and Cullis 2010).

all parties as to how to access resources and how and by whom the resources should be managed. In the next step, the rangeland management plan is drawn, by specifying the roles and responsibilities of the rangeland management institution; its rangeland management unit (which includes information on resources and their condition); and an outline of the rangeland management processes that will be followed, including monitoring, evaluation, and adaptive management (see details in Tables 11.2 and 11.3). The rangeland management plan forms the basis of the rangeland management agreement and is the final step in the negotiation process. This is then drawn up, approved, and signed by the rangeland management institution and the appropriate local government body. The agreed rangeland management plan, providing lawful authority for the rangeland management institution or group to manage the resources in the rangeland management unit, should be recognized by the pastoral communities, tribal leaders, local institutions, and government bodies.

3. Implementing PRM: The final stage of the PRM process is the implementation of the rangeland management plan and the adherence to the agreed rangeland management agreement. Supported by the appropriate government office through the provision of necessary technical advice and legal backing, adherence is the responsibility of all pastoral community members and local institutions. Regular monitoring and evaluation of the PRM is vital to ensure the implementation of the agreed-upon management plan, with appropriate changes being made based on a system of adaptive management. The rangeland management institution and the appropriate government office should work together to ensure the implementation of the plan. This new partnership will require people to take on new roles and develop new ways of working. With the establishment of PRM, the relevant and agreed-upon customary institution(s) and/or defined community rangeland management groups are legally enabled to oversee the sustainable management of the natural resources found in a defined rangeland area. Although customary institutions have been governing rangeland resources for centuries, the difference with the PRM process is that the agreed-upon institutions/groups are provided rangeland governing roles supported by legal authority. This is enabled by a negotiated and legally binding rangeland management agreement developed by the pastoral communities and the local authority.

Table 11.2 Procedures of participatory rangeland management (PRM) for rangeland rehabilitation and improvement in the Borana areas of southern Ethiopia as a case study.

Types of rangeland improvement	Types of detailed PRM procedures to be implemented
Rehabilitation of degraded rangeland through reseeding	• Identify rangeland resources users interested in rangeland rehabilitation to avoid conflicts of interest.
	• Develop partnerships and roles of stakeholders during rangeland rehabilitation.
	• Define the rangeland management unit (size of the degraded rangeland units) for rehabilitation through reseeding with the communities.
	• Negotiate with relevant stakeholders and institutions for rangeland rehabilitation planning.
	• Develop a defined rehabilitation plan with stakeholders.
	• Formulate rehabilitation agreements with various stakeholders according to the plan.
	• Begin implementation of rehabilitation (reseeding) activities with various stakeholders.
	• Define and develop rangeland resource use strategies and agreements after rehabilitation.
Control of bush encroachment	• Identify stakeholders interested in the control of bush encroachment at the beginning to avoid conflicts of interest.
	• Set up community-level bush encroachment control and management groups.
	• Decide on the size of the selected bush encroached rangeland units for control.
	• Negotiate with relevant stakeholders and institutions for planning (customary institutions, livestock herders and others).
	• Formulate RM and rehabilitation agreements with various stakeholders according to the agreed plan.
	• With the involvement of stakeholders, develop bush encroachment control through bush thinning/debarking and ring-barking at different heights.
Communal grazing improvement through grazing enclosures and resource sharing	• Identify stakeholders interested in grazing enclosures at the beginning to avoid conflicts of interests.
	• Set up community-level grazing enclosures and develop management groups.
	• Define the size of rangeland for grazing enclosures at community and private levels.
	• Start negotiations with relevant stakeholders and institutions for planning.
	• Formulate grazing enclosure agreements with various stakeholders.
	• With stakeholders, develop grazing enclosures through fencing with locally available resources.
	• Develop and facilitate rangeland resources sharing among stakeholders with the agreed upon plan and through community customary systems.

11.3 Drought Cycle Management as a Tool for Climate-Smart Pastoral Development

Pastoral communities in Ethiopia have been adapting their livelihoods to environmental change for centuries (ISDR 2009). Recurrent droughts have also been major issues throughout history in the pastoral areas; thus, strategies to cope with and adapt to these droughts are embedded in traditional social structures and resource management systems of these communities. The magnitude and rate of current climate change, however, combined with additional environmental and social issues, are amplifying environmental degradation and food insecurity, forcing pastoral communities to rapidly find new and diversified livelihood strategies.

Droughts within the arid and semi-arid areas have typically been viewed as a disaster that requires an emergency response. Such responses have focused on the delivery of food, aid, and life-saving humanitarian support, including drilling or rehabilitating boreholes, emergency vaccination campaigns, and so on. Following a drought, agencies tend to move on to rehabilitation programs, such as restocking, and then return to "normal" development activities in various sectors, such as health and education. Given the frequency of drought in the arid and semi-arid pastoral systems of Africa, however, development work is increasingly disrupted and often undermined by the shift to an emergency response. During the late 1980s and the 1990s, the view that drought is a normal occurrence in eastern Africa became increasingly common and accepted (IIRR 2004, ISDR 2009.).

From this thinking came the drought cycle management (DCM) model, which conceptualizes drought as a cycle that is divided in four phases: normal, alert, emergency,

Table 11.3 Detailed rangeland rehabilitation and improvement activities to be done through participatory rangeland management (PRM) as a case study in Borana, southern Ethiopia.

Type of rangeland improvement	Types of activities
Degraded rangeland rehabilitation	• Dialogue (discussion) with the community for area demarcation and sign agreement.
	• Identify the contribution of the community during the rehabilitation activities.
	• Demarcate the areas with GPS coordinates.
	• Close area through fencing by local materials.
	• Inventory vegetation and resources within the excluded area.
	• Establish soil bunds or soil & water conservation structures for rehabilitation.
	• Apply cattle manure on areas b/n soil bunds for enriching SOM (soil organic matter) and structure.
	• Reseed with local and adaptable grass species
Communal grazing enclosure establishment and resource sharing	• Dialogue (discussion) with the community for area demarcation and sign agreement.
	• Demarcate the areas with GPS coordinates.
	• Close area through fencing by local materials.
	• Inventory vegetation and resources within the enclosure areas.
	• Develop bylaws for resources sharing/grazing during dry and rainy seasons.
Bush thinning	• Dialogue (discussion) with the community for area demarcation and sign agreement.
	• Identify the contribution of the community during the bush thinning activities.
	• Demarcate the areas with GPS coordinates.
	• Fence off the selected area from the thinned shrubs.
	• Identify the important and useful species through vegetation and resources inventory within the enclosure areas.
	• Bush thinning for the encroacher species like *Acacia drepanlobium* (Fulensa), *A. busei*, and *A. senegal* within the fenced areas.
	• Develop bylaws for resources sharing/grazing during dry and rainy seasons at the end of the bush thinning and rehabilitation.
	• Remove the cut materials within the demarcated areas.

and recovery (Figure 11.4) (IIRR 2004). There are clear advantages to viewing drought as a cyclic process, rather than an isolated event preceded and followed by normal development activity. Some of the attributes of the model are as follows (IIRR 2004, ISDR 2009):

- The DCM model assists practitioners in improving the timelines, appropriateness, and ultimately, the effectiveness of work by inviting them to consider whether activities are appropriate given the current stage of the drought cycle. It provides a common framework against, which humanitarian development and advocacy work can be aligned to reinforce each other.
- The DCM model is an excellent tool for mainstreaming disaster risk reduction (DRR) in the pastoral livelihood context. The DCM model reduces the prominence of traditional relief activities and emphasizes the need for disaster mitigation and preparedness activities. The multi-sectoral nature of the DCM model is very compatible with a livelihood approach to address pastoral development. By considering the multifaceted ways in which drought affects pastoralists' lives, it is easier to consider cross-sectoral linkages.
- The DCM model serves as a guide for development agencies supporting pastoral communities in planning and responding to droughts. By putting the drought cycles as the central reference point, it ensures that appropriate interventions are implemented before, during, and after droughts. This ultimately reduces the risks and consequences of drought.
- Users of the model recognize that conceptualizing drought (and the associated responses) as four distinct phases is a simplification. But, the DCM model remains a well-accepted concept that fits well with

Case Study 11.1 Improving Climate-Smart Pastoral Systems in Pastoral Areas of Ethiopia

Background

There is a growing concern that global climate change and the increasing incidence of drought are undermining pastoral livelihoods in rangeland areas in the Horn of Africa. Unless rangelands are better managed and given the opportunity to recover, highly palatable species will be selectively grazed out and extirpated from the system, leading to the loss of biodiversity, rangeland degradation, and food insecurity in pastoral areas. Hence, in response to the challenges that pastoral systems are facing, the concept of participatory rangeland management (PRM) has been introduced in eastern Africa since 2008 by Save the Children and FAO, with the local governments, for better management of key rangeland resources and improve livelihoods.

Approach

The process of PRM takes into account the interests and needs of all rangeland users in pastoral areas and offers opportunities among different stakeholders to reach an agreement for the proper use of rangelands. PRM has a legally binding rangeland management agreement between a local community and the local government office. It provides a suitable and legitimate right for the use of communally owned rangeland resources that fits both the priorities of pastoralists, as well as government bodies. PRM is divided into three stages: (1) Investigation for identifying rangeland resources and users; (2) Negotiation for strengthening rangeland management institutions, defining the rangeland management unit and preparing rangeland management assessment, developing rangeland management plan, and establishing rangeland management agreement; and (3) Implementation for arresting and reversing the declining trends of rangeland productivity and monitoring and evaluation of the activities among the users.

Impact

With the establishment of PRM, the relevant and agreed-upon rangeland management group has the legal authority to properly manage their rangelands to enhance livestock production and productivity, as well as conservation of rangeland resources. For instance, in 2008, the direct financial value of pastoral systems in Ethiopia was estimated to be 1.22 billion USD per annum. In addition, through proper management of rangelands in pastoral systems, the indirect economic values such as providing sources of draught power for highland farmers, tourism, and gums and resins, were estimated to exceed 458 million USD. This gives a total estimated economic value for pastoral systems in Ethiopia of at least 1.7 billion USD per annum (SOS Sahel Ethiopia 2008), in addition to biodiversity conservation and other ecosystem services.

Policy Implications/Relevance

With the current policies in pastoral areas in Ethiopia, pastoral communities, local governments and other stakeholders have recognized the importance of a more comprehensive approach to enhance rangeland productivity that takes into account the interests and needs of all stakeholders. This PRM is in line with the government climate-smart green economy strategy and resettlement program. Moreover, it is in agreement with the customary rangeland management practices of pastoralists for equitable use of rangeland resources among pastoral communities, which reverses rangeland degradation and enhances livestock production and productivity against climate variability, in order to achieve food security and maintain pastoral livelihoods. Therefore, several regional governments in Ethiopia are currently actively developing land use policies, and it is anticipated that PRM will be scaled-up in the future during the resettlement program of pastoralists.

For more information see: Flintan, F, and A Cullis, compilers. 2010. *Introductory Guidelines to Participatory Rangeland Management in Pastoral Areas*. SAVE the Children USA, Ethiopia Country Office, FAO Emergency and Rehabilitation Coordination Addis Ababa Office, and European Commission Directorate General for Humanitarian AID- ECHO Addis Ababa Office. 35 p.

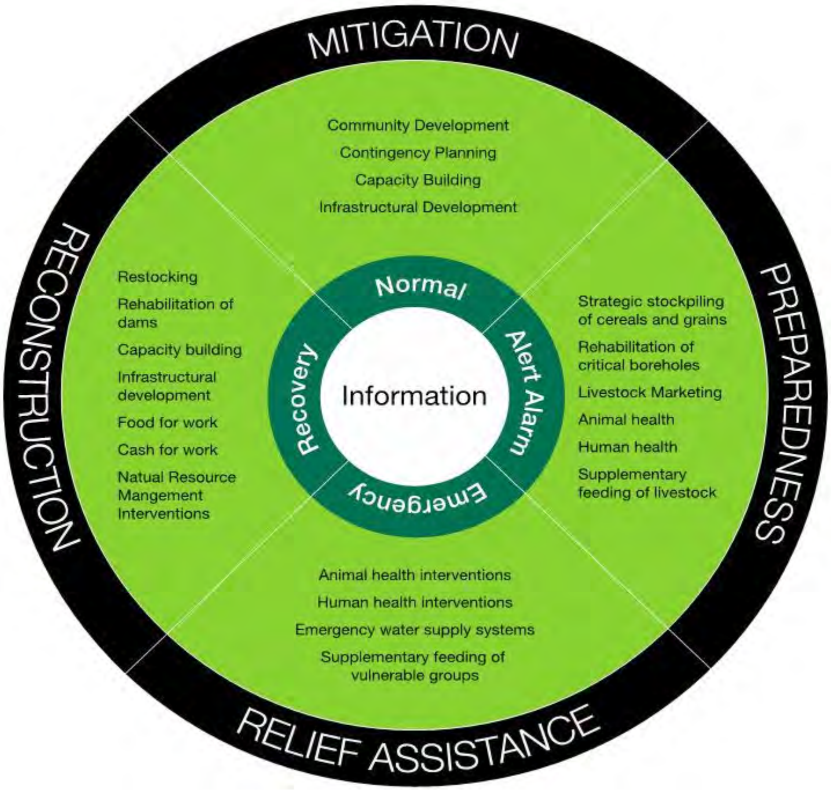

Figure 11.4 Phases of drought cycle management in pastoral areas (Oxfam, n.d.).

programmers' and pastoralists' own understanding of the drought cycle. The DCM model follows a simple logic that is easily understood and accepted by both pastoralists and staff in drought-prone areas. While underplayed in DCM, there are, however, some gaps arising from the model which are stressed by related approaches such as DRR. For example, concerns frequently raised by program managers are their ability to properly assess risk and vulnerability. For many working in the field, such concepts seem rather academic. In practice, this means understanding and monitoring the hazards, vulnerabilities, and coping mechanisms of the target population, disaggregated by wealth or livelihood grouping.

11.4 Carrying Capacity and Grazing Enclosures for Coping with Climate Variability in Pastoral Areas

In rangeland ecology, carrying capacity (CC) of rangelands is defined as the maximal number of herbivores that the vegetation can support within a given time without degradation (Dodd 1994, IFAD 1995, McCabe 2004). The concept has been applied mainly to the management of the arid and semi-arid rangeland regions of the world and especially to pastoral systems in Africa, where livestock are primarily dependent on grazing resources for feed supply. The CC concept in rangelands, more than in other disciplines, has provided a planning and management tool which has formed the basis of many proposed development interventions designed to ensure continued and sustainable exploitation of these rangeland ecosystems (Stoddard et al. 1975). In the past, when the equilibrium ecosystem paradigm was the rule, rangeland management and pastoral development planning were oriented towards adjusting herd size to carrying capacity throughout the semiarid and arid pastoral regions of the world (McCabe 2004). For example, removal of pastoralists from their rangelands or reducing their herd size was practiced as a rangeland resource management strategy during the colonial period in Africa (Lamprey 1983).

Since the emergence of the non-equilibrium ecosystem paradigm (Ellis and Swift 1988), however, researchers have pointed out the limited relevance of carrying capacity to non-equilibrium range ecosystems (de Leeuw and Toothill 1993). There are two current paradigms in the management of dryland rangelands in Africa according to Vetter (2005). These are the equilibrium and the non-equilibrium rangeland models or paradigms. The equilibrium

Figure 11.5 Establishment of grazing enclosures by Borana pastoralists of southern Ethiopia to cope with climate variability and drought. Photo by Tessema Zewdu.

model stresses the importance of biotic feedbacks such as density-dependent regulation of livestock populations and the feedback of livestock density on vegetation composition, cover, and productivity. Range management under this model centers on carrying capacity, stocking rates, and range condition assessment. In contrast, non-equilibrium rangeland systems are thought to be driven primarily by stochastic abiotic factors, notably variable rainfall, which results in highly variable and unpredictable primary production. Livestock populations are thought to have negligible feedback on the vegetation as their numbers rarely reach equilibrium with their fluctuating resource base. Accordingly, researchers have indicated the non-feasibility of applying carrying capacity to range management, which is a concept of equilibrium rangeland management (Ho and Azadi 2001).

In reality, to cope with climate change, the pastoral communities in eastern Africa practice improved range management through establishing fenced rangelands or grazing enclosures (Figure 11.5). Enclosures are open for grazing during the peak dry period and closed just before it starts to rain. This is considered as a feed security strategy for the core breeding stock, mainly calves, and may ensure the continuity and sustainability of pastoralism as a livelihood option. In addition, new range management practices such as hay making and large enclosures have been practiced with the aim of stocking fodder for use during the dry season (Angassa and Oba 2008, Angassa et al. 2010). For example, the rangeland enclosures in Borana of southern Ethiopia contain highly nutritious and palatable grass species, as well as nitrogen-fixing shrubs and trees which produce pods (fruits) as feed and provide good shade for the livestock. In southern Ethiopia, Borana pastoralists traditionally classify their rangelands into *Kalo, Warra* and *Foora* land use units (Coppock 1994, Bikila et al. 2014, 2016). *Kalos* are grazing enclosures made by fencing off communal grazing areas using thorny bushes or shrubs as dry season grazing reserves, whereas the *Foora* rangeland units are grazing areas kept for herds that include dry cows, oxen, bulls, immature males, and heifers. The *Warra* rangeland units are grazing areas kept for herds that consist of milking cows, emaciated animals, sick animals, and calves that cannot walk long distances in search of feed and water (Coppock 1994, Gemedo et al. 2006, Angassa and Oba 2007). Whenever the *Foora* and *Warra* rangeland units are encroached upon by bushes, pastoralists have traditionally used fire to control bush encroachment to improve the growth and palatability of the herbaceous vegetation for their livestock (Bikila et al. 2014).

11.5 Conclusions

Global warming coupled with increasing numbers of people and livestock, make the sustainable utilization of arid and semi-arid rangelands in Ethiopia ever more important. Climate change and variability are long-term environmental issues and pose serious threats to vulnerable and impoverished pastoralists in Ethiopia. Livestock are a critical asset for pastoralists, and the loss of livestock due to drought has a negative impact on pastoral livelihoods through losses of milk production, revenue from livestock sales, and the asset value of livestock itself due to the effects of drought. Therefore, the timely provision of drought interventions to support livestock is critical because most interventions should be implemented before livestock are weakened.

Pastoralists have several coping and adaptive strategies to protect livestock assets that they typically implement during droughts, which include moving the animals to areas with better forage and water, selling some animals, splitting herds or exchanging animals, and changing herd species composition over time. Interventions aimed at supporting these strategies must be timely; for example, destocking is more successful when done early so that the animals fetch higher prices. Similarly, conflict resolution to enable pastoralists to move to key grazing areas must be done in advance by involving pastoralists and other stakeholders among various ethnic groups before large numbers of animals need pasture. Moreover, supplementary feeding needs to target breeding stock and lactating cows, as well as weak animals, and be accomplished within a sufficient time period to ensure that the animals stay healthy—because late interventions are both more costly and less successful.

For recurrent droughts (which have happened throughout history in the pastoral areas), coping strategies have been embedded in the traditional social structures and rangeland-resource management systems of pastoral communities and constitute an appropriate drought-cycle management model. Therefore, management strategies and practices that contribute to mitigating climate change will also play a major role in climate change adaptation and in reducing vulnerability to natural disasters, which will in turn benefit millions of pastoralists—including the poor—who depend on dryland rangeland resources.

Proper implementation of participatory rangeland and drought cycle management could play a key role in achieving climate-smart pastoral and agro-pastoral development objectives in Ethiopia. Accordingly, consecutive trainings on the roles that participatory rangeland and drought cycle management could play in the improvement and management of rangeland should be organized and given to various stakeholders involved in pastoral production systems in Ethiopia. Equally important is the management of livestock numbers in rangelands, taking into account the carrying capacity of the rangelands as an important concept for achieving climate smart pastoral systems. It is also important to consider other smart pastoral development tools, including new range management practices, such as hay making and grazing enclosures to stock fodder, for use during the dry season, mainly for coping with the impacts of climatic variability and drought.

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12. Access to Fuelwood and Impacts on Workload and Rural Women's Livelihood: Evidence from Northern Ethiopia

Emiru Birhane[a]*, Tewodros Tadesse[b], Mesfin Tilahun[c], and Sarah Tewolde-Berhan[a]

Summary

Most rural households in Ethiopia use fuelwood as a main source of energy; and women are largely responsible for both its collection and use. Existing analyses of fuelwood in the literature are more or less limited to demand, supply, and consumption issues. In this study, we examined women's workloads in rural areas, vis-à-vis the collection and consumption of fuelwood. Based on data collected from a survey of female-headed households, we used probit and Ordinary Least Square (OLS) models to analyze decisions regarding "own collection" (i.e., collection for household use) and consumption of fuelwood, respectively. Content analysis and simple descriptive statistical tools were also used to present and analyze qualitative data. The major results indicated that donkey ownership, household income, and accessibility to tree lots were positively associated with high fuelwood consumption, while travel time to tree lots was inversely related to consumption. From the qualitative data, it was observed that women significantly participate in fuelwood collection and other household activities. Developing and improving women's access to human and physical capital/assets through education, land, and draught power are important factors in whether women decide to collect fuelwood and how much fuelwood they consume.

Keywords: rural women, fuelwood, work load, livelihood, northern Ethiopia

12.1 Introduction

Beginning in the 1980s, there has been a policy shift among donors and NGOs, with a wide range of policy-making institutions targeting women (Cecelski 1987). This shift in focus ranges from better management of women's time and labor to the empowerment and reduction of poverty prevalence among women (Razavi 1997, Murthy et al. 2008). In many developing countries such as Ethiopia, men and women assume different roles in livelihood activities (such as natural resource use and management, farming activities, and domestic work), often with unequal power (Cecelski 2000). These different livelihood activities can be influenced by the surrounding environment. Among others, poor availability and quality of means of production and degrading environmental conditions can be some of the influential factors. Land degradation may affect women much more than men, and the poorer they are, the worse it impacts them (Lambrou and Piana 2006). Women spend a lot of time and labor on collecting fuelwood, which limits their ability to engage in other productive and income-generating activities (Cooke 1998ab). In addition, deforestation makes it more difficult for women to collect wild herbs, fruits, natural medicines, and fuelwood for cooking and heating (Cecelski 1987). The resulting limited choice of natural resources may affect women and female-headed households due to varying cultural variability and poverty levels. The conditions that put women at a disadvantaged position can be ameliorated through various mechanisms. Some of these mechanisms that can help ensure better living conditions for women are improved access to natural resources and assets, access to modern facilities, proportionally shared

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a Mekelle University, Department of Land Resources Management and Environmental Protection, Mekelle, Ethiopia

b Mekelle University, Department of Agricultural and Resource Economics, Mekelle, Ethiopia

c Mekelle University, Department of Economics, Mekelle, Ethiopia

* *Correspondence:* Emiru Birhane (email: emibir@yahoo.com)

livelihood activities, and participation in societal issues (Oglethorpe and Gelman 2008).

Fuelwood is an important natural resource in Ethiopia, and women play a big part in its collection and use. Fuelwood is the major source of energy for cooking and heating in most rural communities and for the majority of urban dwellers in countries like Ethiopia. In Africa, it was estimated that wood comprises 80% to 90% of the biomass used for fuel (IEA 2002), although fuelwood accounts for only 4.92% of the energy consumed globally (Türker and Kaygusuz 2001). This marked difference emphasizes the importance of fuelwood as an energy source for households in many developing countries. Given that cooking represents the single largest energy use in some societies (Cecelski 2000), an opportunity arises to study energy supply in regard to women's labor and time saving and participation in in-house income-generating activities, which are managed by women. Energy is an important element in improving livelihoods and ensuring economic development. It is therefore imperative to have a clear understanding about how decisions (activities) and policy issues influence rural women. To our knowledge, the current literature is limited with regard to the role of gender in fuelwood management, specifically, fuelwood collection and use. A notable study by Parikh (1995) investigated women's need for and role in procuring wood at a macro level and recommended detailed studies at a micro-scale through surveys. Clancy et al. (2007) also examined energy policies' approach to women at a higher level. In addition, Amacher et al. (1996) and Heltberg et al. (2000) examined the relationship between fuelwood energy demand and deforestation, showing the tendency toward energy substitution as a result of deforestation. Furthermore, Türker and Kaygusuz (2001) assessed the different factors that influence household fuelwood consumption.

In this study, we investigated rural women's allocation of labor and time spent in the collection and use of fuelwood. This partly contributes to knowledge that exists regarding gender-specific behavior in the consumption of fuelwood. In addition, we examined the different factors that influence the decision to engage in the collection of fuelwood, as well as the quantity of fuelwood consumed. In order to meet the objectives, data were collected through household surveys among women in rural areas of northern Ethiopia. For data analysis, OLS and probit regression were used.

The chapter is organized into six sections. The first section reviews background literature on policy issues and the involvement of women in wood collection and use. The second section presents a brief description of fuelwood as a source of energy in Ethiopia. Section 12.3 discusses the conceptual framework of the research and lays out the background for modeling. The study area and data are described in the fourth section. The results and discussion of the study are included in section 12.5. Finally, findings and insights are summarized in section 12.6.

12.2 Fuelwood as a Source of Energy in Ethiopia

The 1970s global oil shocks rekindled an alarming concern within international development circles, as well as the Ethiopian government, because of the emerging complicated issues, i.e., the relationship between energy and environmental resources and how informed policy decisions could be made to resolve the crisis (Shanko and Rouse 2005). Ethiopia is endowed with substantial energy resources that include biomass, natural gas, hydropower, and geothermal energy. Of these, about 93% of the energy demand is covered by traditional biomass resources (Wolde-Ghiorgis 2004). Different studies have shown that Ethiopia, particularly the rural area, is heavily dependent on biomass fuel. This, coupled with a rapidly dwindling forest resource and the growing household energy demand, has resulted in a serious household energy crisis (Shanko and Rouse 2005). In response, a number of policies were crafted and implemented to encourage households to switch from using biomass fuels to utilizing kerosene and electricity. While the urban areas have the choice to substitute biomass fuels with other types of fuel, such as electricity, the rural areas keep on using biomass fuels. In the year 2001 alone, an equivalent of 400,000 tonnes of wood was "substituted" by "modern" fuels, preserving about 50,000 ha of forest stock in Addis Ababa (Shanko and Rouse 2005).

In Ethiopia, the household sector is the largest single energy consumer, accounting for more than 90% of total energy consumption. In Tigray, 99% of fuel consumption is met from biomass, although access to fuelwood is declining (Tesfay 2006, Gebreegziabher 2007). In Tigray, for example, households clearly dominate biomass fuel consumption, utilizing 89% of the total, followed by industry (7%) and transport (3%). The remaining 1% is shared among the agricultural, public, and commercial sectors (WBISPP 2003). Traditional fuels (i.e., fuelwood, dung, and crop residues) constitute 99.6% of the total household energy consumption, in which fuelwood (81%), dung (9%), and crop residues (8%) comprise the share, in descending order. Among other fuels types, kerosene has the largest share

(48%), followed in diminishing order by electricity (36%), LPG (10%), and diesel oil (6%). Per capita consumption in Tigray, for instance, was estimated at 2.69 Gcal per year, or 756 kg of fuelwood equivalent (WBISPP 2003).

The Tigray region faces an accelerated rate of deforestation and land degradation. Deforestation and the removal of natural vegetation for cropping, cattle-raising, overgrazing, and the over-exploitation of vegetation for domestic use (i.e., fuelwood, fencing, etc.) are major causes of degradation in the drylands of Tigray. The costs of deforestation and land degradation in the region are expressed in terms of yield reduction and shortage of fuel energy. To meet energy needs, most households in Tigray resort to public natural reserves, such as forests and farmland, to collect biomass fuels, which mostly consist of fuelwood, but also include crop residues and animal dung. The supply of wood and woody biomass products in the Tigray region comes from natural forests, woodlands, plantations, woodlots, farm forests, and other production systems (TFAP 1996). According to TFAP (1996), these areas produced an incremental yield of 737,717 m^3 available as wood products in 1994 while the demand for wood products was 4,402,439 m^3, of which the demand for fuelwood was 4,313,700 m^3. This demand was expected to reach 9,551,400 m^3 in 2017, while the supply was expected to drop from 737,717 m^3 to 563,517 m^3; thus, the gap between demand and supply was expected to widen from 3,664,722 to 8,951,883 m^3. TFAP (1996) estimated that 587,552 metric tonnes of dung and 277,887 metric tonnes of crop residues were burned annually for fuel in rural Tigray as part of household energy consumption. As a result of using dung for fuel, about 10% of the estimated annual grain production of the region is lost (Sutcliffe 1993). Similarly, as a result of using crop residue, the annual grain loss is about 8,336,600 kg. A study by the Woody Biomass Inventory (WBISPP 2003) indicated that in rural areas, there appears to have been an increase in annual consumption rates of fuelwood, from 358 kg per capita in 1984 to 545 kg per capita in 2000 (WBISPP 2003). This represents an annual increase of about 2.6%. The same study had forecast an increase of about 1.9% per annum in per-capita consumption of biofuels in Tigray. There also appears to have been an increase in the use of crop residues as fuel of from zero to 38 kg per capita. The consumption rate of dung also increased from 133 kg to 215 kg per capita (an increase of about 3% per annum) since 1984. There has also been an overall increase in annual household energy consumption, from 1.75 Gcals per capita to 2.90 Gcals, an average increase of about 3.4% (WBISPP 2003).

12.3 Conceptual and Analytical Framework

Fuelwood collection in Ethiopia is largely the responsibility of women and children. Given this fact, we assume that household members decide collectively on labor allocation for fuelwood collection. In rural areas of Ethiopia, the collected fuelwood is used mostly for personal rather than commercial consumption. This is because there is a lack of market access to fuelwood. In addition, there is not an institutionalized system in place that sets a price for fuelwood and regulates businesses. Rather, fuelwood has only a household-specific shadow price, which depends on the opportunity cost of household labor allocation on fuelwood collection. The imperfect nature of the labor market in rural areas of developing countries also suggests that household labor allocation decisions on fuelwood collection and on other activities (both farm and non-farm) are made simultaneously. As a result, the traditional non-separable household models form the basis for the analysis of fuel demand and supply (Heltberg et al. 2000).

When a household decides on allocation of labor, the objective is assumed to be utility maximization. Following Heltberg et al. (2000), the model presented in Eq. [12.1] captures the situation of rural households that allocate their time endowment (T) to farm activities (T_F), non-farm activities (T_{NF}), and fuelwood collection (T_{FW}), as well as consumption of goods that require energy from fuelwood as an input (c_g), consumption of other goods (c_o), and leisure (l),

$$Max\ U = U\left(c_g, c_o, l; Z^h\right) \qquad [12.1]$$

Where U is the utility, c_g represents household consumption goods that require fuelwood energy for production, c_o denotes consumption of other goods, l is overall leisure consumed by the household, and Z^h is the row vector of household features.

It was also assumed that there were goods that were produced by fuelwood. Keeping the application simply to fuelwood collection, the amount of fuelwood collected and the time spent for fuelwood collection is shown in Eq. [12.2]

$$q_{FW} = \left(T_{FW}; Z^a\right) \qquad [12.2]$$

Where q_{FW} is the amount of fuelwood collected, T_{FW} is labor time spent on fuelwood collection, and Z^a denotes a vector of factors related to access to forest, forest stock, and distance to the forest. In this regard, specification of the participation in fuelwood collection and use is presented in Eq. [12.3] as

$$\left.\begin{array}{l} k_{FW} \\ q_{FW} \end{array}\right\} = f\left(T_{FW}, Z^{h}, Z^{a}, s, p_{F}, p_{NF}, p_{FW}, w\right) \qquad [12.3]$$

Where k_{FW} denotes the participation in fuelwood collection; s shows ownership of a stove; w is wage rate; and p_F, p_{NF}, and p_{FW} represent the prices of farm products, non-farm products, and fuelwood, respectively. For data analysis, Eq. [12.4] was postulated as:

$$y_i = f\left(x_i, \theta\right) \qquad [12.4]$$

Accordingly, Eq. [12.5] was derived to quantify the amount of fuelwood consumed:

$$y_i = \theta x_i' + \varepsilon_i \qquad \varepsilon \approx NID\left(0, \sigma^2\right) \qquad [12.5]$$

$$\left(i = 1,2,\ldots, n\right)$$

Where *y* represents the quantity of fuelwood consumed by household *i* and ***x*** is a vector of different factors and some random components (*ε*). Eq. [12.6] depicts a probit model that was used to illustrate participation in fuelwood collection, in an attempt to identify the different factors that may influence the decision to participate.

$$Prob\left(y_i = 1\right) = \Phi\left(x_i'\theta\right) \qquad [12.6]$$

The probability of participating in fuelwood collection *Prob* ($y_i = 1$) was given by the cumulative distribution function, denoted by Φ. According to Greene (2002), an Ordinary Least Square regression and the Maximum Likelihood probit was applied for estimation purposes for Eqs. [12.5] and [12.6], respectively.

12.4 Study Area and Data Description

Data for the study were collected from the Tigray region. Tigray is the northern-most region of Ethiopia, extending from lat 12°15′ to 14°50′ N and long 36°27′ to 39°59′ E, with an area of approximately 50,230 km^2 (Hagos 2005). It belongs to the African drylands (African Sahel), which are often referred to as the Sudano-Sahelian region (Gebreegziabher 2007). The Tigray region has seven administrative zones: Southern, Southeastern, Eastern, Central, Northwestern, Western, and Mekelle, the capital city of the region. Included in these seven zones are 45 districts, of which 33 are rural and 12 are urban (Gebreegziabher 2007). With an annual increment of 2.5%, the population is estimated to be around 1.2 million, with an average family size of five persons per household, 83% of which are rural dwellers. The region had a total of about 0.72 million households, and the dependency ratio was 94.9 (Gebreegziabher 2007). The average population density of the region is 63 persons per square kilometer (CSA 2007), and this figure can reach up to 137 persons per square kilometer in the highlands (Pender et al. 2004). The landholdings range between 0.5 and 0.75 ha per household, except for in the Western Zone, where the average size is more than 2.0 ha.

The climate is characterized as tropical, semi-arid, with a long dry season and erratic rainfall between June and September. Precipitation occurs during a very brief period in which runoff values are high (TFAP 1996). Some parts of the Southern and Eastern zones of the region have a bimodal type of rainfall, with short rains between February and April (Tesfay 2006). The mean annual rainfall in the region varies from 200 mm in the east to over 950 mm in the southwest. The average annual temperature ranges from 15° to 25°C. The major types of land use are as follows: 36.2% bush and shrub land, 28.21% cultivated land, 22.7% grass land, and 10.81% other forms of land use (Tesfay 2006). Intensively cultivated land covers a large portion of the region. The natural high forest resource of the region is overexploited and now covers only about 0.2% of the total land area (Tesfay 2006). Nearly all land is open for cropping and grazing, and hardly any vegetation cover is seen in the arable lands, except in exclosures, around churches, and in some fallow areas from the previous cropping season. The decline in forest cover is mainly attributed to human economic activities and population pressure (Nyssen et al. 2004). Rehabilitation activities, such as area exclosures, afforestation programs, and community mobilization, are underway to reverse this situation.

12.4.1 Household sampling techniques and sample size

The data on women's workloads vis-à-vis access to fuelwood was collected from Alaje, Ganta Afeshum, Naeder Adiet, Laelay Adiabo, the Humera District, and the Mekelle area, from the Southern, Eastern, Central, Southwestern, Western, and Mekelle zones, respectively. Selection of sample households was done randomly, using a two-stage sampling technique, after stratifying them into rural and urban groups. In the first stage, sample villages were selected randomly, whereas in the second stage, sample households were selected from the sample villages in such a way that every household had the same chance of selection into the random sample. Finally, 120 female respondents were selected. Many of these female respondents were heads of households and have had sufficient knowledge of the household to provide more or less accurate data.

12.4.2 Data collection, analysis method and descriptive outputs

Three study-area categories were created in order to capture differences due to natural resources endowments and climatic conditions, access to infrastructure, and proximity to towns and urban areas. The categories were labelled as A, B, and C, with A representing all the study areas, excluding Humera and Mekelle and villages from Humera and Mekelle sub study areas. Study villages, excluding those from the Humera district and Mekelle area, are labelled as "sub study area B," or simply, "B." Study villages from the Humera District and Mekelle area are labelled "sub study area C," or simply, "C."

Once the key variables and data to be collected were identified, a structured questionnaire was developed for survey administration on the randomly selected female households. To obtain useful feedback and improve some contents of the questionnaire, a pre-test was carried out on 15 female households and useful feedback was incorporated. Enumerators were trained on the contents of the questionnaire and on methods of survey and interview before they were sent out to the selected study areas to administer and fill out the questionnaires. Most of the data needed for analysis was obtained using this survey method of administering questionnaire interviews to the selected sample households. To supplement these interviews, data were also collected by using focus group discussions and key informant interviews, which yielded detailed data on the challenges women face, access to natural resources, and women's burdens at the household level. After data were recorded and cleaned, they were used for analysis.

Much of the qualitative data collected from the households was analyzed by using content analysis. Female households decide whether to collect fuelwood. They make this decision by weighing the utility they are going to obtain from their decisions. A number of factors play a role in this regard; hence, a probit model (see Greene 2002) was used to identify the different factors that influence the decision to engage in the collection of fuelwood. The OLS model (see Greene 2002) was used to identify the different factors that influence the quantity of fuelwood consumed. Some robustness tests, such as multicollinearity and heteroscedasticity, were also conducted and the results indicated that the OLS model is robust.

About 82% of the women in the sample households were illiterate, and that figure was even higher if sample households from Humera and Mekelle were excluded. The proportion of illiterate women for households from Mekelle and Humera was relatively smaller than for both the total average and that of sub-study area B. The average family size of sample households in the study area was 5.17, which is nearly equal to the average family size of 5.15 for rural households in Ethiopia (CSA 2003). The family size of sample households in sub-study area B was slightly larger than in sub-study area C. This can be explained in terms of the difference in place of residence and the associated socioeconomic differences between the sub-study areas.

For these households, on average, every family member of working age was expected to work and support himself- or herself, while approximately one additional family member fell into the dependent age group (i.e., youth and the elderly). There was a high dependency ratio, which had a negative impact on household savings by increasing the demand for consumption expenditures. The dependency ratio (ratio of dependents and working household members) was highest among sample households in sub-study area B.

The mainstay of households in the study area was agriculture. The average landholding size for the sample households in the study area was less than 1 ha (0.93 ha) and was almost the same as the national average. The landholding size in sub-study area B was 0.11 ha less than the national average, whereas the landholding size in sub-study area C was 0.29 ha more than the national average. However, the small land-holding size, coupled with low agricultural productivity, was one of the main problems for most farm households in rural Ethiopia. Data showed that the productivity of land owned by households in the study area was much lower than the national average. Households in the study areas earned income from different sources, but their incomes remained low. According to the World Bank, a per-capita daily income of 1 USD is considered the poverty line; those who fall below the poverty line are considered absolutely poor. By this measure, the average household in the study area lives below the poverty line (Table 12.1). There are differences in access to social and economic services such as health services, education, family planning programs and services, and others that will affect the fertility of women, and consequently, family size.

Table 12.1 Socioeconomic comparisons across the clusters.

Variables	Sub-study area A (all villages)	Sub-study area B(Alaje, Ganta Afeshum, Naeder Adiet, Laelay Adiabo)	Sub-study area C(Humera and Mekelle areas)
Youth dependency ratio (%)	96.4	96.3	98.6
Illiterate family members (%)	46	60	30
Per-capita income (USD)	203.7	138.2	300.2
Share of income from crop production (%)	56.2	58.2	62.3
Share of income from off-farm (%)	27.5	11.8	32.9
Share of income from livestock (%)	5.4	8.9	3.75
Share of income from food-for-work (%)	9.9	19.9	0.9

12.5 Results and Discussion

Productivity measures are exhibited in Table 12.2 to give a general impression of labor and land efficiency in the study areas. Households in the study areas were characterized by low labor productivity in terms of both crops produced per unit of labor and annual income earned per unit of labor. The productivity of household croplands in the study areas was very low and was much lower than the national average. As shown in Table 12.2, the productivity varied among the three categories, and households in the B category exhibited the lowest productivity measures.

The major activities for rural women in the study areas were crop production; domestic activities, which included food preparation, cleaning, and childcare; fuelwood collection; fetching water; traveling to marketplaces for selling agricultural products and purchasing consumer goods; and carrying cereals to flour mills. Table 12.3 shows that the average daily amount of working time of rural women was 9.75 hours, taking all days of the week into account. This number could increase to 13.6 hours if we consider working days only (excluding weekends). This shows the existence of a very high work burden on women in the study areas (these are estimates of the time women themselves spent on different activities). Of the total annual labor allocation by women on household activities, domestic activities (food preparation, cleaning, childcare, etc.) took the highest share, averaging 55%. The second most important factor that imposes a burden on women's workload was fetching water, which accounted for almost 28.5%. The remaining 16.5% of the total annual labor hours was spent on performing tasks such as participating in crop production activities, fuelwood collection, community work on land reclamation through food-for-work and work-for-free programs, and going to market and flour-mill houses. Women spent significantly less time collecting fuelwood than they did fetching water. For men, it was the reverse (see Table 12.3). Moreover, women spent four times more labor time in livelihood activities than did men, although this amount could vary in different seasons.

In the study area, women participated in all crop production activities, such as plowing, seeding, weeding, harvesting, thrashing, cleaning, and sorting. The only crop-production activity that women did not participate in was guarding the farm crops during the growing season. The level of participation in these activities varied among households, which may be the result of varying resource endowments. The main crop-production activities in which female household members participated were weeding, harvesting, thrashing, cleaning, and sorting. In 77.1% of all households, women participated in weeding during crop seasons. The number of households in which women participated in crop

Table 12.2 Agricultural and labor productivity of households.

Productivity measures	A	B	C
Land productivity in kg/ha/yr	470.40	473.73	434.12
Labour productivity in kg/labour/yr	159.04	130.41	221.91
Crop production in kg per household	426.23	335.16	643.54
Per capita crop production in kg	82.44	63.36	130.54
Annual income in Birr per household labour	3348.39	2416.94	4354.50

Table 12.3 Labor allocated by male and female household members on different activities.

	Labour time in hrs/person/year	
Activity	Female	Male
Crop production	195.98	336.78
Domestic activities	1958.90	0.00
Fuelwood collection	114.00	121.35
Fetching water	1015.16	117.84
Flour making	77.40	0.00
Market	107.34	151.54
Community work : FFW	50.93	50.93
: WFF	41.83	41.83
Total	3561.54	820.27
Labor hours per day	9.75	2.25
Labor hours per working day	13.64	3.14

FFW= Food for Work, WFF= Work for Free

harvesting accounted for 70.5% of the total households. These figures showed that the two most common farming activities that women heavily participated in were weeding and harvesting. Women, on average, spent about 95 hours in weeding and 45.5 hours in crop harvesting per growing season. This workload is particularly large when it is compared to the growth period of cereal crops (which averages 3 months). They also largely participated in other activities. Women participated in plowing and seeding activities in 46% and 31% of the households, respectively (Table 12.4). The sample households in which women participated in the thrashing, cleaning, and sorting work of crop production accounted for 52%.

The average labor hours required to cultivate a hectare of land by households in the study area was 965 hours (Table 12.4). Taking the average landholding size of 0.93 ha per household, households spent 896.2 hours working on crop production activities per year. In households where females participated in crop production activities, the labor contribution of all women in the productive age group accounted for 34.3% of the total labor time per household spent on annual crop production activities. In other words, each woman in the productive age group contributed about 22% of the labor time needed to produce crops.

Women also contributed labor time to the marketing of agricultural inputs, farm products, consumer goods, and other commodities. In the study area, a female household member traveled, on average, four times per month to nearby marketplaces, which averages once per week. There may be a need to visit the market frequently, but accessibility and distance can be big obstacles. The time required for visiting the market places speaks for itself (Table 12.5): on average, it took women 3.4 hours just to travel to and from marketplaces for every visit; this does not include the time spent at the market to accomplish all of the required tasks. Thus, the travel alone required a total of 107 hours per woman per year. This labor time made up about two-thirds (64%) of the total household labor input invested in marketing activities. This is another indication that the workload for women in marketing activities is a lot higher than for men.

In rural areas, among the most important inputs for different livelihood activities are fuelwood collection and fetching water. Households need water and fuelwood in order to accomplish their domestic activities. The problem of access to these environment-based resources creates a work burden for rural households in general and for rural women in particular. Continuous deforestation and environmental degradation have resulted in dwindling forest and water resources, such that rural households face water and fuelwood shortages, forcing people to travel

Table 12.4 Household labor allocation on crop production and participation of women.

Crop production activity	Labor time in hr/ha/yr	Labor time in hr/hh/yr	Labor time in hr/woman/yr	Participation of women (%)
Ploughing	68.30	63.52	23.84	45.80
Seeding	19.62	18.24	6.85	30.50
Weeding	274.14	257.95	95.13	77.10
Guarding	398.92	370.99	0.00	0.00
Harvesting	130.41	121.29	45.52	70.50
Thrashing, cleaning, and sorting	72.30	67.24	25.23	51.90
Total	963.69	896.23	195.98	

hh = household

Table 12.5 Household and women's labor allocation for marketing and flourmills.

Activity	Labor hours
Market activities	
Number of travels to market places per month	4.08
Travel time (to and from) in hours per travel	3.40
Labour time for travelling to market in hours per household per year	168.20
Total labour time in hours per woman per year	107.34
Flour making activities	
Number of travels to flour mills per month	2.34
Total labor time in hours per household per year	30.30
Labor time in hours per woman per year	19.35

long distances to obtain them. The average daily household water consumption in the study area was 55.34 L (or 10.70 L per person per day). In order to fetch this quantity of water, households spent 4.72 hours of labor per day, of which 4.4 hours was contributed by female household members, with the remaining 19 minutes per day contributed by male household members. Every day, a woman had to travel for 2.2 hours in order to fetch water and carry it home, and she also spent an additional 2.5 hours waiting her turn at the water point. These long waiting and travel times showed the problem of the lack of access to drinking water that, in turn, has created a work burden for women in the study area (Table 12.6).

Fuelwood is the other environmental resource that households require daily as a source of energy for cooking, heating, lighting, and other domestic uses. In order to obtain this resource, households spend considerable labor time on collecting and transporting fuelwood from nearby (or distant) forest- and bush lands. The labor time required for collecting and transporting fuelwood depends on the distance between the houses and the place where fuelwood was collected, as well as the availability of biomass. Seasonal variation also impacts the labor time that women invest in collecting fuelwood. For instance, during the rainy season, women invested more time in collecting fuelwood than they did in other seasons. This may be because the energy required for cooking and heating is higher during the rainy season. In every season, women still allocated more time to collecting fuelwood than did men. Female household members contributed around 57% of the annual labor time dedicated to fuelwood collection, with male household members contributing the remaining 43% (Table 12.7).

Households usually collected their own fuelwood, although they did occasionally purchase it. The average price of fuelwood was found to be 16.7 Birr ($ 0.75 cents) per donkey load, but the standard deviation for this value was very high. The variation was not a result of differences in price in the different zones (villages), however; rather, it was the result of the fact that over 70% of the women surveyed stated that they collected their own fuelwood, and the prices stated are rough estimates given by the women. Fuelwood tended to be more expensive in *Kiremt* (rainy

Table 12.6 Labor time spent to fetch water by households.

Activity	Labour hours
Number of travels to water point per day	2.77
Travel time from home to water point in hours per travel	0.36
Waiting time in hours per travel	0.90
Travel time from water point to home in hours per travel	0.44
Total labour time for fetching water in hours per day	4.72
Total labour time for fetching water in hours per month	143.5
Total labour time by male for fetching water in hours per month	10.90
Total labour time by female for fetching water in hours per month	133.6
Total labour time for fetching water in hours/woman/year	1015.16

Table 12.7 Women's share in household labor allocation on fuelwood collection by season.

Activity	Kiremt (Summer)	Kewi (Autumn)	Belg (Spring)	Hagay (Winter)
Total number of travels per month	7.47	6.87	6.86	6.62
Number of travels by male per month	2.99	2.99	2.99	2.99
Number of travels by female per month	4.48	3.88	3.87	3.63
Travel time from home to fuelwood collection place in hours per travel	1.03	1.03	1.03	1.03
Time for collecting a load of fuelwood at collection place in hours per travel	1.43	1.43	1.43	1.43
Travel time from fuel wood collection place to home in hours per travel	1.21	1.21	1.21	1.21
Total labour time in hours per season (household)	84.23	77.48	77.35	74.60
Total labour time by female in hours per season	50.50	43.70	43.60	40.80

season)[1] and *Kewi* (autumn), which is the result of higher demand for heating during both seasons. The fuelwood and dung consumption patterns are summarized in Table 12.8.

There was a greater reliance on collected and dried dung for energy during *Kiremt* and *Bega* (*Kewi)*. Apart from the wood being wet during *Kiremt*, women, who usually collect fuelwood, were helping with farm activities during that time. Therefore, they are forced to rely more on the dung they collected during *Belg* and *Hagay*. A test checking the correlation between dung consumed in *Bega* (Kewi) and the different zones (villages) showed that the correlation was not significant. This indicates that there was more variation in dung consumption rates within zones than among them. This can be explained by the fact that most of the poor families completely relied on dung and fuelwood they could collect, thus limiting their source of fuel to their zones. In contrast, wealthier families could afford to buy fuel from other *tabias* or zones. The amount of fuelwood and dung consumed did not vary from zone to zone, but the parts of trees used as fuel varied greatly, with a correlation being significant at 0.01 (see Table 12.9). This can be explained by the availability of trees in the vicinity of the study areas; in

Table 12.8 Fuelwood and dung consumption patterns by season.

	Kiremt (Summer)	Kewi (Autumn)	Belg (Spring)	Hagay (Winter)
Fuelwood in donkey load per week	1.4	1.45	1.26	1.26
Fuelwood in woman load per week	1.57	1.28	1.19	1.18
Fuelwood in man load per week	0.34	0.27	0.27	0.27
Dung in kasha (50kg) per week	2.0	2.7	1.42	1.52

Table 12.9 Correlations between zones and tree part used as fuel.

		Zone	Tree part used as fuel
Zone	Pearson Correlation	1.000	-0.652***
	Significance (2-tailed)		0.000
	N	120	72
Tree part used as fuel	Pearson Correlation	-0.652***	1.000
	Significance (2-tailed)	0.000	
	N	72	72

*** Correlation is significant at the 0.01 level (2-tailed)

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[1] *Kiremt* is the rainy season (June-August), *Kewi* (Sep-Nov) is autumn, *Hagay* is winter (Dec-Feb), and *Belg* (Mar-May) is spring.

Humera and Alaje, mainly large branches and stems were used, and in others, except for the Mekelle area, mostly twigs and small branches were used. However, deforestation is also very serious in the "better-forested" areas, and is expressed in the time spent collecting fuelwood. There was no significant difference in the amount of time women and other family members spent collecting fuelwood, even between Humera (a better-forested area) and Ganta Afeshum or Naeder Adet (denuded areas).

When asked whether they would be willing to have trees planted in order to solve future fuel shortages, 58.7% of the women preferred the establishment of private woodlots, 7.5% wanted area exclosures, 6.3% wanted to be involved in community forests, and 27.5% wanted to be involved in all of the above activities. The majority of women were interested in the more tenure-secure intervention of private woodlots as well as the currently functional area exclosures. These show that in Ethiopia, tree tenure-related issues are very important to future afforestation and other forestry-related issues

We also examined the factors that influence household decision-making regarding the procurement and use of fuelwood. The emphasis was on the identification of factors that influence households' decisions on whether to collect fuelwood for their own consumption or to buy it from the market. Households have the options of obtaining their fuelwood requirements either from their own labor time investment (for collection) or from market sources (purchasing). This choice is influenced by different factors, and degree of impact for each may vary. In addition, analysis was made on how the consumption of fuelwood (per donkey load) was affected by different factors. For this purpose, we estimate models by using econometric techniques to analyze the influential factors. Most of the activities (by women and other household members) that have been discussed thus far can directly or indirectly influence the decision of whether to collect fuelwood, as well as the amount consumed. Estimation of the variables that affect households' decisions on whether to collect fuelwood for their own consumption was done using a probit model (Table 12.10). The amount of fuelwood consumed was estimated by using ordinary least squares (OLS), and is presented in Table 12.10, which shows the direction and magnitude of the impact of different factors that may have influenced the quantity (in donkey loads) of fuelwood consumed.

Family size, education level of the female household head, and land holding size were some of the factors that were hypothesized to have relationships with the collection of fuelwood and fuelwood consumption. Among these, education level and land holding size were found to have a statistically significant effect on fuelwood collection. There was a negative association between literate female heads and the quantity of fuels consumed. As the results show, they were less likely to use fuelwood as source of energy. Different arguments can be presented to explain this result. One is that literate female heads tend to use fuel-saving technologies, such as improved stock, as opposed to fuelwood or other biomass-based sources of energy. Another possible explanation is that literate women may depend more on fuelwood than on animal dung and straw, which women without educations tend to depend on more heavily. On the other hand, the landholding size of the household was found to have a strong influence on fuelwood consumption. The results showed that a 1-ha increase in the size of a landholding led to a 0.63-donkey load increment in fuelwood consumption, ceteris paribus. There may not be a clear theoretical explanation for this positive relationship. However, empirical evidence (and observation) indicates that households with large landholdings (more plots) can invest some fuelwood sources in their holdings. This may lead to higher fuelwood consumption. In the study

Table 12.10 Average number of meals and meal dependence on fuelwood.

Item	Mean	Standard deviation
Number of meals served per day during Kiremt	2.57	0.70
Number of meals served per day during Kewi	2.76	0.63
Number of meals served per day during Belg	2.75	0.63
Number of meals served per day during Hagay	2.76	0.64
Number of meals cancelled in the last one week due to lack of fuelwood	0.25	0.88
Number of semi-cooked meals served in the last one week due to shortage of fuelwood	0.14	0.58
Number of uncooked meals served in the last one week due to shortage of fuelwood	0.07	0.28

areas, for example, about 24% the fuelwood came from private woodlots. An implication in this case could be that households with more plots (large land holdings) may use a fraction of the landholdings for woodlots, which brings more fuelwood and more consumption.

Another interesting result is the effect that the ownership of donkeys had on both the collection of fuelwood for a household's own consumption (probit model) and the quantity of fuelwood consumed (OLS model). Given the long hours of travel that women have to undertake for fuelwood collection, the availability of donkeys becomes important. Ownership of donkeys significantly influenced fuelwood consumption (at 5%) and collection (at 10%). These results indicate that higher donkey numbers were associated with more fuelwood consumption and an increased likelihood of individuals collecting their own fuelwood to provide for their households. This was particularly true in the study areas where donkeys have historically been used (donkeys share the largest burden of the transport system in rural areas of Ethiopia). On the other hand, it can be hypothesized that the ownership of a large number of livestock may compete with the time needed for fuelwood collection, since rural households usually rear their herds themselves. In the case of livestock ownership, it may be argued that a large number of livestock can give households opportunities to utilize dung as an alternative fuel source. Nevertheless, results showed that the number of livestock did not have a statistically significant effect on households' own collection of fuelwood or fuelwood consumption.

Factors associated with the use of fuelwood for income-generating activities also influenced the collection of fuelwood. Rural women, predominantly, participate in such income-generating activities as preparing and selling local drinks (alcoholic drinks, tea, coffee) and food. In the study area, 18.3% of the women participated in such small income-generating ventures. These income-generating activities usually are produced by using fuelwood collected by the women themselves (although to some extent, animal dung is also used). The results indicated that engaging in income-generating activities powered by fuelwood was associated with households' collecting their own fuelwood. In other words, there was a positive association between participation in income-generating activities that use fuelwood as a source of energy and the collection of fuelwood. This, however, does not imply that women do not buy fuelwood to participate in income-generating activities. In relation to this, while income affected fuelwood consumption positively, it was inversely associated with their own fuelwood collection activity. The positive association of income with fuelwood consumption makes fuelwood a "normal good" relative to other sources of energy in rural areas, such as dung and straw. Households (women) cannot go one step further and abandon fuelwood in favor of using electric stoves because electric power is virtually non-existent in rural areas. However, alternatives such as improved stoves can be used, as the results showed a positive association vis-à-vis fuelwood consumption (Table 12.11). In another case, the results showed that households (women) opt not to collect fuelwood by themselves as their income rises.

Table 12.11 Estimates of consumption and source of fuelwood.

Variables	Model 1 (OLS)	Model 2 (Probit)
	Coefficients	Coefficients
Fuelwood consumption in donkey load [dependent variable for Model 1]		
Source of fuelwood (1 if own collection 0 otherwise) [dependent variable for Model 2]		
Education of female household head (1 if literate 0 otherwise)	-0.22 (0.041)**	-0.19 (0.808)
Family size	0.05 (0.951)	-0.30 (0.166)
land holding size in hectare	0.63 (0.008)***	-0.007 (0.985)
Ownership of donkeys (number of donkeys)	0.95 (0.048)**	0.53 (0.084)*
Ownership of cattle (number of livestock)	-0.02 (0.683)	0.14 (0.321)
Practicing income generating activities that use fuelwood (1 if yes 0 otherwise)	-0.08 (0.800)	1.74 (0.034)**
Average monthly income in Birr	0.001 (0.042)**	-0.02 (0.006)***
Travel time to fuel wood collection places in hours	-0.71 (0.019)**	-0.45 (0.030)**
Use of improved stove (1 if yes 0 otherwise)	0.61 (0.036)**	
Main occupation of the household (1 farming 0 otherwise)		2.06 (0.042)**
Accessibility to open forest (1 if yes 0 otherwise)	1.94 (0.014)**	1.30 (0.049)**

Significance levels: ***1%, **5%, and *10%. Figures in parentheses are P-values.

Instead, the higher purchasing power means that they can use market sources to obtain fuelwood.

Other major influential factors were access to fuelwood resources, indicated by travel time to and from collection places, and access to forest lots. The labor time invested in traveling to collect fuelwood significantly influenced fuelwood consumption and collection. Specifically, it had a statistically significant and negative effect on consumption and on households' own collection of fuelwood. When the distance was large, which meant more traveling time, the opportunity cost of investing time to collect fuelwood (and, hence, consume more fuelwood) increased. Rational economic agents (in this case, households or women) tend to act in the opposite direction. That is, they reduce their consumption of fuelwood or prefer not to collect fuelwood by themselves. Results specifically showed that as traveling time increased on average by 1 hour per week, consumption of fuelwood decreased by 0.71 donkey loads, ceteris paribus. On the other hand, open access to forest lots encourages households' own collection of fuelwood, as the results of the probit model show. This increased access can also pave the way for increased consumption, as is shown in the results. One more interesting result was the effect that women's major occupations had on the collection of fuelwood. Farming was associated with a higher likelihood of collecting fuelwood for own consumption, as is observed in rural areas of Ethiopia.

12.6 Conclusion and Recommendation

Women in rural areas of Ethiopia carry the heavy burden of participating in major household and farm activities, such as domestic work, farming, and off-farm and non-farm activities. In rural areas of Ethiopia, they also shoulder the significant burden of collecting, managing, and using fuelwood. The single biggest portion of the workload of rural women in Ethiopia is domestic activities, which includes virtually all in-house activities and to which men contribute almost nothing. Women also allocate a lot of their labor time to securing resources, such as fuelwood and water. It is particularly appalling to see women traveling for hours to fetch fuelwood and water. They remain largely responsible for collecting these resources, though children and men also contribute, to some degree. Apart from these tasks, women allocate a large amount of labor time toward traveling input-output marketing, which also imposes a heavy workload on women.

Women's human and physical capital/assets, as expected, play significant roles in the decision to collect (or not collect) fuelwood. They also exert similar strong influence on the quantity of fuelwood consumed. Through education, women develop awareness and the capability to shift to less-resource dependent energy sources, such as stoves. The indication is that education for women discourages fuelwood consumption, but this may not mean that they are aware of health and environmental consequences. Because this result is not definitively conclusive, further research in this areas is warranted. Otherwise, the importance of building women's capacity cannot be overemphasized. For instance, women's participation in supplementary income-generating activities through the use of fuelwood energy may help them create and amass resources that in turn allow them to use alternative and sustainable sources of energy. Although such technology was not in place when this study was conducted, there are now solar energy technologies available that are helping women (and men alike) utilize cleaner and healthier courses of energy. They are able to fund such technologies by using income that is separate from their main income and is obtained from additional sources. Draught animals, such as donkeys, place significant leverage on the transport of fuelwood; limited access to these key assets means decreased likelihood of fuelwood consumption. Furthermore, an extra plot of land creates an opportunity for women to invest in plantation both for the purpose of fuel production and for other interests, such as supplementary income to cover other expenses. On the other hand, open access to forest areas and woodlots further perpetuates the propensity toward fuelwood collection by women, and hence, the degradation of resources, which ultimately exacerbates the fuel shortages that women already face.

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13. Climate-Smart Energy Use (Management)

Gebreyohannes Girmay[a] and Zenebe Gebreegziabher[b]*

Summary

Climate change is a threat to our planet and has a negative impact on sustainable growth and development, particularly in Sub-Saharan African countries. Climate-smart energy use and management is among the potential approaches to simultaneously achieve sustainable food production and consumption, reduce GHG emissions, and increase carbon storage to make agriculture and landscape systems more resilient. Integrating climate-smart energy approaches into agriculture and improved landscape restoration practices can offer multiple benefits including improved food security, livelihoods, and ecosystem resilience. This chapter presents four climate-smart energy practices and management options—biogas, agroforestry, efficient cooking stoves, and modern energy sources—with potential for climate change mitigation and adaptation at both farm and landscape levels in Ethiopia. Each section discusses technological/management features of these four options in terms of improving access to energy sources and/or increasing the efficiency of available energy use, potential benefits for climate change mitigation and/or adaptation, and statuses and challenges of dissemination.

Keywords: energy-smart cooking, biogas, agroforestry, fuel efficient cookstoves, fuel switching

13.1 Introduction

Climate change is a real threat to our planet and has a negative impact on sustainable growth and development, which has visible and serious negative consequences for the economy, society, and the environment. Climate change will therefore pose a serious threat to global food security through its negative impacts, which include changes in temperature and precipitation patterns. By 2050, global food production will have to produce approximately 70% more food than at present in order to feed the growing population, particularly in developing countries (FAO 2011, UN 2009).

Although it contributes the least to global carbon emissions (in terms of average per-capita emissions), Africa is the region that is most vulnerable to the effects of climate change, because the majority of African farmers are dependent on rain-fed agriculture. This vulnerability is compounded by factors such as widespread poverty, conflicts, and a weak capacity to adapt to natural disasters such as droughts and floods (Gebreegziabher et al. 2012a).[1] Ethiopia is not an exception in this regard. Recent vulnerability and poverty mapping for Africa put Ethiopia as one of the continent's most vulnerable countries to climate change, with the least capacity for responding to the impacts of climate change, especially in the form of frequent droughts (Thornton et al. 2006, Stige et al. 2006). Ethiopia has already suffered significantly from climate extremes, manifested in the form of frequent droughts (von Braun and Webb 1995). Yet Ethiopia released only 150 Mt CO_2 of total greenhouse

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a Mekelle University, Department of Land Resources Management and Enviromental Protection, Mekelle, Ethiopia (email: gebreyohannes.girmay@gmail.com)

b Mekelle University, Department of Economics, Mekelle Tigrai, Ethiopia

* *Correspondence:* Zenebe Gebreegziabher (email: zenebeg2002@yahoo.com)

[1] Africa currently contributes only 4% of global GHG emissions (UNFCCC 2005). Africa's forest resources are also serving as a sink for about 25% of its emissions (Gebreegziabher et al. 2012a).

gas (GHG) emissions, from the entire economy, in 2010; agriculture and forestry accounted for 50% and 37% of the total, respectively (FDRE 2011).

Climate-smart energy use is among the potential approaches to simultaneously achieve sustainable food production and consumption, reduce GHG emissions, and increase carbon storage while making agriculture and landscape systems more resilient to the negative impacts of climate change (FAO 2013, GSCCSA 2011). Integrating climate-smart energy approaches into agriculture and improved landscape restoration practices can offer multiple benefits including improved food security, livelihoods, and ecosystem resilience (FAO 2010, Foresight 2011, Beddington et al. 2012a, Beddington et al. 2012b, HLPE 2012).

This chapter aims to introduce the concept of the climate-smart energy approach based on a review of the pertinent literature. Specifically, the objectives of this chapter are to (1) identify/enumerate climate-smart energy use options in the context of rural Ethiopia; and (2) review and synthesize potential contributions to climate change mitigation and adaptation, as well as the driving factors that influence the availability and sustainability of these options. Specifically, we examine four climate-smart energy options: biogas, agroforestry, use of improved or fuel efficient biomass cookstoves, and switching (transitioning) to modern/renewable energy sources, which include solar, wind, hydro, and geothermal energy, as well as bioenergy. Moreover, key technological features, potential contributions to climate change mitigation and adaptation, and key driving factors that influence availability and sustainability are discussed for each of the four options. The chapter concludes with policy implications for scaling up climate-smart energy approaches.

13.2 Concept and Context

Figure 13.1 provides the research conceptual framework in which climate-smart energy use (management) its two-way linkage between energy and agriculture is depicted. As can be seen in the figure, agri food production involves energy use for traction power (for plowing) as well as for household or domestic consumption, including for cooking. In high-income countries, the greater proportion of the energy used is for processing and transport, whereas in low-income countries, cooking consumes the highest share (FAO 2011). Approximately 2.6 billion people worldwide rely on local trees for the energy used in cooking and heating, and reliance on such trees for fuelwood is expected to increase globally, with approximately 2.8 billion people relying on local trees for energy by 2030 (MEA 2005, IEA 2010). Fuelwood use in developing countries has resulted in deforestation and forest degradation, which contribute to increased GHG emissions (Angelsen and Brockhaus 2009, IPCC 2007). For example, recent evidence shows that the combined emissions contribution from deforestation and forest degradation accounts for about 18% of global GHG emissions (Stern 2007). In many developing countries, like Ethiopia, most of the traditional uses of wood for cooking (plus baking) are carried out in stoves which have low heating use efficiency (Dunkerley et al. 1981, Gebreegziabher 2007, Gebreegziabher et al. 2012b); this low efficiency of the stoves leads to an excessively large quantity of wood use, which consequently aggravates the rate of deforestation for extracting wood for household energy consumption. The growing gap between fuelwood demand and supply, and the resultant scarcity of fuelwood, prompts farmers to resort to burning animal dung and crop residues for fuel, resulting in the loss of potential soil organic matter and thus fertility (Newcombe 1989, Gebreegziabher 2001, 2007). In Africa, agriculture constitutes the second greatest source of GHG emissions (Gebreegziabher et al. 2012a), and the emission of methane, which is 22 times more damaging than carbon dioxide, is increasing, mainly because of methane emissions from the livestock sector (EPA 2015).

Agriculture, agroforestry, and forestry have always been traditional sources of household biomass energy, whereas the agri food system is an important consumer of energy. Although agriculture and energy have always been closely interlinked, these linkages have been changing over time and are now growing stronger. In promoting energy-smart,[2] productive, and sustainable food production, livelihoods, and ecosystems, there is a need to strike a balance between improving access to energy sources, increasing the efficiency of available energy use, and sharing renewable energy sources. For example, improvement in energy efficiency may translate into reduced energy costs/expenditures and, hence, greater net returns. However, these returns may result in further extensification of agriculture, which, in turn, means more energy consumption and more CO_2 emissions from land use changes. It is also important to note that efforts to achieve food and energy security in a climate-smart way imply that this will have to be accomplished through low-carbon approaches. This can be done either directly, through increased uses of renewable energy in the agri food sector, or indirectly, through measures to

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[2] The concept "energy smart food" emphasizes energy efficiency, energy diversification through renewable energy, and energy access and food security through integrated food and energy production (FAO 2012).

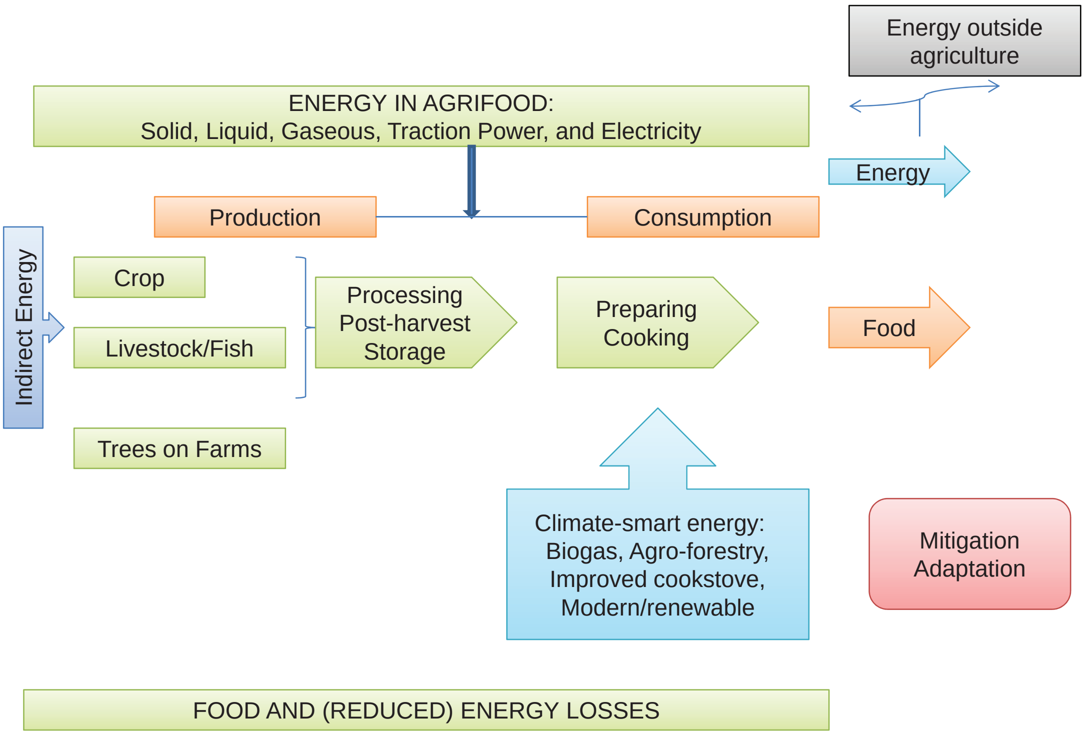

Figure 13.1 Research framework. (Source: Adapted from FAO 2013).

increase energy efficiency (FAO 2012). Climate-smart energy management options should, thus, target both the demand and supply sides of the problem, which also indicates that there is a need for a broadly conceived approach.

Climate-smart energy approaches must be based on a solid understanding of contexts, meaning, the local circumstances and the economic trade-offs of available options. In the context of Ethiopia, deforestation has been occurring for many years and has made scarcity of fuelwood a critical problem, as it is in other African countries. As a result, farmers have switched to burning animal dung and crop residues for fuel instead of using the dung as a source of nutrients to amend depleted soils (Newcombe 1989, Gebreegziabher 2001, 2007). The use of dung as a fuel source has increased Ethiopian farmers' vulnerability to drought shocks and low productivity, food insecurity, and poverty (Amsalu 2006); hence, reversing this practice of using dung for burning instead of manuring is vital for avoiding soil nutrient depletion, reducing environmental degradation, improving food security, and alleviating poverty (Sanchez et al. 1997). At the same time, in Ethiopia, GHG emissions from agriculture, mainly from the livestock sector, account for over 85% of aggregate emissions. In order to contribute to climate-change adaptation and mitigation in Ethiopia, it is important to consider climate-smart options for reducing GHG emissions as well as closing fuelwood demand-supply gaps, which should also bring about multiple benefits including improved food security, livelihoods, and ecosystem resilience (FAO 2013).

The following sections present biogas, agroforestry, use of fuel efficient biomass cookstoves, and the process of switching (transitioning) to modern/renewable energy sources as climate-smart energy approaches in the context of Ethiopia. Each section discusses the unique technological and management features of the above in terms of improving access to energy sources and/or increasing the efficiency of available energy use; their potential benefits for climate change mitigation and/or adaptation; and both the current status and the future challenges of disseminating the technologies or practices.

13.3 Biogas

13.3.1 Technology

Biogas is a multilateral renewable energy source that can replace traditional fuels, i.e., both dung and fuelwood. Human and animal wastes can be converted into biogas as a source of methane that can be used for cooking and lighting (FAO 2013). Biogas is a clear-burning fuel free of indoor air pollution. Because biogas has different properties from other commonly used gases, such as propane and butane, and is only available at low pressures, its use requires specially designed stoves capable of burning biogas efficiently (Gebreegziabher and Oskam 2008). Generally, there are two technological options for the use of biogas as a domestic energy source in rural areas, one at the household or family level and another at the village or community level. Due to relatively high numbers of cattle per capita in rural areas (Shapiro et al. 2017), Ethiopia is among the most attractive countries for biogas production. Even though the free-grazing system poses some challenges in terms of the amount of cow dung that could actually be collected, it is still speculated that biogas generation could provide rural areas with more fuel than is needed to fulfil the country's subsistence-level requirements (Gebreegziabher 2007). In addition to contributing to poverty reduction, mainly through enhancing fuel and food availability, biogas also generates other co-benefits. For example, in terms of environmental health, it destroys pathogenic microorganisms, thus protecting humans and animals, as well as mitigates family health hazards from indoor air pollution and exposure to the smoke generated by conventional burning (Gebreegziabher and Oskam 2008, Yiridoe et al. 2009). It is also beneficial in terms of climate change adaptation and mitigation through the capture and use of methane, as reviewed below.

13.3.2 Potential contributions to adaptation and mitigation

Firstly, the use of biogas technology reduces or eliminates nutrient losses. That is, the bioslurry (effluent) from biogas production can be used for soil fertility maintenance and for redressing land degradation, which is the major cause of agricultural stagnation and rural poverty in Ethiopia (Wood 1990, Hagos et al. 1999, Hengsdijk et al. 2005). Evidence has shown that the use of effluent for soil fertility maintenance increased yields of various crops by up to 20% (Marchaim 1992). Hence, the level of yield increment from the use of bioslurry in Ethiopia is expected to be substantial. For example, results from a field trial station at Mekelle University suggest that the application of bioslurry on wheat and teff fields generates marginal benefits that are more than double the marginal costs (Girmay et al. 2014).

Biogas also has climate change mitigation potential. Table 13.1 presents the mitigation potentials of biogas using simplified calculations, which include inputs (feedstock) used, driving variables, and resultant outputs. To begin with, consider a family-size biogas plant (3 m^3 capacity) operated with the dung collected from five cattle (i.e., an average number of cattle possessed by an average household) (CACC 2003), calculated using a rate of 0.5 m^3 biogas kg^{-1} dry dung (Khendelwal and Mahdi 1986).

Until recently, most household uses of biogas were for lighting and cooking. In rural Ethiopia, baking *injera*[3] is the largest consumer of energy, which accounts for over two-thirds of the total domestic fuel consumption, with the remainder going for cooking and lighting (Gebreegziabher 2007). In order to improve the efficiency of biogas energy, a biogas burner or stove technology that can be used for *injera* baking has been developed by Bahr Dar University and is now at the pilot stage. The technology assumes that 80% of the generated biogas would replace all fuelwood and 20% of the kerosene now in use. Kerosene and fuelwood equivalents to the produced biogas were then calculated using the calorific values of these fuels (Pathak et al. 2009). This implies that a family-size biogas plant would save the calculated quantities of 316 lt of kerosene and 5535 kg of fuelwood with global warming potential (GWP), in kg CO2e, of 762 and 10,371, respectively, which would otherwise be emitted to the atmosphere as GHG when burned as fuel.

Composition of bioslurry consists of 1.4% N, 0.5% P, and 0.8% K (Subrian et al. 2000, Tandon and Roy 2004). Substitution of mineral fertilizer with the slurry reduced CO_2 emissions, which would otherwise be emitted during the production of fertilizer. With all of these issues in mind, emission of CO_2 was calculated following Pathak et al. (2009), and especially using equation [3] presented in Pathak et al. (2009).[4]

In summary, the potential of biogas for global warming and climate-change mitigation can be envisaged in two dimensions: (1) its potential to mitigate global-warming and associated carbon credit earnings from a family-size biogas plant; and (2) the aggregate GHG mitigation potential (GMP) of biogas plants at a region or country level. On average, a family-size biogas plant produces fuel that can substitute 13.3 L of kerosene, 624.26 kg fuelwood, and 1,364.59 kg of cattle dung cake, and reduces emissions of NOx, SO_2, CO, and volatile organic compounds to the atmosphere by 16.4, 11.3, 987.0, and 69.7 kg $year^{-1}$, respectively (Pathak et al. 2009). The GMP of a family-size biogas plant was found to be 9.7t CO_2 equiv. $year^{-1}$. If linked to the Clean Development

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[3] *Injera* is a pancake-like bread typical to Ethiopia.

[4] The calculations presented in Table 13.1 assume a continuous loading fermentation process and normal digestion and gas production, beginning a certain period of time after the initial feeding. Feedstock is then fed continuously into the digester every day, and effluent is discharged simultaneously, in the same quantity as that of the added influent. Using this process, constant fermentation and uniform gas production can be achieved (Gebreegziabher and Oskam 2008).

Mechanism (CDM), and with the current price of USD \$9 t^{-1} CO_2 equiv. (Gebreegziabher et al. 2012a), a carbon credit of USD 87 year $^{-1}$ could be earned from such reductions in GHG emissions. The 5 million biogas plants targeted for installation by the government of Ethiopia would thus have a GMP of 50 Mt CO_2 equiv. year $^{-1}$ and USD 125 million in carbon credit under the CDM.

13.3.3 Dissemination challenges

Biogas was first introduced to Ethiopia in the 1970s. Most of the biogas plants were installed at demonstration centers (Kebede 1995). Various institutions/agencies were involved in biogas technology dissemination, including the Ministry of Agriculture (MoA), through its Rural Technology Promotion Centers (RTPC). The different types (brands) of biogas technologies introduced included Indian, Chinese, Nepalese, and Cambodian models. The low cost and fixed-dome Chinese (or Deenbandhu) model was preferred to the floating-drum Indian model, which was considered costly and generated the same amount of biogas per day (EESRC 1995, AFREPREN 2001). Figure 13.2 presents a floating drum (Indian model) biogas plant. The high initial investment cost was seen as a serious impediment to the

Table 13.1 Annual GHG mitigation potential (GMP) and carbon credit from a family-size biogas plant for Ethiopia.

Parameter	Value
No. of cattle	4
Total dung (kg dry wt.)	4,400
Biogas production (m^3)	2,200
Kerosene saving L(liter)	316
GWP for kerosene (kg CO_2 equiv.)	762
Firewood savings (kg)	5,535
GWP for wood (kg CO_2 equiv.)	10,571
Slurry produced (kg C)	1,725
Fertilizer N equivalent (kg)	62
Fertilizer P equivalent (kg)	22
Fertilizer K equivalent (kg)	35
GWP for fertilizer (kg CO_2 equiv.)	302
CH4 leakage per plant (kg)	94
GWP of leaked CH_4 (kg CO_2 equiv.)	1,968
GMP (kg CO_2 equiv.)	9,667
Price of carbon credit (US \$ t^{-1} CO_2 equiv.)	9
Carbon credit per plant (US \$)	87

Source: Gebreegziabher (2010).

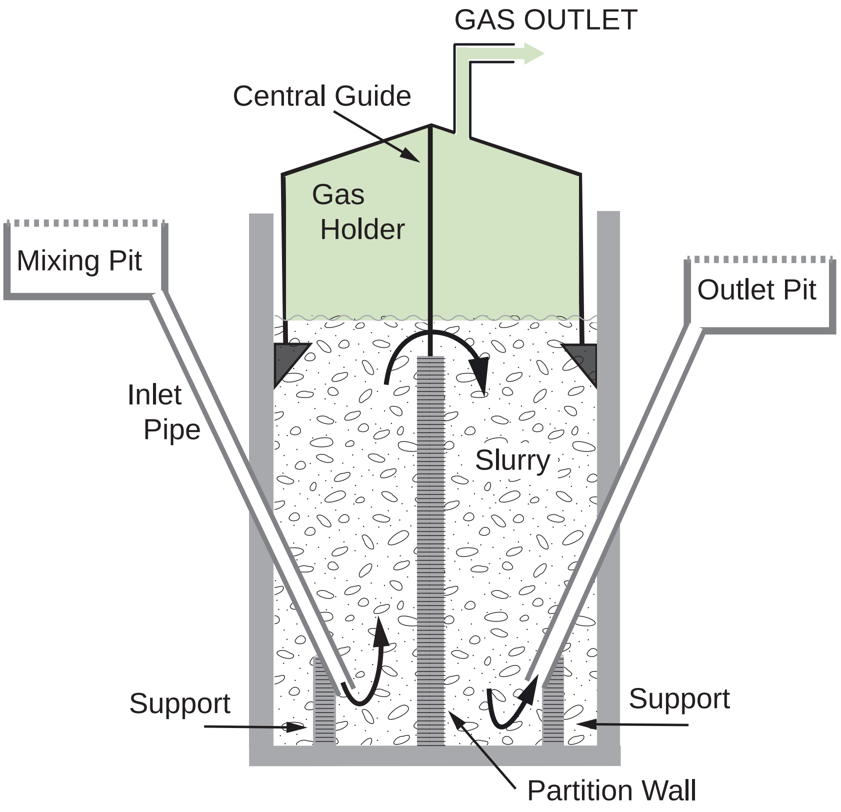

Figure 13.2 Floating drum (Indian) digester model. (Source: Adapted from FAO 1992.)

dissemination or adoption of biogas technology. However, the potential roles for biogas in replacing fuelwood and kerosene, redressing land degradation, and helping with climate-change adaptation and mitigation were not recognized (Gebreegziabher 2010). This may have contributed to the low policy attention biogas technology received in the past. Although Ethiopia has currently embarked on the construction of about one million biogas plants, the technology is not as widespread as expected, and farmers cannot adopt it. Factors contributing to lack of widespread biogas technology adoption include lack of sense of ownership, intermittent promotion efforts/high staff turnover, poor recruitment of farmers into the program, and lack of spare parts or after sale maintenance services. In addition to these barriers, lack of policy/government attention is also a contributing factor.

13.4 Agroforestry

13.4.1 Practices

This section discusses agroforestry mainly in the context of trees in farm and homestead areas, which provide important benefits, including fuelwood, fodder, timber for construction, and fertility enrichment (WBISPP 2002). Trees on farms may include remnant trees on individually owned fields, trees in communal areas, and trees planted by farmers, including multipurpose trees and improving fallow with fertilizer shrubs (Neufeldt et al. 2011). Agroforestry involving trees grown on farms and around homestead areas is a long standing tradition in Ethiopia. The most common farm agroforestry practices include inter-planting or intercropping of scatter trees in farm fields, boundary planting of trees on border ridges of cultivated lands, and farm woodlots (Bishaw and Abdelkadir 2003, Bishaw 2001, and EFAP 1994).

13.4.2 Potentials to contribute to adaptation and mitigation

The contributions of agroforestry to adaptation can take different forms. For example, nitrogen-fixing trees can be intercropped among rows of food crops to provide nutrients to crops and improve farm productivity. Agroforestry techniques also include the use and sale of tree crops, such as fuelwood, fruit, and timber, which enhance resilience (Gebreegziabher and van Kooten 2013). Agroforestry practices also offer best-fit options for climate-smart energy management by enhancing carbon sequestration in an ecosystem and conserving natural forests, particularly when managed sustainably. Agroforestry provides both above- and belowground carbon (C) sequestration benefits. It is argued that aboveground and belowground parts of trees (i.e., the soil, including roots and other living biomass) are estimated to hold, on average, about one-thirds and two-thirds of the total C stored in tree-based land use systems, respectively (Lal 2010). It is also generally argued that the incorporation of trees in croplands and pastures would result in greater above- and belowground C net storage (Palm et al. 2004, Haile et al. 2008). As compared to pastures or field crops growing under similar ecological conditions, agroforestry systems are believed to have a higher potential to sequester C (Kirby and Potvin 2007). Agroforestry also has the potential to provide substantially higher carbon storage than that found in an extensive vegetation type. A study in Indonesia (Roshetko et al. 2002) indicated that average aboveground C stocks of home-garden agroforestry systems could vary from 30 to 123 Mg C ha^{-1}. The authors predicted that this could potentially be as high as 80 Mg C ha^{-1} if these systems were to be expanded into currently degraded and underutilized lands.

13.4.3 Drivers of adoption

Enhancing the role of trees in climate-smart energy management in agroforestry systems requires an understanding of the drivers of the adoption of these systems, both at the household and community levels. A number of factors may affect a household's decision regarding whether to plant trees. Gebreegziabher and van Kooten (2013), for example, examined factors determining tree planting decisions and the number of trees grown by households (Table 13.2). Results showed that households with smaller homestead areas grew more trees than did those with relatively larger homestead areas, as trees do not compete with other land-use options, such as crop cultivation and vegetable gardening. It is also worthwhile to note that male-headed households planted more trees than did female-headed households, perhaps because men play an active role in tree-planting activities. In turn, the effects of land tenure security and the ownership of livestock on tree planting decisions contrasted between Tigrai (tenure security +) and Amhara (tenure security −; livestock ±) (Mekonnen 2009). These differences may mean that factors influencing households' decisions to plant trees are site- and context-specific.

As an alternative to private tree planting, a greater reliance on community woodlots can be viewed as a means of climate-smart energy management. Although community woodlots have problems relating to open-access exploitation, they can be more effective in addressing fuel shortages if (1) they are sponsored locally, (2) the

Table 13.2 Correlates of extent of tree planting (dependent variable is the total number of tree planted) and of the decision to plant trees of households in Ethiopia.

	Gebreegziabher & van Kooten 2013		Gebreegziabher et al. 2010	Mekonnen 2009
Explanatory Variable[a]	Effect	b	a	a
Outcome equation (level of tree planting)				
Gender of household head	(+)	*	(+)***	
Age of household head			(+)***	
Education of head/ Max. edu of member			(+)**	(+) **
Male labor	(+)	*	-0.004	
Female labor				
Family size				(+)**
Corrugated roof (1 if yes)				
Number of cattle/Livestock owned (TLU)			(-)*	(+) ***
Land size (hectares)			(+)**	
Tenure security/ Expected land size next 5 years (1 if decrease)			(+)**	
Land area cultivated				
Homestead area	(-)	**		
Middle highland	(+)	**	(+)***	
Upper highland			(+)***	
Age of household head squared				
Exogenous income	(+)	**		
Lent at least 50 birr in last 2 years (1 if yes)				(+) ***
Type of stove (1 if three stones)				
Distance to town (in minutes)				
Year 2002 (1 if yes)				
Year 2005 (1 if yes)				
Constant			(-)***	
Selection equation (decision to plant trees)				
Gender of household head			(+)***	
Age of household head			(+)***	
Education of head/ Max. edu of member			(+)**	
Male labor	(+)	***		
Female labor				
Family size				
Corrugated roof (1 if yes)				
Number of cattle/Livestock owned (TLU)	(+)	***	(-)*	
Land size (hectares)			(+)**	
Tenure security/ Expected land size next 5 years (1 if decrease)	(+)	***	(+)**	
Land area cultivated	(-)	***		
Homestead area	(+)	*		
Middle highland			(+)***	
Upper highland			(+)***	
Age of household head squared	(+)	**		
Exogenous income			(+)***	
Lent at least 50 birr in last 2 years (1 if yes)				
Type of stove (1 if three stones)				
Distance to town (in minutes)				
Year 2002 (1 if yes)				
Year 2005 (1 if yes)				
Residual				
Constant				
Statistics				
r	-0.118		1	
s	45.853		0.182	
Heckman's l	-5.429		0.182	215.932
Number of observations	481		200	3,138
Wald X^2 (12)	170.56		23.862	
Prob > X^2	0.000	***	3008.01***	

a Wald test of independent equations ($\rho = 0$): X^2 (1) = 3.53, probability > X^2 = 0.0604.
b ***, **, and *, respectively, indicate statistical significance at the 1%, 5%, and 10% levels or better.

surrounding population density is not too large, (3) economic incentive is a major driver, and (4) the community is more distant from the marketplace (Gebremedhin et al. 2003). Cooke et al. (2008) argued that community forestry can potentially address the open-access issues related to local forest resources in meeting the demands of the very poorest households, who rely on and exploit such forests for fuelwood, but there is little evidence to date that this is being done.

13.5 Use of Improved (Fuel Efficient) Biomass Cookstoves

13.5.1 Technology

Some argue that biomass fuel burning with inefficient stoves could even contribute more to global warming than do stoves that use fossil fuels (Sagar and Kartha 2007). Barnes et al. (2005) also argue that poorer people, particularly in urban areas, are paying higher prices for usable energy than are well-off consumers. This could be attributed to inefficiencies of the traditional or biofuel-using cooking stoves and kerosene lamps coupled with the financial burden or inequity incurred through the use of the inefficient stoves. Another consequence of the use of inefficient stoves is indoor air pollution, which is one of the major causes of death and disease for people in the world's poorest countries. Smoke from cooking fires also causes coughs, runny eyes and noses, and dirty clothes.

In Ethiopia, efforts to disseminate improved stoves began in the 1980s with the World Bank Energy Sector Assessment (World Bank 1984). Among other things, the assessment also carried out kitchen-lab investigations of fuel-saving efficiencies of various stoves, and *injera* cookers. The World Bank (1984) found the *Tigrai*-type[5] stove to be twice as efficient as open-fire tripods, and recommended it to be part of the cooking efficiency program. Consequently, a program for the massive diffusion of efficient cooking stoves was designed in 1986, with the intention of disseminating Tigrai-type stoves with some improvements or modifications (ENEC and CESEN 1986a).[6] Because these stoves had no chimney, a second-generation stove was developed. An improved and partially clay-enclosed stove and a "three-stove model," which was entirely enclosed and included a chimney with an even lower grate height,[7] were subsequently introduced (RTPC 1998). With little additional effort, the three-stove Tigrai variant yielded more fuel savings, and it served as a baking oven, a stove for heating water and sauces, and a grain-roasting compartment (Gebreegziabher et al. 2012c, 2017).

The more recent, third generation, known as a *Tehesh*,[8] is an improvement of the Tigrai variant that drops the separate compartments of the three-stove model, replacing them with a double-walled stove with a baffle that permits it to recycle heat (and smoke) before it escapes out of the chimney—essentially a combined-heat stove. The *Tehesh* yielded additional fuel savings of 22% compared to the Tigrai variants that had only a single wall. During 1998 and 1999, a pilot dissemination program was initiated for the *Tehesh* stove in eight districts in Tigrai regional state, northern Ethiopia (BoANR 1998, Gebreegziabher et al. 2012c). The fourth generation stove, the *Mirt*,[9] is a pumice-cement stove (Figure 13.3). Compared to the open-fire tripod, recent refinements on the *Mirt* stove achieved further increases in efficiency and increased fuel savings, to 50% (Bess and Kenna 1994, Gebreegziabher et al. 2013). In 2005, GIZ[10] also introduced a less massive version in order to reduce input requirements, while maintaining the stove's efficiency. By 2011, approximately 455,000 stoves had been commercially distributed (GIZ ECO 2011).

13.5.2 Contribution to adaptation and mitigation

Essentially, adoption or dissemination of improved (fuel-efficient) biomass cookstoves, as a climate-smart energy technology, could envisage the following advantages: (1) reduce deforestation as a result of reduced fuelwood consumption; (2) reduce smoke and indoor air pollution, and consequently, reduce rates of respiratory disease, infection, and death; and (3) improve the quality of life for rural people.

Gebreegziabher et al. (2017) also estimated that the predicted savings from using an improved stove would come mainly from reduced cooking frequency, time spent collecting fuelwood, and time spent collecting dung, as well as increased livestock numbers/holdings (see Table 13.3).

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[5] The *Tigrai* type stove was an indigenous innovation by local people in response to the growing fuel scarcity and high fuel prices in the area (ENEC and CESEN 1986b).

[6] The extension service was regarded as essential for providing assistance in the use of the new stoves in households and monitoring to determine the degree of use and whether they were being used appropriately, as well as monitoring the physical condition of the stove itself (ENEC and CESEN 1986a).

[7] Refers to the height of the wall or insulation, i.e., from the hearth to the *mogogo* or baking plate.

[8] This latest R&D effort is unique, and is the sole initiative of the provincial government of Tigrai, in collaboration with GTZ (German Technical Cooperation Agency) (Tadesse 1996). The stove design and efficiency tests, including kitchen-lab and field-testing, were undertaken by the Rural Technology Promotion Center (RTPC) in Mekelle (Gebretsadik et al. 1997). Six stove designs of various attributes were tested, revealing that the *Tehesh* stove had the highest efficiency, compared to all others.

[9] Cooking efficiency and the new fuels marketing project, under the Ethiopian Energy Study and Research Center (EESRC) in Addis Ababa, developed this stove (Bess and Kenna 1994).

[10] Deutsche Gesellschaftfür Internationale Zusammenarbeit (GIZ) GmbH (German Corporation for International Cooperation).

Figure 13.3 Mirt stove just installed at farmer's house kitchen. Photo by Zenebe Gebreegziabher.

Table 13.3 Predicted time and other savings from adopting an improved stove, standard error (in parentheses) and t-tests of difference from zero.

Item	Cooking frequency	Number of cattle	Time collecting wood	Time collecting dung	Fuelwood (kg/mo)[a]	Dung (kg/mo)[a]
Predicted savings	4.697	-0.599	472.665	40.840	68.278	19.899
$(\Delta\hat{x}_2)$	(0.708)	(0.142)	(66.171)	(18.950)	(22.575)	(11.371)
t-values	6.63	-4.22	7.14	2.15	3.02	1.75

Source: (Gebreegziabher et al. 2017)

Note: [a] Predicted saving obtained from derived demand functions estimated in Table 13.3.

Cattle savings,[11] as indicated in Table 13.3, increased average household cattle holding by about 0.6 animals because cattle are kept and considered as a symbol of wealth and status. The results indicate that any change that affects the value of cattle also affects household livestock holdings.

The savings, in terms of woody biomass and dung (Table 13.3), suggest that the adoption of a new stove reduces fuelwood collection and pressures on local forest stands. This implies that less wood and dung are being used for cooking purposes, which also indicates decreased time being spent for collecting dung and wood. The results also indicated that adopters collected 68.28 kg less wood and about 19.90 kg less dung each month, which were also significantly different, at $P < 0.01$ and $P < 0.05$, respectively. However, the results suggest that the adoption of an improved stove could produce mixed environmental benefits. If the number of cattle increases by an average of 0.6 per household, grazing pressure on communal lands is likely to go up.

13.5.3 Drivers of adoption

Understanding the factors that affect the adoption decision is important and could provide information for targeting

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[11] Predicted savings in number of cattle is calculated as the difference in number of cattle owned by non-adopters less that of adopters. A greater number of cattle owned by adopters over the non-adopters is regarded as a savings.

policies. Some studies on adoption focus on socioeconomic factors characterizing adoption, such as household literacy level, education status, and attitudes. Gebreegziabher et al. (2017), however, emphasized the role of economic savings for inducing adoption. The study argues that utility gains, including expected savings, in terms of cooking frequency, time spent for collecting fuelwood, and cattle numbers ultimately matter in determining whether or not a household adopts a stove. The results from Gebreegziabher et al. (2017) in Tigrai, as presented in Table 13.4, indicate that savings in cooking frequency, time spent collecting fuelwood, and cattle number, were all statistically significant factors in determining adoption. Because cattle or livestock in Tigrai are regarded as a storehouse of value, gains in fuel savings are invested in cattle. Only households located in the upper and middle highlands were found to be less likely to adopt new stoves, perhaps due to lack of awareness or access. On the other hand, Woubishet (2008) found that multiple factors, including which members of the family participated in fuel collection; stove compatibility (convenience); and age, education status, and income of household head, were important factors in determining the adoption of fuel-efficient stoves in the central highlands of Ethiopia.

13.6 Switching to Modern Energy Sources

Another avenue for energy technology in climate-smart energy management is switching or transitioning to "modern energy" sources, such as solar, wind, hydro, and geothermal, as well as bioenergy. Understanding household fuel-choice behavior and the drivers of fuel switching are of vital importance in developing policies to support the transitioning process. However, such studies are rare in the context of the rural areas of Ethiopia. The "energy ladder" model is an exceptional model which is commonly used in developing countries to describe household fuel choices

Table 13.4 Determinants of improved biomass cookstove adoption in rural Ethiopia (n = 200).

Explanatory variable	Gebreegziabher et al. (2017)	Woubishet (2008)
Saving in cooking frequency	0.0160* (0.0092)	
Saving in cattle numbers	1.5606**(0.7587)	
Saving in time collecting fuelwood	0.0009*(0.0005)	
Saving in time collecting dung	0.0057(0.0040)	
Household income	0.0167**(0.0076)	
Household income squared	-0.00002^b(0.00001)	
Middle highlands (=1; otherwise 0)	-1.2333***(0.4395)	
Upper highland (=1; otherwise 0)	-1.8988**(0.7852)	
Family size	-0.3482(0.2188)	0.1073(0.0872)
Member part cpn for collection		-0.6808**(0.0872)
Dwelling status		0.5499(0.8081)
Separate kitchen		-0.7334(0.6057)
Compatibility		1.382**(0.6815)
Spouse education		1.3884***(0.8413)
Age		-0.0734**(0.0230)
Head of the household		1.11360(0.9436)
Access to credit		0.787(0.515)
Education		1.7467**(0.8403)
Income		2.2085*(0.6098)
Constant	-1.3884(0.9657)	-12.386*(3.1867)
LR χ2(9)	17.59**	
Pseudo R^2	0.0652	

a ***, **, and * indicate statistically significant at 1%, 5%, and 10% level (or better), respectively;
b p-value = 0.108

Source: Gebreegziabher et al. (2017) and Woubishet (2008)

(Hosier and Dowd 1987). This model ascribes household differences in energy-use patterns to variations in economic status. The model suggests that as income increases, households turn to more sophisticated energy sources and move away from the fuels that many lower income households still depend on (Van der Kroon et al. 2013). A study by Heltberg (2005) in Guatemala indicated that many factors, apart from price, matter for fuel choice. Moreover, the study argued that the uptake of modern fuels, such as liquid petroleum gas (LPG), often goes hand-in-hand with continued wood usage (fuel-stacking). The LPG subsidies may not induce households to abandon wood fuel in order to bring about the intended results. The same study, however, argued that traditional cooking techniques and taste preferences might make people prefer wood fuel, even in situations where wood fuel is as expensive as the available alternatives. He also found that the high startup costs of modern energy appliances, such as those of LPG, have played a role in limiting their uptake.

Among the alternatives in this regard is rural electrification. However, Ethiopia has much lower average connection (electrification) rate, even by Sub-Saharan African standards. With most of the population, i.e., about 85%, living in rural areas, the rate (electricity access/coverage) for rural areas has been negligible, i.e., less than 5% (Gebreegziabher et al. 2012b). In light of this problem, the GoE (Government of Ethiopia) established the REF (Rural Electrification Fund) in 2003 through Proclamation No. 317/2003 to provide loans and technical services for rural electrification projects, as well as to enhance productive uses, among other things (Hadgu 2006). The REF was entrusted with the responsibility of supporting and promoting decentralized off-grid rural electrification projects through cooperatives and private sector operators acting outside the national grid (Lighting Africa 2012). The GoE also launched a universal electricity access program (UEAP) in 2008 to be implemented by EEPCo through grid-based extension (EEPCo 2009). The UEAP involved both rural and urban components, with plans to electrify 1700 towns/villages per annum. Under the UEAP and REF, the GoE has managed to increase electricity access, which now reaches 15% in rural areas of the country (Lighting Africa 2012), where access is defined in terms of total number of households connected to the grid and to off-grid sources.

Tucho and Nonhebel (2017) attempted to determine efficient solar energy production and utilization options for small-scale village energy supply applications in rural Ethiopia. They argue that concentrated solar cookers could be a good alternative to traditional cooking methods in areas where other technologies, such as biogas, are not feasible. They also argue that lighting and appliance energy demand could be met with photovoltaic (PV) energy produced using reasonably sized panels. Nevertheless, given the available technologies, the use of PV-generated electrical energy cannot be an economic option for cooking. On the other hand, Tesfay et al. (2014) argue that solar-powered heat storage can supplement the existing biomass *injera* baking in Ethiopia and provide an inexpensive and clean energy solution for food preparation.

Kebede and Mitsufuji (2014) emphasize that lack of integration among solar actors and the financial problems facing both sides of the supply chain have been critical factors behind the slow rate of diffusion of solar innovations in Ethiopia. Gebreselassie (2018) identifies that the lack of local technical expertise and availability of spare parts, high interest rates without a clear agreement, and poor after-sales service from providers were the most pronounced limitations on the adoption of solar home systems (SHSs) technology. Thus, the government and other stakeholders should address those challenges and reach out to a wider part of rural poor communities with limited modern energy access.

Overall, affordability of the technologies is a key constraint to more rapid expansion of modern energy services throughout the developing world. Beyond simple pricing instruments, climate-smart energy should be supported by policy options designed to encourage households to switch to cleaner and more modern energy sources linked to subsidies or credit access for purchasing the necessary goods.

13.7 Conclusions

Through integrating climate-smart, productive, and sustainable approaches, agriculture coupled with improved landscape restoration should simultaneously enhance food security and ecosystem resilience through increasing productivity and income, adapting to climate change, and contributing to climate change mitigation. Landscape and agricultural management practices should also improve and enhance climate-smart energy management. Although agriculture and agroforestry have been traditional sources of energy (through providing bioenergy), there are critical challenges related to use of such energy sources:

- Agriculture-related emissions, especially methane emissions, from livestock in Ethiopia account for over 85% of total emissions through burning or traditional disposal of cow dung.

- Carbon emissions from unsustainable use of local forests, for fuel and other purposes, contribute to deforestation and forest degradation.
- Inefficient use of biomass energy increases demand for biomass fuels and can have severe implications for human health, the environment, and economic development.
- Universal reliance on biomass fuels places a burden on particular household members, particularly women and children.

The chapter concludes that biogas innovation is an appropriate technology for climate-smart energy management from the view point of sustainability and resource-use efficiency. Biogas technology meets energy demands of farm households and enables farmers to replenish most of the nutrients that would otherwise be lost when conventional burning practices are used. Through reducing methane emissions from livestock, biogas technology also contributes to climate-change mitigation. Given the high cattle numbers in rural areas of Ethiopia, biogas technology is viable in terms of per-capita and average holdings. However, the lack of policy/government attention, lack of sense of ownership, intermittent promotion efforts/high staff turnover, poor recruitment of farmers into the program, and lack of spare parts or after sale maintenance services have all been among the main barriers to its wider adoption. Hence, addressing these barriers appears to be very important for widespread adoption of biogas.

Another climate-smart energy technology is agroforestry, which provides a supply-side solution for household energy. In addition to providing a source of energy, agroforestry also complements crop production by fixing nitrogen and providing other benefits. Evidence suggests that factors influencing households' decisions to plant trees are site- and context-specific, and that policy interventions aimed at promoting agroforestry should take into account these site- and context-specific factors.

The adoption of improved (fuel-efficient) biomass cookstoves largely depends on the economic savings in terms of cooking frequency and time spent collecting wood. Biomass cookstove technologies also contribute to climate change mitigation by reducing pressures that lead to forest and agricultural land degradation. Lack of awareness or access is one of the bottlenecks to the widespread adoption of fuel-efficient stoves in Ethiopia. In addition, stove compatibility (convenience), as well as age, education status, and income of the household head, are important factors determining adoption. Modern energy is another form of climate-smart energy management, yet its affordability is a key constraint that determines its adoption in Ethiopia. Beyond simple pricing instruments, climate-smart energy should be supported by policy options designed to encourage households to switch to cleaner and modern energy sources; policy options should be linked with subsidies or credit access for purchasing the necessary and durable goods in order to support continued use of climate smart technologies. The lack of local technical expertise and availability of spare parts, high interest rates without clear agreements in place, and poor after-sales service from providers seem to be the most pronounced limitations to wide-scale adoption of off-grid options such as SHSs. Thus, the government as well as other stakeholders should address these challenges in order to reach a wider part of the rural poor communities that have limited access to modern energy systems. In addition, actors engaged in the promotion of solar power need to identify faster diffusion mechanisms. Moreover, further research is needed on how to build a well-functioning institutional support system for the promotion of renewable energy technologies in Ethiopia.

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14. Shocks and Insurances in Rural Tigray: Do Forests Have A Role to Play?

Nigussie Abadi[a,b,*] and Nick Chisholm[b]

Summary

Rural households in developing countries are exposed to covariate and/or idiosyncratic risks, and have developed their own risk reduction, mitigation, and coping strategies, often resorting to forests and natural resources as a kind of insurance. This chapter examines the potential role of forests for farm households to cope against covariate weather and idiosyncratic health shocks at the margins of protected forests in the northern highlands of Ethiopia. In order to analyze the data collected from 251 sample households using a semi-structured questionnaire in northern Ethiopia, a propensity score matching (PSM) technique was used to account for a selection bias that normally occurs when unobservable factors influence both the treatments and outcome variables, .e.g., labor allocation to forests. Compared to the households that were not affected by the shocks, the households affected by idiosyncratic and covariate shocks made significantly more frequent trips to forests and were more dependent on forest resources as a source of their incomes (by selling more forest products). Broadly, the survey results revealed that forests appeared to play a significant role in insuring households against covariate and idiosyncratic shocks by providing them with safety nets. With projected increases in the severe impacts of climate change, especially in covariant risks affecting entire rural communities, urgent actions are needed to mobilize individual farmers and communities to collectively hedge against climate risks through the adoption of climate smart agriculture, especially investing in sustainable forest and natural resource management.

Keywords: covariate and idiosyncratic shocks, insurance, forest, propensity score matching, north Ethiopia

14.1 Introduction

Low and volatile incomes coupled with the absence or poor development of financial or risk-sharing institutions make consumption smoothing an important issue in low-income countries like Ethiopia. A typical household in rural areas of those countries may also be exposed to covariate and/or idiosyncratic risks (Asfaw and von Braun 2004). Covariate risks include uncertainties associated with: nature, markets (both input and output), social unrest, and policy and institutional failures, which affect many households in the same geographical locations. On the other hand, idiosyncratic risks include household-level shocks, such as death, injury, or unemployment, which can lead to income failure, and shortage of agricultural inputs (Weinberger and Jutting 2000). Usually, due to the absence of the best solutions (formal risk-sharing institutions), rural households in low income countries have developed their own risk reduction, mitigation, and coping strategies (Weinberger and Jutting 2000). Coping is broadly defined as a short-term strategy undertaken by households to prevent the negative effects of crises (Sauerborn et al. 1996), and it may take several forms. Some of the most common coping mechanisms in rural areas are well documented (see Rosenzweig 1988, Paxson 1992, Rosenzweig and Wolpin 1993, Besley 1995, Udry 1995, Kochar 1999, Rose 2001, Shively 2001, Fafchamps and Lund 2003, Dercon et al. 2005, Barrett et al. 2006).

An emergent literature also shows that the commons, particularly forests, provide the rural poor with insurance,[1]

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[a] Mekelle University Department of Agricultural and Resource Economics, Ethiopia
[b] Department of International Development and Food Policy, National University of Ireland, Cork Ireland
* *Correspondence:* Nigussie Abadi (email: nigussieabadi@yahoo.com)

[1] In the livelihoods literature, forests are often identified as a prominent safety-net source, accessed principally by reallocating more household labor to forest extraction. Natural forests and other wildlands with non-cultivated natural resources are supposed to provide households (especially asset-poor households) with additional flexible options in times of trouble.

which could mitigate risks and provide safety nets to withstand economic misfortune (Angelsen et al. 2008). This could be due to three reasons. First, forests are often held under state or communal tenure, with forest resources essentially freely available to local populations, either due to government failure to enforce property rights or weakened traditional systems of resource-use regulation (Baland and Platteau 1996). The second reason is that extraction of forest goods may generally require little financial and physical capital (Neumann and Hirsch 2000). Third, forest resources are diverse and provide a range of products and opportunities for income generation. In addition, forest products are often available at times when other income sources are not, for example, when crops fail (Byron and Arnold 1999, Pattanayak and Sills 2001), and they have better insurance properties than insurance markets in the presence of information and enforcement problems (Baland and Francois 2005), which are typical to the situation in developing countries. This "natural insurance" concept has led to increasing recognition that environmental conservation is important for the poor, not only as a means of earning income, but also as a safety net (Takasaki 2009).

The importance of resource extraction is amplified in the presence of risk, which is expected to intensify as future climate change precipitates more extreme weather events, especially in marginal agricultural areas (Sivakumar et al. 2005) such as Tigray and other areas in the northern highlands of Ethiopia. Yet, the empirical literature on biodiversity, as a means of risk coping mechanism, is ethnographic (McSweeney 2004) and considerably smaller than that on biodiversity as a source of livelihood (Vira and Kontoleon 2010). However, there is very little systematic analysis to help guide conservation and development promoters in their efforts to understand how the poor (and others) deal with negative shock (McSweeney 2004). Thus, many critical questions still remain unclear, for example, do rural households cope with idiosyncratic and covariate shocks by increasing the rate of forest extraction? And if they do, what are the characteristics of households most reliant on forests for coping with shocks? Does reliance on forests for coping with shocks depend on the endowment of physical and human capital as well as access to institutional services? Answering these and other questions can enable us to develop recommendations that maximize the potential for a "win-win" between development and conservation of the environment. Thus, the primary objective of this chapter is to examine the potential role of forests for coping against covariate weather and idiosyncratic health shocks of farm households at the margins of protected forests, particularly forests in the northern highlands of Ethiopia.

14.2 Theoretical Model for Shocks and Labor Allocation to Forests

The theoretical framework underlying the empirical analysis of forest extraction as a coping mechanism is based on the "new home economics" theory (Becker 1965) adapted by Ellis (1993) and Völker and Waibel (2010). The emphasis of the "new home economics" theory is on the household's time allocation, assuming that labor is the major factor of production. Figures 14.1 and 14.2 give a graphical presentation of the basic home economics household model, showing household output in relation to available time, assuming there is no access to off-farm wage employment opportunities. Time, depicted on the horizontal axis of the graphs, is divided into labor for agriculture (0TA), forest extraction (TATF), and leisure (TFT). The time constraint is determined by the total number of person-days available for agricultural production, forest extraction, and leisure. The graphs (Figure 14.1 and 14.2) depict two cases of household labor allocation, comparing a situation with and without shocks. Figure 14.1 represents a weather shock scenario, with effects on agricultural output, while Figure 14.2 represents a scenario where a family member has fallen ill, with corresponding effects on labor capacity.

Figure 14.1 is used as analytical tool to investigate the effects of a covariate weather shock on the time allocation of the household (following Völker and Waibel 2010). According to the authors, weather shocks, such as heavy rain or flooding, lower agricultural output. A key assumption of their model is that weather-risk associated with agricultural production is uncorrelated with forest extraction, and that even for weather risks like storms, the effect on forests is comparatively small (unless it is an extremely strong typhoon) due to the diversity of products that can be extracted. Therefore, the effect of a weather shock is modeled solely by its effect on the household's agricultural production function, while the household's average returns to forest extraction (ARF) remains unaffected. Weather shocks reduce the household's agricultural production (output) in the form of crop yields and livestock products, thereby decreasing labor productivity. The shape of the agricultural production function then changes (APF to APF'), and reflects a relatively poor input-output response, as compared to the initial case. Using the same amount of time for farm work, a household produces less output because the marginal productivity of time allocated to agricultural production decreases. This results in a new

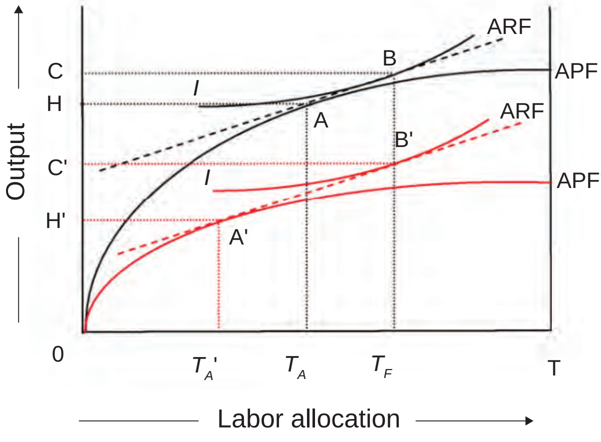

Figure 14.1 The Home Production Model under a weather shock scenario. Adapted after Ellis (1993) and Völker and Waibel (2010).

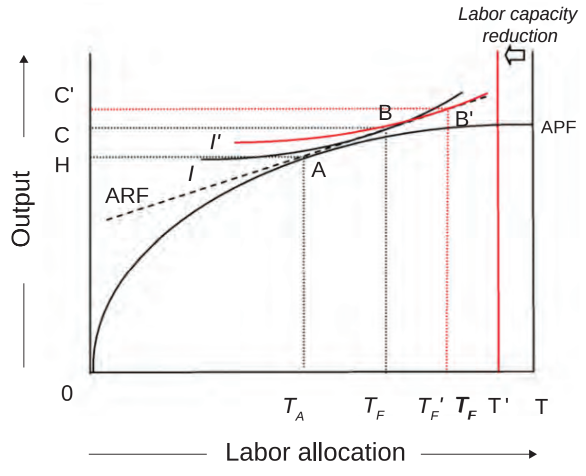

Figure 14.2 The Home Production Model under a health shock scenario.

equilibrium of the household in terms of agricultural production (point A’ instead of point A), which shows that the household allocates less time to agriculture (0TA’ instead of 0TA) and, accordingly, more time to forest extraction (TA’TF instead of TATF).

Figure 14.2 presents the effects of a health shock. According to Völker and Waibel (2010), illnesses of household members are assumed to have two effects. First, an illness reduces the total household time capacity. For example, if the household member becomes ill, he/she cannot carry out his/her normal amount of work. This is reflected by a shortening of the horizontal axis to the left. Secondly, a household member may face additional needs for health care, which increases the family’s preferences on consumption of goods instead of leisure. This is also reflected by the shape and position of the consumption-leisure indifference curve, which has a shallower slope than the baseline scenario (I’ instead of I). Provided a household is able to reallocate leisure time to forest extraction, a new equilibrium emerges in the consumption of goods (point B’), which shows that the household may allocate less time to leisure (TF ‘ T ‘ instead of TFT) and, accordingly, more time to forest extraction (TATF ‘ instead of TATF). The optimal production level of consumption goods (point A) remains the same, as both the agricultural production function and the average returns to forest extraction function are assumed to remain unaffected by the health shock (Völker and Waibel 2010). Accordingly, the theoretical models in Figures 14.1 and 14.2 imply that a covariate weather shock and an idiosyncratic health shock, as well as decision makers’ future expectations of such risks, will make the household allocate more labor to forest extraction.

14.3 Materials and Methods

14.3.1 Study areas and data collection

Primary and secondary data used in this study were collected from Tigray regional state of Ethiopia, located in the northernmost part of Ethiopia, at a latitude of 12° to 15°N and a longitude of 36°30’ to 41°30’ E (Figure 14.3), and covering an area of 53,000 km^2 (Hagos et al. 1999, Tesfay 2006). Tigray’s population is around 4.3 million, growing at 2.5% annually, and of which 80.5% reside in rural areas (Central Statistics Authority 2007). Administratively, the region has 35 *woredas* (districts), 12 town woredas, and 665 *tabias* (lowest administrative unit). Each woreda is subdivided into tabias, and each tabia is divided into *kushets* (equivalent to village) (Babulo 2007).

Data from 251 randomly selected households were collected using a household survey conducted in 2010–2011. A two-stage sampling design was followed to collect the household data. The primary sampling units (PSUs) were tabias. Sample tabias were selected on the basis of secondary information collected from all the woredas. In this category, a total of ten tabias, namely Arato, Derga _ajen, Hugumburda, Meswaeti, Kara_adishawo, Worebayu Kal_amin, Kelisha_emni, and Felege_woini were selected for the survey using purposively sampling (Figure 14.3). The selected tabias were representative of the three different agroecological zones in Tigray, identified on the basis of altitude and proximity to the forest reserves. A multi-purpose questionnaire was used to gather information on household income, expenditures, off-farm income, household assets, vulnerability to shocks, coping mechanisms, and local institutions, alongside a host of other information

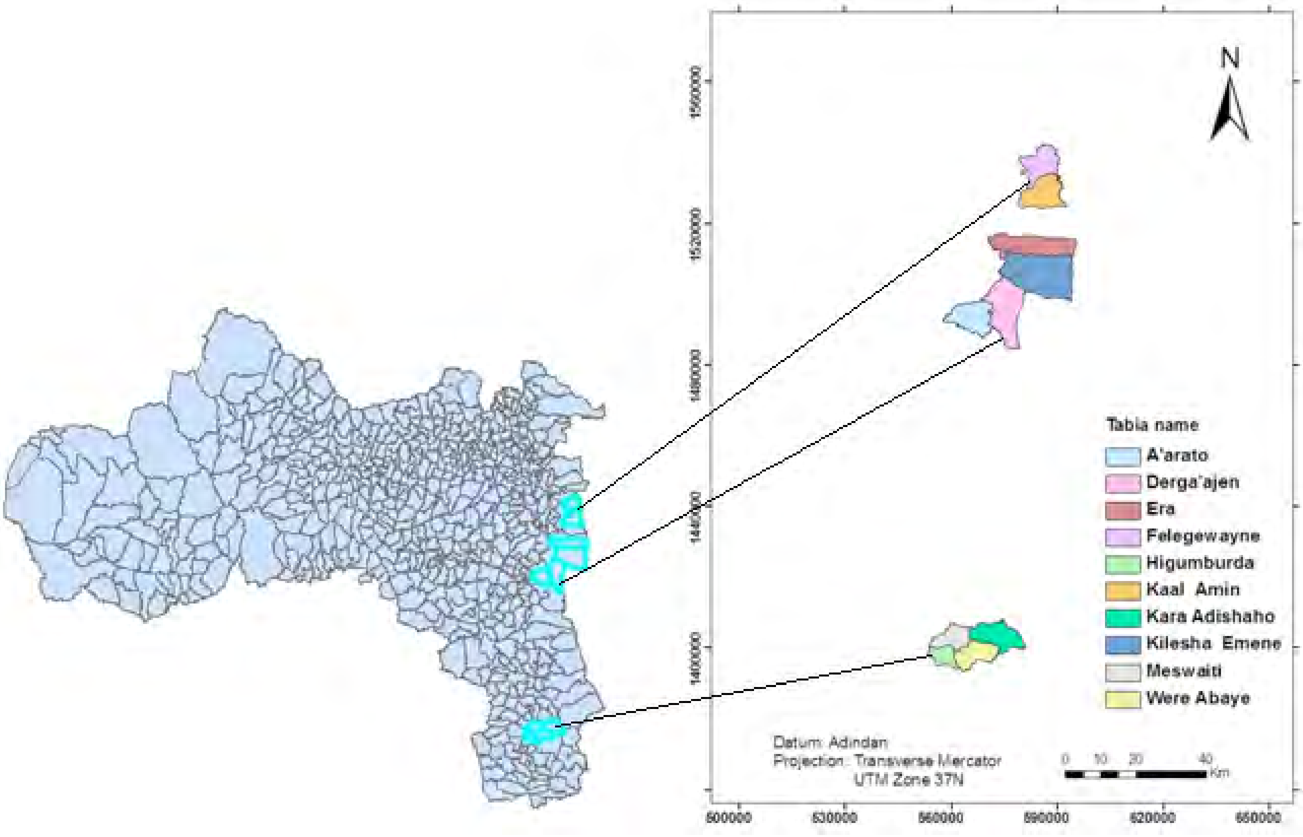

Figure 14.3 Map of the study area.

related to production and sales. Data from the household survey was analyzed using STATA 12 software.

14.3.2 Data analysis

The main objective of the survey was to measure the role of forests for coping with idiosyncratic and covariate shocks. The main econometric issue that arises in attempting to identify this role is the potential endogeneity of those shocks. For instance, the standard probit estimate of the effect of weather shocks on forest labor supply could suffer from endogeneity bias, as forest extraction in previous periods may determine both the frequency of weather shocks (because forest extraction deteriorates the erosion-protection function of forests) and the probability of engaging in forest extraction (Völker and Waibel 2010). To avoid the endogeneity problem, we used the propensity score matching methods, following the program evaluation literature[2] (see for example Rosenbaum and Rubin 1983).

Our empirical strategy relies on the possibility of conditioning on sufficient observable information to obtain a credible counterfactual, against which we may measure the impact of the shocks. Thus, let T = 1, 0 indicate treatment (households affected by shock) and control (households that did not report shock), respectively, and let Y_1 and Y_0 denote the outcome of interest (number of trips to forest) for households with treatment and without treatment, respectively. Since we observe households to be either with treatment or without treatment, we cannot observe the causal effect of interest: $Y_1 - Y_0$. Some features of this distribution are nevertheless estimable. In particular, we may consider the average treatment effect of the treated (ATT):

$$\mathrm{ATT} = E\left(Y_1 - Y_0 \,\middle|\, T = 1\right) \tag{14.1}$$

This magnitude measures how much the outcome of interest changes on average for those households who undergo the treatment (who reported shock, to be defined below). Clearly, simply computing the difference in the average outcomes of those under treatment and those not under treatment is open to bias, as there are observed and unobserved characteristics that determine whether the household undergoes the treatment.

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[2] In our case, PSM compares households who reported the incidence of shock to those that did not, with the same (or similar) values of those variables thought to influence both shock and coping strategy.

That is,

$$\begin{aligned}&E(Y_1|T=1)-E(Y_0|T=0)= \qquad [14.2]\\&E(Y_1|T=1)-E(Y_0|T=1)+(Y_0|T=1)-E(Y_0|T=0)=\\&E(Y_1-Y_0|T=1)+E(Y_0|T=1)-E(Y_0|T=0)=\\&\underbrace{E(Y_1-Y_0|T=1)}_{ATT}+\underbrace{(Y_0|T=1)-E(Y_0|T=0)}_{BIAS}\end{aligned}$$

Only if we can guarantee that outcomes of the control group are equal, on average, to what the outcomes of the treatment group would have been in the absence of treatment does this consistently estimate the ATT. With non-random sorting into treatment and control, this condition is rarely met.

Now suppose that conditioning on an appropriate set of observables, *X*, the non-participation outcome Y_0 is independent of the participation status T. This is the weak version of the un-confoundness assumption, also called ignorable treatment assignment (Rosenbaum and Rubin 1983), or conditional assumption (Lechner 2000) or selection on the observables, which suffices when the parameter of interest is the ATT, as only assumptions about the potential outcomes of comparable individuals are needed to estimate counterfactuals.

$$Y_0 \perp T|\mathrm{X} \qquad [14.3]$$

This implies that

$$E(Y_0|T=1,X)-E(Y_0|T=0,X)=0 \qquad [14.4]$$

In order to identify the ATT, the overlap or common-support condition is assumed. It ensures that, for each treated household, there are control households with the same *X*.

$$Pr(T=1|X)<1 \qquad [14.5]$$

Therefore, under the assumptions stated in equation [14.3] and [14.5] above, we could estimate the ATT from the differences in outcomes between treated and controls within each cell, defined by the conditioning variables (Blundell and Dias 2002). Using the law of iterated expectations and the conditional independence assumption, the ATT can be retrieved from observed data in the following way:

$$\begin{aligned}&\mathrm{ATT} \qquad [14.6]\\&=E(Y_1|T=1)-E(Y_0|T=1)\\&=E_X\Big[\big(E(Y_1|X,T=1)-E(Y_0|X,T=1)\big)\,|\,T=1\Big]\\&=E_X\Big[\big(E(Y_1|X,T=1)-E(Y_0|X,T=0)\big)\,|\,T=1\Big]\end{aligned}$$

The estimate of ATT as shown in equation [14.6] turns out to be prohibitive in terms of data when the set of conditioning variables *X* is large. An alternative is to use the results of Rosenbaum and Rubin (1983) and condition on the probability of treatment as a function of *X*, the propensity score *P (X)*, since the conditional independence assumption also implies that

$$E\left(Y_0|T=1,P(X)\right)-E\left(Y_0|T=0,P(X)\right)=0 \qquad [14.7]$$

Therefore, we could estimate ATT from the differences in outcomes between treated and controls within each cell, defined by values of *P (X)*.

$$\begin{aligned}&\mathrm{ATT} \qquad [14.8]\\&=E(Y_1|T=1)-E(Y_0|T=1)\\&=E_{P(X)}\Big[\big(E(Y_1|P(X),T=1)-E(Y_0|P(X),T=1)\big)\,|\,T=1\Big]\\&=E_{P(X)}\Big[\big(E(Y_1|P(X),T=1)-E(Y_0|P(X),T=0)\big)\,|\,T=1\Big]\end{aligned}$$

Provided that the conditional participation probability can be estimated using a parametric method as a probit model, matching on the univariate propensity score reduces the dimensionality problem.

To estimate the propensity score, we estimate a probit model with a binary dependent variable, whether a member of household was reporting a shock (=1) or not (=0), using our sample data. So, we control for unobservable factors that may influence households reporting shock. We then discard observations that do not have any common support and observations with households having very low or very high probability of reporting shock. We consider nearest neighborhood and kernel matching[3] while investigating the effect of shocks and the role of forests in mitigating the consequences of shocks or serving as a coping mechanism.

14.4 Results and Discussion

14.4.1 Descriptive statistics

Table 14.1 presents the definitions and sample statistics of the variables used in the analysis, including the treatment variable. We used self-reported weather and health shocks during the survey period. This approach, while being simple to understand and compute, is not particularly

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[3] Results from radius and calliper matching also show consistent results. However, reports from both matching algorisms can be found from the correspondent author on demand.

informative because of its binary nature. The problem is that an individual's self-reported health status, for example, is subjectively affected by an individual's social and cultural background, given the individual's subjective health. For example, individuals who are more educated, are wealthier, and are from socially advantaged groups, are typically more aware of the limitations imposed on them by their health status and are more likely to report themselves (and their family) when their health conditions worsen (Schultz and Tansel 1997). To control these unobservable characteristics of reporting health- and weather-related shocks to the researcher, we used a rich data set of control variables based on literature.

Nineteen percent of the respondents reported that some members of their households were affected by illness in the survey year. The average frequency of health shocks was reported to be 2.12 during the survey period. Likewise, almost 80 percent of the respondents reported that they were also affected by drought-related shocks in the same year.

Tables 14.2 and 14.3 present the difference in means of the variables for households affected by health and weather shocks and those that were not, respectively, alongside their significance levels. The significance levels suggested that there were some differences between the two groups with respect to sociodemographic characteristics. For example, the average forest income for households that had been affected by health-related shocks was 3,427 Ethiopian Birr (190 USD), whereas it was 2,534 Ethiopian Birr (141 USD) for the households that had not been affected by the same shock. In terms of forest dependency, households affected by the shock earned 31% of their income from forests, while households not affected by the shock earned only 24% of their income from that source.

Table 14.2 also presents number of trips made to forest areas in order to fetch firewood. A significant difference was observed between households affected and not-affected by health-related shocks in trip frequency for fetching firewood. On average, households affected by health-related shocks made 92.9 trips to collect forest resources, whereas the non-affected households made only 70.6 trips. This trip frequency implies that households affected by health-related shocks were generally more dependent on forest resources than were the unaffected ones.

The findings from section 14.4.1 simply compared mean differences in the outcome variables and other sociodemographic variables between households that reported shock and those that did not.

14.4.2 Propensity score matching results

The results of the propensity score indicated that the education level of the household, age, land size, livestock ownership, and access to extension were associated with a higher probability of reporting shocks. Consistent with our results, Etile and Milcent (2006) and D'uva et al. (2008) indicated that people who are educated and have a good income are willing to report shocks. On the other hand, households with access to credit and awareness of climate change were associated with a lower probability of reporting shocks. This is also expected, because access to credit can improve households' abilities to cope with risks and reduce the risks that lead to health problems. Moreover, households that have awareness about climate change may use different adaptation strategies to cope with the changing climate and report less shock than their counterparts.

Before estimating the average treatment effects, we used the standardized bias differences between the treatment and control samples as a convenient way to quantify the bias between treatment and control samples as shown in Table 14.4. In many cases, we found that sample differences in the unmatched data significantly exceeded those in the samples of matched cases. The process of matching thus creates a high degree of covariate balance between the treatment (households affected by shock) and control groups (households not affected by shock), as used in the estimation procedure. The results before matching showed that several variables exhibited statistically significant differences, and after matching, the covariates were balanced. The density distributions of the propensity score for households affected by health and weather shocks and those that were not showed a good overlap. This suggests that the common support condition is satisfied (see Figure 14.4).

We also found low R^2 and insignificant likelihood ratio tests (see Table 14.5). This supports that both groups have the same distribution in covariate X after matching. These results clearly show that the matching procedure is able to balance the characteristics in the treated and the matched comparison groups. We, therefore, used these results to evaluate how covariate and individual shocks lead households to depend on forests.

14.4.3 Average treatment effects of shocks

Tables 14.6 and 14.7 show the results of the average treatment effects of the treated groups (ATT) that were estimated by the nearest neighbor and kernel matching techniques for the outcome variables along with average differences and T-values for treated and control groups,

Table 14.1 Variables and summary statistics of the sample households.

Variables	Descriptions and measurements	Mean	S.D
Treatment variable			
Ill_hhs	1 if the household is affected by health shock, 0 otherwise	0.19	0.39
Shock_freq	Frequency of the health shock in the household in 2010	2.12	1.17
Weather_shock	1 if the household is affected by weather related shock, 0 otherwise	0.79	0.40
Outcome Variables			
Forest _extraction	1 if the household participates in forest environmental resource extraction, 0 otherwise	84.9	0.36
Ntrips_forest	Number of trips per annum to forests by the household	74.8	51
Forest_sale	1 if the household participates in forest commercialization, 0 otherwise	0.33	0.47
Forest_dep	Share of forest income to the total household income	0.25	0.21
Hhh_sex	Sex of the household head (1 if male,0 otherwise)	0.85	0.36
Age_hh_1	Age of the household head in years	46.7	12.5
Edu_hhh	Education of the household head in years	1.17	2.18
Family_size	Number of household members per adult equivalent	5.74	2.11
Aware_cc	Awareness of climate change in the household(1= yes, 0 otherwise)	0.35	0.47
Male_adults	Number of male adult labour in the household	1.37	0.91
Female_adults	Number of female adult labour in the household	1.49	0.87
P_size _tsimdi	Plot size of land owned by the household in Tsimdi	4.36	2.93
TLU	Number of livestock owned by the household in TLU	3.11	2.59
t_assets	Total value of assets owned by the household	1315	2099
t_hh_income	Total household income in Ethiopian Birr	11859	9054
Fooda_months	Number of months in a year that the household had enough food stock	5.7	3.42
Jewelery	Ownership of jewelery in the household (1= yes, 0 otherwise)	0.33	0.47
D_health_post	Distance in minutes to the nearest health center	40.1	42.9
D_seasonal_road	Distance in minutes to the nearest seasonal road	9.1	14.6
M_hh_package	Household is a member of household package (1= yes, 0 otherwise)	0.18	0.37
Access_extension	Access to extension service (=1 yes, 0 otherwise)	0.84	0.36
N_ext_visit	Number of extension visit per year	7.79	9.92
Social_capital	Membership to any social network (1=1 yes, 0, otherwise)	0.50	0.50
D_transfer	Dummy if the household access to transfer (1=1 yes, 0, otherwise)	0.31	0.46
Access_irrigation	1 if the household has access to irrigation, 0 otherwise	0.14	0.34
Log_dis_forests	Log transformed distance to forests in minutes	1.71	0.83
Log_dis_market	Log transformed distance to markets in minutes	1.24	1.33
Locational variables			
Southern Zone	1 if the household lives in southern zone, 0 otherwise	0.41	0.49
South_Eastern	1 if the household lives in southern eastern zone, 0 otherwise	0.20	0.40
Eastern Zone	1 if the household lives in Eastern zone, 0 otherwise	0.39	0.48
Average rainfall in mm	Average rainfall in millimetre	589.4	100.5

Table 14.2 Mean Separation Test of households affected by health shock and households that were not.

Variable definition	Households reported health shock (n= 47)	Households did not report health shock (n= 204)	T-value
Age of household head in years	48 (1.660)	46(0.894)	0.446
Sex of household heads (=1 if male, 0, otherwise)	0.89(0.045)	0.83(0.03)	0.342
Family size of the household	6.1 (0.14)	5.7(0.30)	0.252
Number of female adult household members	1.83(0.153)	1.42(0.056)	0.003***
Number of male adult household numbers	1.43(0.113)	1.36(0.066)	0.646
Education of the household head in years	1.45(0.32)	1.10(0.15)	0.331
Ownership of land in Tsimdi (equals 0.25 hectare)	3.80(0.40)	4.48(0.21)	0.146
Log total household expenditure per adult equivalent	7.48(0.006)	7.52(0.034)	0.638
Access to irrigation (=1 if yes, 0 otherwise)	0.26(0.064)	0.11(0.022)	0.007***
Number of months that the household had enough food in a year	4.79(0.480)	5.91(0.240)	0.042**
Ownership of land in TLU	3.24(0.36)	3.08(0.18)	0.694
Forest income in Ethiopian Birr	3427(397.1)	2534(170.2)	0.027**
Participation in forest resource extraction (=1 if yes, 0, otherwise)	0.91(0.04)	0.83(0.02)	0.160
Participation in forest resource sale (=1 if yes, 0 otherwise)	0.40(0.07)	0.31(0.03)	0.236
Forest dependency (share of forest income to overall household income)	0.31(0.035)	0.24(0.014)	0.036**
Average number of trips to forest per annum	92.9(7.50)	70.6(3.52)	0.006***
Access to any transfer (=1 if yes, 0, otherwise)	0.43(0.07)	0.28(0.03)	0.051*
Access to household extension package loans (=1 if yes, 0, otherwise)	0.32(0.07)	0.13(0.02)	0.002***
Participation in the Productive safety net program (=1 if yes, 0, otherwise)	0.55(0.07)	0.70(0.03)	0.061*
Access to extension visit (=1 if yes, 0, otherwise)	0.81(0.06)	0.86(0.02)	0.397
Membership in any organization ((=1 if yes, 0, otherwise)	0.57(0.07)	0.49(0.04)	0.272
Mean annual rainfall in MM	558(12.13)	596(7.21)	0.020**
Awareness of climate change (=1 if yes, 0 otherwise)	0.47(0.074)	0.33(0.329)	0.071*
Distance to the nearest health centre in minutes	63.0(7.8)	34.8(2.7)	0.000***
Log distance to local market	3.98(0.177)	3.39(0.100)	0.010**
Distance to fuelwood collection	7.42(0.66)	10.39(0.47)	0.004***
Distance to seasonal road	17.8(3.39)	7.09(0.762)	0.000***
Distance to all weather road	46.4(6.96)	24.0(2.266)	0.001***

* Significant at 10%; ** significant at 5%, *** significant at 1 %

where treatment is defined as binary equals as one, if the household has been affected by health related shocks in 2010, and zero if otherwise. The results from both the matching algorithms produced consistent estimates of the treatment effects for health and weather shocks. Focusing first on the number of forest collection trips, the ATT reported in Table 14.6 indicated that vulnerability to health-related shocks exerts a positive and significant effect on the number of trips for forest collection. The difference in ATT for treated and control groups from the nearest neighbor and kernel matching results was found to be 18.3 and 22.4, respectively. The same results were found significant at the 5% and 1% levels, respectively, i.e., households that reported health shocks made 18.3 and 22.4 more trips to collect forest products, on average, than did the households who did not report health shocks

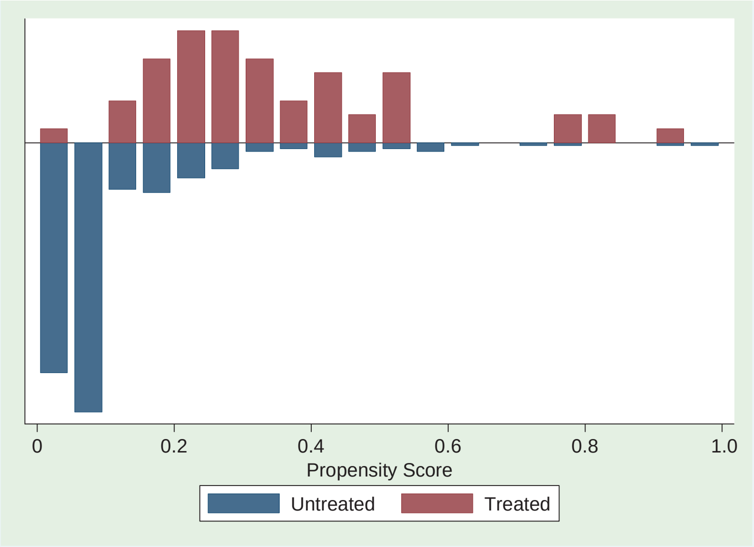

Figure 14.4 Distribution of propensity scores.

Table 14.3 Mean Separation Test of households affected by weather related shock and households that were not.

Variable definition	Households reported weather shock (n= 200)	Households did not report weather shock (n= 50)	T-value
Age of household head in years	46.2(0.86)	49(1.87)	0.153
Sex of household heads (=1 if male, 0, otherwise)	0.86(0.02)	0.80(0.05)	0.321
Family size of the household	5.92(0.14)	5.05(0.28)	0.009***
Number of female adult household Members	1.5(0.06)	1.47(0.10)	0.082*
Number of male adult household numbers	1.4(0.06)	1.25(0.13)	0.031**
Education of the household head in years	0.97(0.13)	1.94(0.42)	0.004***
Ownership of land in Tsimdi (equals 0.25 hectare)	4.57(0.21)	3.53(0.29)	0.023**
Log total household expenditure per adult equivalent	7.46(0.03)	7.68(0.67)	0.004***
Access to irrigation (=1 if yes, 0 otherwise)	0.14(0.03)	0.09(0.04)	0.383
Number of months that the household had enough food in a year	5.1(0.22)	8.1(0.48)	0.000***
Ownership of land in TLU	3.1(0.18)	3.1(0.36)	0.973
Forest income in Ethiopian Birr	2949(183)	1727(258)	0.002***
Participation in forest resource extraction (=1 if yes, 0, otherwise)	0.86(0.02)	0.78(0.05)	0.152
Participation in forest resource sale=1 if yes, 0 otherwise)	0.37(0.03)	0.17(0.67)	0.009***
Forest dependency (share of forest income to overall household income)	0.65(0.03)	0.41(0.07)	0.002***
Average number of trips to forest per annum	77.3(3.67)	64.9(6.59)	0.124
Access to any transfer (=1 if yes, 0, otherwise)	0.29(0.03)	0.35(0.07)	0.425
Access to household extension package loans (=1 if yes, 0, otherwise)	0.14(0.03)	0.27(0.06)	0.021**
Participation in the Productive safety net program (=1 if yes, 0, otherwise)	0.71(0.03)	0.53(0.07)	0.017**
Access to extension visit (=1 if yes, 0, otherwise)	0.85(0.03)	0.84(0.05)	0.903
Membership in any organization ((=1 if yes, 0, otherwise)	0.51(0.04)	0.49(0.07)	0.851
Awareness of climate change (=1 if yes, 0 otherwise)	0.37(0.03)	0.29(0.06)	0.313
Log distance to local market	1.44(0.09)	0.45(0.16)	0.000***
Distance to fuelwood collection	9.87(0.46)	9.69(0.84)	0.862
Distance to seasonal road	10.1(0.28)	4.47 (0.79)	0.011**
Distance to all weather road	3.27(0.11)	2.90(0.18)	0.121

* Significant at 10%; ** significant at 5%, *** significant at 1 %

Table 14.4 Propensity score and covariate balances.

		Mean		% reduction		t- test	
Variable	Sample	Treated	Control	% bias	|bias|	t	p>|t|
Propensity Score	Unmatched	0.4433	0.1784	121.8		8.98	0.000
	Matched	0.4433	0.4477	-2.0	98.3	-0.08	0.936
Age_hh_1	Unmatched	47.462	46.417	8.4		0.51	0.612
	Matched	47.462	49.212	-14.1	-67.6	-0.67	0.502
Edu_hhh	Unmatched	1.4615	0.9325	24.9		1.63	0.104
	Matched	1.4615	1.0192	20.8	16.4	1.12	0.264
Male_adult	Unmatched	1.3269	1.3374	-1.2		-0.07	0.941
	Matched	1.3269	0.9231	47.7	-3746.1	3.24	0.102
Female_adult	Unmatched	1.8077	1.3926	44.9		2.98	0.003
	Matched	1.8077	1.4615	37.5	16.6	2.03	0.045
D_asset	Unmatched	973.4	1333.6	-23.8		-1.36	0.174
	Matched	973.4	1039.3	-4.3	81.7	-0.27	0.782
Fin_asset	Unmatched	531.96	1691.3	-20.3		-1.04	0.299
	Matched	531.96	934.62	-7.0	65.3	-1.06	0.294
Log exp_per_capita	Unmatched	8.9775	8.9679	2.2		0.14	0.892
	Matched	8.9775	8.8705	24.0	-1011.7	1.32	0.189
Social_capital	Unmatched	0.5385	0.5092	5.8		0.37	0.715
	Matched	0.5385	0.6731	-26.8	-360.1	-1.40	0.165
Access_extension	Unmatched	0.7885	0.8712	-22.0		-1.46	0.146
	Matched	0.7885	0.8846	-25.6	-16.3	-1.32	0.188
Hh_ext_package	Unmatched	0.3269	0.0982	57.8		4.12	0.000
	Matched	0.3269	0.3654	-9.7	83.2	-0.41	0.684
CC_awareness	Unmatched	0.4423	0.2822	33.6		2.17	0.031
	Matched	0.4423	0.3077	28.2	15.9	1.42	0.159
D_transfer	Unmatched	0.3846	0.2883	20.3		1.30	0.194
	Matched	0.3846	0.2692	24.4	-19.9	1.25	0.214
Fooda_months	Unmatched	4.8077	5.7975	-28.2		-1.77	0.079
	Matched	4.8077	5.0385	-6.6	76.7	-0.36	0.718
Log_dis_forest	Unmatched	1.6432	1.7577	-14.2		-0.87	0.385
	Matched	1.6432	1.6829	-4.9	65.3	0.27	0.791
D_healthc	Unmatched	58.788	35.196	51.9		3.57	0.000
	Matched	58.788	66.827	-17.7	65.9	-0.77	0.442
D_wroad	Unmatched	44.365	27.785	40.9		2.79	0.006
	Matched	44.365	54.558	-25.1	38.5	-1.09	0.277
D_sroad	Unmatched	16.788	7.3252	54.0		4.12	0.000
	Matched	16.788	24.750	-45.5	15.9	-1.72	0.088

Note: Figures in bold are significant variables.

As shown in Panel B of Table 14.7, the second outcome estimated for the treated and control groups was forest dependency. This was also found to be positive and statistically significant, again implying that households affected by health shocks were more dependent on forest resources than the unaffected households. The difference in ATT for the treated and control groups was found to be substantial, i.e., the ratio of forest income to total household income for households that reported health shocks was higher than for the control households by 1.5 and 5.9 for nearest neighbor and kernel matching, respectively; and both results were significant, at the 10% level. However, despite positive differences in the ATT for both groups, we found the difference in forest sales insignificant. Similarly, Table 14.7 indicates that households that were affected by weather-related shocks travelled more frequently to forest areas and were more dependent on forest resources than were households that were not affected by weather-related shocks.

To check whether the results in Tables 14.6 and 14.7 were sensitive to unobserved selection bias, we conducted the Rosenbaum test. Critical values of Γ clearly indicated that even the unobserved heterogeneity would not alter the results, which suggested that the findings were generally insensitive to unobserved bias. As a result, we could conclude that the treatment effects as presented in Tables 14.6 and 14.7 were pure effects of the shock, which exerted dependency on forest resources.

Table 14.5 Other covariate balance indicators before and after matching.

Indicator	Sample	
Pseudo R2	Unmatched	0.24
	Matched	0.19
LR X2 (p-value)	Unmatched	56.51(0.001)***
	Matched	27.23 (0.175)

* significant at 10%; ** significant at 5%, *** significant at 1 %

14.5 Discussion and Conclusions

The chapter analyzed the role of forest resources in helping households to cope with covariate weather and idiosyncratic health shocks based on a broader array of outcome variables (i.e., forest dependency, forest sales, and number of trips to forests). Most of the variables were treated as exogenous variables by previous economic studies on the impact of shocks and coping mechanisms, in contrast to

Table 14.6 Differences in ATT for households affected by health related shocks and not affected.

Outcome	Matching algorism	E(Y) H = 1	E(Y) H = 0	Differences in average outcome (ATT)	P–value
PANEL A: Number of trips to forests per year					
Treatment : Dummy =1 if the household was affected by health related shocks, 0 otherwise					
Impact : Mean Impact					
Forest_trips	N-neighbor	92.9	74.6	18.3	0.010**
	K-matching	94.7	72.3	22.4	0.005***
PANEL B: Forest Dependency (Ratio of forest income to overall household income)					
Treatment : Dummy =1 if the household was affected by health related shocks, 0 otherwise					
Impact : Mean Impact					
Forest_dep	N-neighbor	31.0	29.5	1.5	0.086*
	K-matching	33.8	27.9	5.9	0.059*
PANEL C: Non-Poor Households					
Treatment : Dummy =1 if the household was affected by health related shocks, 0 otherwise					
Impact : Mean Impact					
Forest_sales	N-neighbor	61.7	40.4	21.3	0.242
	K-matching	56.8	39.0	17.8	0.299

Note: H = 1 and H = 0 refer to households that were affected by health shocks or not affected, respectively.

Table 14.7 Differences in ATT for households affected by weather related shocks and not affected.

Outcome	Matching algorism	E(Y) W = 1	E(Y) W = 0	Differences in average outcome (ATT)	P–value
PANEL A: Number of trips to forests per year					
Treatment : Dummy =1 if the household was affected by weather shocks, 0 otherwise					
Impact : Mean Impact					
Forest_trips	N-neighbor	77.3	64.9	12.4	0.012**
	K-matching	78.1	63.9	14.2	0.007***
PANEL B: Forest Dependency (Ratio of forest income to overall household income)					
Treatment : Dummy =1 if the household was affected by weather shocks, 0 otherwise					
Impact : Mean Impact					
Forest_dep	N-neighbor	65.6	41.2	24.4	0.008***
	K-matching	65.9	42.1	23.8	0.032**
PANEL C: Non-Poor Households					
Treatment : Dummy =1 if the household was affected by weather shocks, 0 otherwise					
Impact : Mean Impact					
Forest_sales	N-neighbor	49.3	31.9	17.4	0.621
	K-matching	49.6	32.1	17.5	0.016**

* Significant at 10%; ** significant at 5%, *** significant at 1 %
Note: H = 1 and H = 0 refer to households affected by health shocks and not affected, respectively.

this chapter, where propensity score matching (PSM) was used to account for, at the household level, factors that may be associated with the underlying shocks and labor allocation to the utilization of forests. On a broader and quite positive note, we found that forest resources appear to play a significant role in insuring the households against idiosyncratic health and covariate shocks.

In turn, if one looks into the definition of "insurance," it is considered a form of risk management primarily used to hedge against the risk of a contingent or uncertain loss. If all community members have to rely on forests as safety nets, but exploit the forest basis without proper longer-term investment in forest management, the strategy to rely on forests as insurance would not be sustainable. Therefore, for forests to play a role of insurance in a more sustainable way, farmers need to routinely invest in tree protection and planting. As climate change projections in the region and beyond would necessitate urgent actions for individual farmers and communities to collectively hedge against climate risks, further research is urgently required to facilitate forest-dependent farmers in adopting climate-smart sustainable forest management.

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15. Enhancing Climate-Smart Forest Management in Sub-Saharan Africa

Tefera Mengistu Woldie[a]* and Emiru Birhane[b]

Summary

Forests provide a number of valuable goods and services to a society. They are crucial for the well-being of humanity and provide the foundations for life on earth through ecological functions, by regulating climate and water resources, and by serving as habitats for plants and animals. In addition to their provision of recreation, spiritual, and other services, forests also provide a wide range of essential goods, such as wood, food, fodder, resins, medicines, etc. However, high returns from alternative land uses and lack of payments for the ecosystem services provided by forests provide incentives for deforestation, leaving forests at risk. Climate-smart forestry (CSF) offers an opportunity to adjust livelihoods to the new realities of climate change. Considerable efforts are required to enhance the concepts, knowledge, and capacities that would make CSF a reality, making sustainable development, with its role in making forests and landscapes productive, resilient, and sustainable, while contributing to climate change adaptation and mitigation, both possible and well-supported. The overall aim of this chapter is to elaborate on the principles of CSF management and demonstrate its potential for achieving multiple benefits in the Sub-Saharan African (SSA) context. Some examples of CSF approaches, which include sustainable forest management and agroforestry, are detailed as climate change adaptation and mitigation options.

Keywords: forest, climate change, adaptation, REDD+, deforestation

15.1 Introduction

More than 1.6 billion people around the world depend, to varying degrees, on forests for their livelihoods—not just for food, but also for fuel, livestock grazing, and medicine (Atrayee and Chowdhury 2013). At least 350 million people live inside or close to dense forests and are largely dependent on them for subsistence and income. About 60 million indigenous people are almost entirely dependent on forests (Bhargava 2006) and have a wealth of knowledge about forest resources.

Today, forests are under anthropogenic pressures from the increasing demands of land-based products and services, which frequently lead to the conversion or degradation of forests into unsustainable forms of land use. On the one hand, deforestation and degradation lead to increasing greenhouse gases (GHG) emissions and reducing woody carbon stocks. On the other, tropical tree growth and woody vegetation expansion may be counterbalancing these losses (Iain et al. 2018). When forests are lost or severely degraded, their capacity to respond positively to the impacts of climate change is also lost, which further exacerbates flood and erosion hazards, reduces soil fertility, and contributes to the loss of plant and animal life. The continued loss of forests makes people more vulnerable, and as a result, the sustainable provision of both goods and services from forests is jeopardized (Bishaw et al. 2013). People in Sub-Saharan Africa, who are disproportionately dependent on forest goods and services, are particularly vulnerable to the impacts of climate change.

There has been a wider discussion on the role of forests in climate change by the international community, national entities, and local institutions. In Africa, forests contribute

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[a] United Nations Development Programme, Congo Building,6- 7th Floor, ECA Compound, P.O. Box 5580, Addis Ababa, Ethiopia

[b] Mekelle University, Department of Land Resources Management and Environmental Protection, P.O. Box 231, Mekelle, Ethiopia

* *Correspondence:* Tefera Mengistu (email: teferamengis2@gmail.com)

to the long-term social and economic development goals of the continent. They provide energy, food, timber, and non-timber forest products and hence play an important role in human wealth and health at the household, community, national, regional, and global level. Increasing pressure linked to deforestation and forest degradation is known to be causing widespread loss of biomass and localized extinction of important species, although there are uncertainties concerning these losses (Iain et al. 2018). In the continent of Africa, where half of the world species of flora and fauna are present, shifting cultivation is thought to be a significant source of carbon to the atmosphere (Iain et al. 2018). Therefore, managing forests in a climate-smart way is necessary. Climate-smart forestry (CSF) offers an opportunity to contribute to making forests and landscapes productive, resilient, and sustainable while contributing to climate change adaptation and mitigation.

However, CSF interventions in Africa are highly limited, while in the meantime, climate change is jeopardizing the delivery of goods and services from forests that are essential for livelihoods, environmental sustainability, and national development (Ravindranath et al. 2006). Although Africa contains about 16% of the world's forests (Eastaugh et al. 2010), there appears to be a shortage of Africa-specific climate change research and a lack of sufficient African input in global discussions. Consequently, this may cause Africa to face particularly high impacts from climate change (Collier et al. 2008). Considerable efforts are required to enhance the knowledge and capacities that would make CSF a reality. An assessment of the likely impacts of climate change on forests and forest-dependent people is, therefore, important for achieving effective climate change adaptation and mitigation strategies. Such an assessment can also assist in developing options for avoiding the harmful effects of climate change and enhance ways to take advantage of the opportunities it provides.

The focus of this chapter is on the importance of CSF. We start by reviewing the impact of climate change on forest resources and the role of forests in climate change mitigation and adaptation. The chapter then introduces CSF principles, as well as management options, and discusses enabling conditions for the achievement of climate-smart forestry practices.

15.2 Climate Change and Forests

15.2.1. Impact of climate change on forests

Recent climate change has had widespread impacts on human and natural systems (IPCC 2014). In Africa, for example, the projected ranges of warming are from 0.2 °C to more than 0.5 °C per decade coupled with a 5% to 20% increase in precipitation in wet months and a 5% to 10% decrease in precipitation in dry months (IPCC 2001). Climate change affects all aspects of human existence and food security, particularly through its impact on ecosystems. The effects of the climate change, such as rising temperatures and changes in precipitation, are undeniably clear, and are already affecting forest ecosystems and their biodiversity in Sub-Saharan Africa (WWF 2006). Climate change in eastern and southern Africa has caused repeated droughts and has affected vegetation patterns, distributions, and structures in the region. For example, deforestation in Ethiopia alone is estimated at 92 thousand ha/year (MEFCC 2013). This, in turn, has fundamental impacts on the livelihoods of millions of forest-dependent people in the country.

Climate change significantly affects vegetation patterns globally, and thus influences the distribution, structure, and ecology of forests. Changes in climate also alter the configuration of forest ecosystems and result in drastic changes in their composition, structure, distribution, and productivity (Ravindranath et al. 2006). The world's climate system and forest ecosystems are inextricably linked, and consequently, changes in either one of these systems inevitably trigger feedback in the other (Eastaugh et al. 2010).

Furthermore, climate change aggravates existing stresses derived from non-climate factors. Forests face both deforestation and degradation challenges as a result of human pressures, which include extensive farming and dependency on forest resources for fuelwood and construction materials. According to FAO (2010), about 11% of Ethiopia's land area (0.13 million km^2) is forested, while the annual rate of deforestation remains at 1.1% (Figure 15.1). Recently, the expansion of croplands has reached its upper limit, to the extent that even marginal lands have now become cultivated lands in the Ethiopian highlands (Reid et al. 2000). Gross anthropogenic pressure and its resultant emissions, from African woodlands alone, is equivalent to 4% to 10% of the current estimated tropical land use emissions, limiting the ability of these woodlands to respond positively against the impacts of climate change (Iain et al. 2018). In conclusion, implementing forest-related initiatives towards climate change mitigation and adaptation requires a comprehensive approach supported by sound policies and appropriate legislative and governance frameworks (FAO 2017).

15.2.2 The role of forests in climate change

Forests and trees provide a range of forest products and ecosystem services. Forest ecosystems play crucial roles

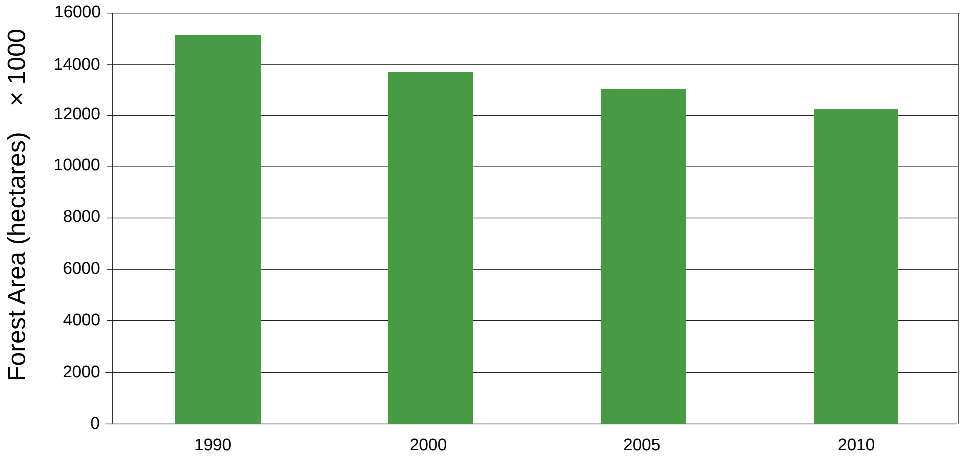

Figure 15.1 National forest cover change in Ethiopia since 1990 (MoA 2013).

in climate regulation through biophysical and chemical processes that control fluxes of air, energy, water, and atmospheric constituents. Forests also play an important role as a sink for carbon dioxide through the assimilation of carbon during photosynthesis, and hence can be used to mitigate global warming, if proper mechanisms are put in place. It is estimated that the total global forest biomass contains more than 80% of all global carbon contained in aboveground biomass, while forest soils contain more than 70% of the carbon contained in soils (Six et al. 2002). Tropical soils are also important carbon stores for about 36% to 60% of ecosystem carbon (Dixon et al. 1994, Malhi et al. 1999). Moreover, the soils of high altitude tropical ecosystems play a significant role in the global terrestrial carbon cycle because of their large stock and potential sensitivity to climate change (Post et al. 2009, Yang et al. 2010).

Human activities are driving widespread and rapid changes in woody biomass cover in Africa, with important implications for both the global carbon cycle and local livelihoods. Across the African region, there exists highly dynamic land cover change, with rapid deforestation and degradation underway in hotspots around population centers. Rising populations and mostly stagnant crop yields are thought to be driving horizontal expansion of agriculture and widespread deforestation. Therefore, the immediate higher returns from agriculture provide incentives for land-use changes, leaving the remaining forests at risk. Moreover, although the carbon dynamics of the continent show higher spatial variation, Africa is facing forest degradation (a reduction in woody carbon density), often due to local timber harvesting or fuelwood harvesting (Iain et al. 2018).

On the other hand, investments for cash crops are pushing the boundaries of forest and woodland resources. Forests are usually cleared because there is money to be made from doing so. For instance, the Amazon forest is being cleared primarily due to agricultural expansion for cattle and soybean farming. In Asia, most of the tropical forests are under pressure because of conversion to plantations of oil palm and of fast-growing timber trees as inputs to the pulp industry (Kanninen et al. 2007). In Africa, deforestation is mainly caused by land-use changes for shifting agriculture. Consequently, in the tropics, conversions of primary forest into croplands and perennial crops result in the highest soil organic carbon (SOC) loss, at levels of 25% and 30%, respectively (Don et al. 2011). The conversion of forests into grasslands also reduces SOC stocks by 12% (Don et al. 2011). In central Africa, for example, forest degradation is responsible for the release of more carbon to the atmosphere than any other source, with 73% of total carbon released through land-use changes (Gaston et al. 1998).

Human influence on the climate system is clear, and recent anthropogenic emissions of GHG are the highest in history. Deforestation and degradation have been attributed to the increased release of GHG into the atmosphere. The latter, which has never been quantified at scale in a spatially explicit manner, is the main cause of biomass loss, being particularly prevalent in higher biomass areas, which are often floristically diverse and of high conservation value. The gases emitted both due to deforestation and degradation include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFC), and sulphur hexafluoride (F_6S) (Forster et al. 2007). Although the global historical highs in the emission of these gases are associated with the industrial revolution (Figure 15.2, source: IPCC 2001), deforestation/degradation-based emissions

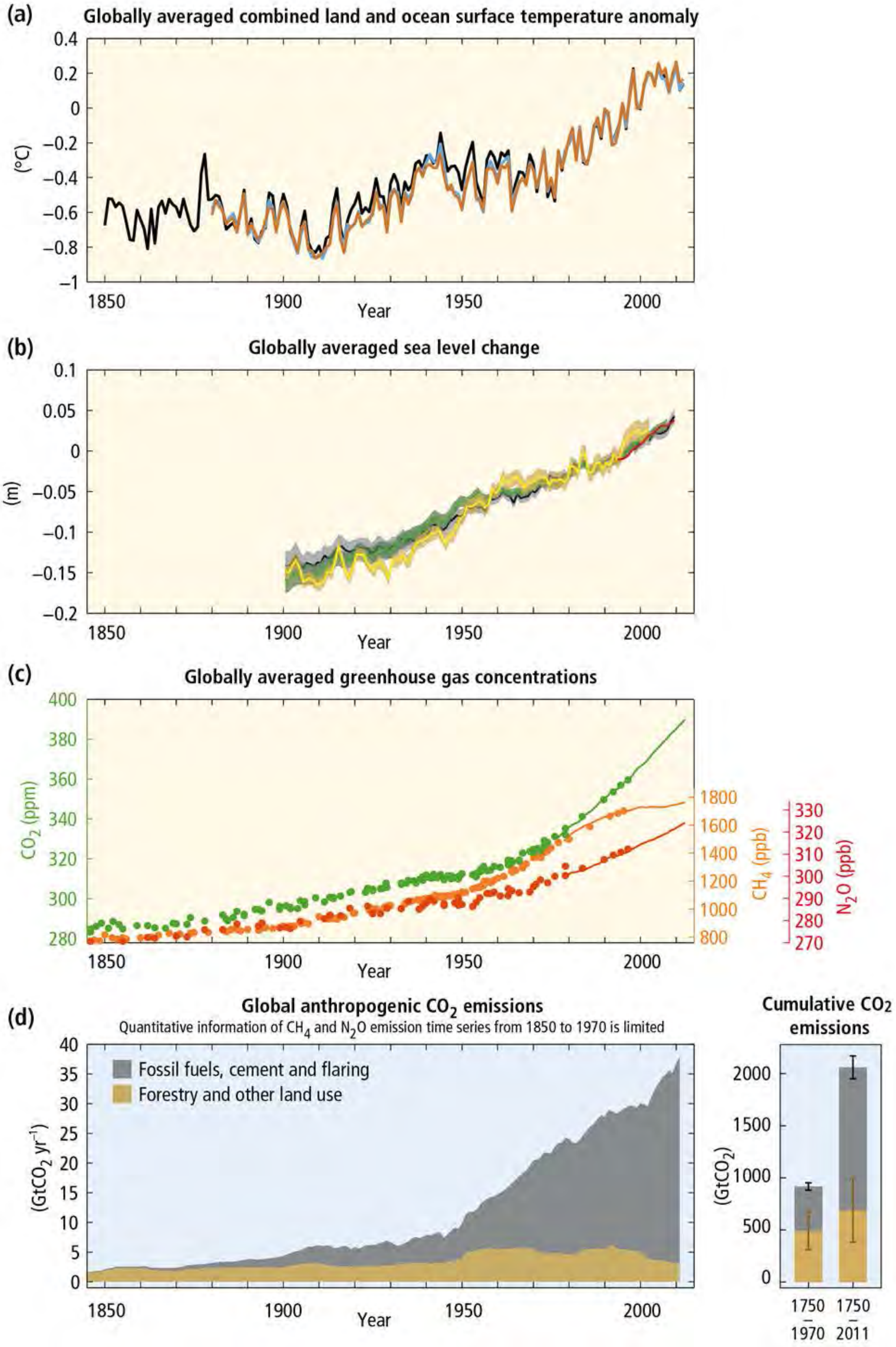

Figure 15.2 The complex relationship between the observations (panels a, b, c, yellow background) and the emissions (panel d, light blue background). Source: Intergovernmental Panel on Climate Change (year 2014).

are increasingly becoming significant sources of GHG emissions to the atmosphere, and are large enough to impact the global climate pattern. If the GHG stored in forests are released, it will take generations to recapture them. So, if large areas of forests continue to be lost, we could then find ourselves in a difficult situation: A self-perpetuating, positive feedback loop will be created, in that more carbon emissions could lead to a warmer climate, which in turn could lead to more frequent droughts and forest fires, resulting in the release of even more CO_2, which could lead to an even warmer climate.

15.2.3 Making forests climate smart

African savanna woodlands not only retain significant biomass, but also are uniquely challenged by large degradation losses (Iain et al. 2018). Many communities in Africa have experienced much environmental change in the past, and consequently, they have developed indigenous coping strategies. These strategies may, however, be inadequate for dealing with the speed and scale of the projected climate change. Moreover, poverty adds significant pressure on such communities and their coping mechanisms. Forest-based livelihoods can play an important role in achieving broader climate change adaptation goals (Eastaugh et al. 2010). They are not, however, the only remedy, and should be pursued with other measures, including a shift to low-carbon energy, crop, and livestock production systems. Forest-based livelihoods will also augment the delivery of other forest-related services to other sectors. In order to make forests and forest-based livelihoods climate smart and contextually fit the needs of local communities, the following key CSF activities should be undertaken to make the sector more productive, resilient, and sustainable, while contributing to the emerging challenges of climate change. Therefore, it becomes necessary to manage forests sustainably to reduce deforestation and degradation while reversing the current trends of forest ecosystems loss. This will also help to make forestry responsive to the complementary role of climate change adaptation and mitigation benefits. Adaptation deals with the consequences of climate change, while mitigation deals with the causes. The following sections elaborate the principles of CSF from both climate change adaptation and mitigation perspectives and provide examples of CSF management options.

15.3 Climate-Smart Forestry Principles

15.3.1 Climate change adaptation

In the forest sector, adaptation encompasses changes in management practices and interventions designed to decrease the vulnerability of both forests and forest communities to climate change (FAO 2017). Improving adaptive capacity of forest-dependent communities is important in order to reduce their vulnerability to the impacts of climate change. The Intergovernmental Panel on Climate Change (IPCC) defines adaptation to climate change as "an adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities." Many adaptation strategies focus on strengthening the ability of a system to absorb the disturbances caused by climate change and to capture the benefits arising from it, or on increasing the degree to which a system can cope with climate change. Adaptation strategies can help people manage the effects of climate change and protect their livelihoods. Moreover, the adaptive actions can restore and conserve biodiversity and are also considered a means of increasing ecosystem resilience to climate change.

The inclusion of effective climate-change adaptation strategies in forest management plans may require diversified local options. For example, having enough forest in watersheds slows soil erosion (anticipating the more intense rainfall that climate change may provoke), and preserving corridors of forest enables wildlife and plant species to move into suitable climates and creates buffer zones to stop the spread of forest fires. Planting tree species that tolerate higher temperatures and extreme weather events is another effective climate change adaptation strategy.

When undertaking climate change adaptation actions, it is essential to involve indigenous/local people in forest management decisions, which will ensure that their rights are recognized and respected. Participatory approaches should be used to obtain a better understanding of local knowledge and to raise awareness about vulnerabilities and related adaptation measures. Information on vulnerabilities to and impacts of climate change at the local level is generally lacking. It is, thus, critically important to increase the awareness of local communities on the impacts of climate change and strengthen local institutions and governance processes in order to enhance their capacities in making sound forest-related decisions. Moreover, relevant information on the impacts of climate change and adaptive management on forest and related sectors should be developed and integrated into the curricula and programs of educational systems.

As part of adaptive management, forest managers should have various tools and options for managing the emerging challenges facing forests at various scales—from large regions to individual forest stands. If appropriate adaptive measures are not implemented, the impacts of climate change could alter forests in many ways, including changing local biodiversity and many of the services available from forests. Therefore, it is critical to implement forest adaptation measures that involve a process of observation, analysis, planning, action, monitoring, reflection, and new action (Figure 15.3). Forest-based climate change adaptation measures require an evaluation consisting of various steps:

1. Explain how forests are affected by climate change, as well as the role forests play in climate change adaptation.
2. Identify priority forest-based activities that could help with climate change adaptation.
3. Apply the various climate change adaptation strategies.
4. Analyze the challenges facing the adaptation actions.
5. Analyze forests' response to climate change.
6. Design new forest-based adaptation strategies/ measures.
7. Assess, monitor, and evaluate forest-based adaptation mechanisms.

15.3.2 Climate change mitigation

Deforestation and forest degradation are often attributed to the high immediate returns from alternative land uses. Therefore, it becomes crucial to identify critical external drivers of deforestation in order to come up with appropriate alternative options.

15.3.2.1 Reducing deforestation

Deforestation, defined as the conversion of forest land to another land use, is a significant feature of global environmental change (FAO 2010). In addition to deforestation, other global anthropogenic changes, such as loss of biodiversity, land-use change, and climate change, have impacted the world's forest resources. The high rates of tropical deforestation have severe consequences, such as loss of biodiversity, flooding, siltation, and soil degradation. Furthermore, tropical deforestation poses threats to the livelihoods and cultural integrity of forest-dependent peoples, as well as to the supply of timber and non-timber forest products for future generations. Moreover, deforestation and the degradation of forest ecosystems are major sources of GHG emissions worldwide. The conversion of natural forest and woodlands together, particularly in the tropics, is estimated to account for 17.3% of global GHG emissions, and thus represents a major contribution to anthropogenic climate change (IPCC 2007).

Along with the new appreciation for the role of forests in climate change mitigation and adaptation among policy makers and the general public, there has been a renewed interest in understanding the drivers of deforestation and forest degradation. The drivers of deforestation result from various causes, most of which originate from outside of the forest sector. Understanding these causes is crucial because it assists with identifying appropriate incentives for curbing deforestation.

The central idea behind reduced deforestation is to achieve reductions of GHG emissions from forests and enhance the global carbon sink in a world that is undergoing rapid industrialization and land-use changes. A national strategy for reducing deforestation and forest degradation can help to deploy various policy instruments in order to achieve goals such as the following:

1. Reform sectoral polices in forestry, agriculture, energy, and other sectors in order to reduce deforestation and forest degradation and transition into other land uses, and introduce decentralization and broader cross-sectoral reforms, like tenure.
2. Introduce decentralized forest ownership and develop performance-based payments for carbon sequestration services, i.e., to pay forest owners and users for reduced emissions or increased carbon sinks.

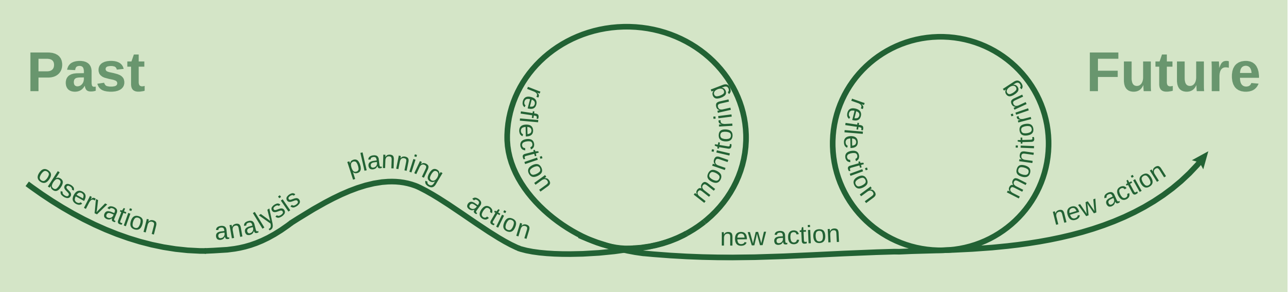

Figure 15.3 Frameworks for Adaptive Management (Source: Colfer 2005).

3. Develop national programs for promoting various forestry actions.
4. Avoid resettlement in degraded areas or productive farmlands.
5. Limit large-scale agricultural investment in areas of natural forests in search of fertile lands.

Policies, projects, and interventions of Reduced Emissions from Deforestation and Forest Degradation (REDD+) are among the most prominent of the recent attempts to mitigate the impacts of climate change (Agrawal et al. 2011). REDD+ is a policy approach that includes positive incentives on issues related to the reduction of emissions from deforestation and forest degradation in developing countries. Such interventions include a set of processes and measures through which financial incentives are offered to countries with tropical forests for their demonstrable and result-based reductions in emissions caused by deforestation and forest degradation and for their efforts to address the role of conservation, sustainable forest management, and the enhancement of forest carbon stocks (Agrawal et al. 2011). Such mechanisms allow fewer forests to be converted to other uses and instead favor more protection for existing forests, which are to be managed in a way that enhances forest carbon stocks, supported through forest-landscape restoration and other activities.

15.3.2.2 Reducing forest degradation

Reduced services and production capacities of forest resources are considered part of forest degradation and are related to reduced canopy cover, ecological function, carbon stocks, forest products, and other measurable attributes of forest and species composition. The partial loss of biomass due to logging or other causes of biomass removal is also part of forest degradation. Degradation, which has never been quantified at scale in a spatially explicit manner, is the main cause of biomass loss, being particularly prevalent in higher biomass areas, which are often floristically diverse and of high conservation value (Iain et al. 2018). Large degradation losses are unique features of many forest resources. Monitoring degradation is more technically challenging than monitoring deforestation because in many cases, degradation may not be clearly observed. Many forest resources may appear physically present and as expected, although they may be functionally and biologically degraded. Such degradation has contributed significantly to carbon emissions. In central Africa, for example, forest degradation is responsible for the release of more carbon to the atmosphere than any other source, and 73% of total carbon released has come through land-use changes (Gaston et al. 1998). Therefore, reducing forest degradation will contribute significantly to the development of CSF in many countries.

15.4 CSF Management Options

15.4.1 Sustainable forest management (SFM)

Forests are socio-ecological systems that deliver important ecosystem goods and services (FAO 2017). Sustainable forest management, therefore, serves both the forest ecosystems and the people and societies that benefit from the provision of ecosystem services. Sustainable forest management (SFM) is a universally accepted concept that guides forest policies and practices (FAO 2017), provides a foundation for climate change mitigation and adaptation, and contributes to food security through various means. SFM includes establishing, restoring, and managing forests for the benefit of both people and the environment. SFM may enhance the storage of carbon on-site while at the same time enabling a sustainable flow of forest products—and these options do not necessarily conflict (Bishaw et al. 2013).

SFM is a continuously evolving concept designed to ensure that forests continue providing a range of ecosystem services. Planting schemes that involve using tree species and varieties that are both adapted to the local climatic conditions and valued by local communities are vital. The development and implementation of these adaptation measures as part of SFM needs to be underpinned by modes of governance that are sensitive to context, take a broad view of community needs, and respond quickly to policy changes. Governance that enables effective stakeholder and community participation, transparency, and accountability in decision-making, land security, and ownership, and the equitable sharing of benefits and responsibilities is needed. In addition, a clear definition of forest and tree tenure is important for achieving SFM benefits and climate change adaptation and mitigation measures. Clarity on the ownership of forest carbon and the rights to trade it is also important and plays a role in incentivizing future forest carbon projects.

15.4.2 Agroforestry

Agroecosystems, as proposed by Schutter (2010), should mimic nature as much as possible through a range of techniques that increase sustainable yield. If properly implemented, agroforestry systems can contribute toward "climate-smart livelihood systems" by improving sustainable productivity and strengthening the resilience of farmers' livelihoods, while at the same time increasing carbon sequestration (Bishaw et al. 2013).

Agroforestry is an ecologically sound farming practice that integrates trees into farming systems in order to increase agricultural productivity and ameliorate soil fertility, control erosion, conserve biodiversity, and diversify income for households and communities (Bishaw et al. 2013). Although many components of agroforestry can be considered core climate smart practices, there are relatively few studies that clearly show how agroforestry systems contribute to managing climate (Bishaw et al. 2013). Agroforestry provides multiple benefits, including adaptation and mitigation against climate change. Agroforestry, including the use of perennial crops as well as the maintenance of shrubs and trees on farm landscapes, improves soil resilience and health and provides diverse products (e.g., food, fuel, fiber, resin and gum, timber) while supporting ecosystem services. Moreover, it contributes to the prevention of soil erosion, facilitates water infiltration, and diminishes the impacts of extreme weather while providing diversified income and livelihood options. Agroforestry systems that integrate compatible leguminous shrubs and trees with crops facilitate increased soil organic carbon and nitrogen, enhance diversity, build healthier soils, and enhance crop and fodder production. Smallholder farmers in developing countries are adopting agroforestry because it diversifies production and livelihoods through efficient utilization of resources, such as nutrients, by integrating legumes with crops or is compatible with mixed crop-livestock systems (Figure 15.4). For example, nitrogen-fixing leguminous trees, such as *Faidherbia albida,* increase soil fertility and yields by helping nitrogen fixation through the symbiotic Rhizobium and leaf litter (Garrity et al. 2010). Some species provide fruits, timber, and biofuels

Figure 15.4 Agroforestry practice in Dilla Zuria district of Gedeo Zone, SNNPR, Ethiopia.

(liquid and solid biofuels). They can also enhance ecological resilience by reducing erosion and providing water quality and habitat benefits through shade and deep rooting.

Many land management systems (e.g., agroforestry) are climate smart practices, which provide multiple benefits to local communities. Among other things, these practices increase carbon content of the soils and aboveground biomass and enhance productivity and societal resilience to climate change (Sara et al. 2012). Sustainable intensification with diversification offers important opportunities for mitigating climate change by decreasing deforestation, rehabilitating eroded soils, and reducing pressure on surrounding natural ecosystems.

Agroforestry measures assist in preventing forest degradation by enabling farmers to produce wood on their croplands, which reduces the pressure placed on forests. Another benefit of agroforestry systems is that they use less fertilizer, and in doing so, reduce emissions, including both the direct N_2O and indirect GHG emissions created by fertilizer production. Moreover, agroforestry increases carbon sinks by increasing above- and belowground biomass. Carbon projects are enhancing the development of agroforestry practices, although the carbon sequestration potential of agroforestry varies widely, depending on the specific practice, individual site characteristics, and the time frame. In addition to carbon storage, agroforestry systems also provide substantial environmental services beyond the areas where they are practiced. Agroforestry systems that include valued tree and plant species (which may become increasingly rare in natural forests, due to climate-induced changes in forest structure) are also an important part of climate-smart forestry.

15.4.3 Community forestry and community-based forest management

The concept of a community forestry, which can support mitigation by increasing carbon stocks in biomass and soils (FAO 2017), is a unique approach to conventional forestry practices. If properly implemented, it will provide positive incentives for communities to consider communal forest establishment and management as an alternative livelihood opportunity. Moreover, communities may be able to participate in the global carbon market and gain additional income from selling carbon credits to re-invest in best forest management options. Community forestry schemes may enhance the interests of forest resource users in protecting and managing their forest, eventually leading to better forest governance and employment opportunities, while at the same time, increasing income from timber and non-timber forest products. This has encouraged many rural communities to engage in community forestry schemes as an alternative livelihood strategy. By diversifying income from both wood and non-wood forest products and services, this type of system strengthens the links between forest ecosystem services and the needs and livelihood strategies of the people. Community forestry and community-based forest management, therefore, contribute to climate-smart forestry, which helps to make livelihoods more adaptive to climate change, while contributing to mitigation efforts.

15.5 Conclusion

Forests provide a wide range of products and are the foundations for life on earth through ecological functions and services. Conversely, forests are under pressure from the increasing demands of land-based practices, which frequently lead to the conversion or degradation of the forest resource. In order to address this pressure, CSF production and management is an essential option to be considered for reducing the vulnerability of people and forests to climate change. Failure to implement CSF limits not only the capacity of forests and people to adapt to climate change but also the contribution of forests to climate change mitigation. Therefore, nations should strive to integrate CSF options into their policies, strategies, and practices using flexible approaches that fit local situations. Moreover, efforts for a transition to CSF must take place at various levels and spatial scales. Further, the planning and implementation of CSF, tailored to the local circumstances, should involve all stakeholders and address equity issues, including gender.

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PART V. Tailoring Climate-Smart Approaches to Livelihood Contexts to Enhance Adoption and Scale-up

Photos (clockwise, from top left): tending to agroforestry fruit trees, in Abraha Atsbeha village, Tigray Region, Ethiopia (by Miyuki Iiyama); girls transporting seedlings for tree-planting program in East Gojam, Amhara Region, Northern Ethiopia (by Aklilu Negussie); hired day workers on private vegetable farm in East Shoa, Oromia Region (by Aklilu Negussie); and salt mining and trading as off-farm income for Afar and bordering regions, Eastern Ethiopia (by Aklilu Negussie).

16. Constraining the Constraints: Factors Affecting Farmers' Investment in Climate-Smart Land Management

Zenebe Adimassu*

Summary

Increased agricultural productivity and food security in Ethiopia are highly dependent on the status of the natural resource base and how natural resources are managed. Available evidence suggests that climate change coupled with land degradation expressed in the forms of soil erosion and nutrient depletion, among others, present threats to food security and the sustainability of agricultural production in Ethiopia. Reversing land degradation on one hand while improving land productivity on the other lies at the heart of the broader imperative for sustainable agricultural production under smallholder agriculture. Despite decreasing land productivity, increasing land degradation, and climatic and socioeconomic changes (e.g., population growth), farmers' widespread adoption of climate-smart land management (CSLM) technologies, practices, and investments is limited. This chapter discusses several key biophysical, social, economic, and policy constraints that affect farmers' investments in the adoption of CSLM technologies and practices. These constraints are classified into three broad categories: capacity to invest (e.g., landholding, labor, finance, and physical capital); incentives to invest (e.g., net and relative returns, risks, discount rate, and biophysical factors); and external factors (e.g., technology, extension services, land policy, political instability, and infrastructure programs) to better contribute to guiding and facilitating a design of informed policies. Finally, the chapter concludes that there is a need for co-investments from multilevel stakeholders in order to achieve the objectives of CSLM in Ethiopia. These actions will, therefore, enhance agricultural production and food security of smallholders while contributing to the climate change adaptation and mitigation agenda.

Keywords: constraints, land management, investments, stakeholders, determinants

16.1 Introduction

Most countries of Sub-Saharan Africa (SSA) depend on the natural resources base for their food, social, and environmental security (Shiferaw and Holden 2001). Because of different human-caused and natural disasters, many countries in SSA are increasingly experiencing the impacts of climate change, which severely affect agricultural production, and consequently, food and nutrition security (Reij and Smaling 2008). Available evidence further suggests that land degradation in the form of soil erosion and nutrient depletion presents an increasing threat to the productivity and sustainability of agricultural production in SSA (Lal 1985, Lal and Singh 1995, Reij and Smaling 2008).

The impacts of land degradation, coupled with climate change, on agricultural production and livelihoods are especially severe in Ethiopia, whose agriculture sector is dominated by rainfed, resource-constrained smallholder systems (Shiferaw and Holden 2000, Descheemaeker et al. 2006, Kassie et al. 2008). Smallholder farmers in Ethiopia are, therefore, urged to take immediate actions to reverse the threats of land degradation and adapt to climate change in order to improve land productivity, which lies at the heart of the broader imperative for sustainable agricultural production (Barrett et al. 2006). In addressing land degradation and climate change challenges, governmental and non-governmental agencies have so far invested substantial resources in promoting sustainable land management practices (Adimassu et al. 2018). These practices, considered climate-smart land management (CSLM) practices, have been expected to contribute to rehabilitating degraded lands; ensuring sustainable and increased agricultural production (Nyssen et al. 2000);

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* International Water Management Institute (IWMI), C/O: ILRI. PO. Box. 5689, Addis Ababa, Ethiopia
Correspondence email: zenebeteferi@yahoo.com, z.adimassu@cgiar.org

mitigating climate change impacts; ensuring economic growth; and reducing poverty (Deininger and Ali 2008). Unfortunately, however, the capacity of Ethiopia's farmers to adopt CSLM has been generally limited over the past decades (Reardon and Vosti 1995, Reardon et al. 1996, Adimassu et al. 2012).

There are many complex and interrelated issues that contribute to the current limited investment in CSLM in Ethiopia (Pender and Kerr 1998, Deressa et al. 2008, Bryan et al. 2009, Reardon and Vosti 1995, Reardon et al. 1996). There have been several studies which attempted to identify major factors affecting farmers' capacity for investments in CSLM (e.g., Adimassu et al. 2015, Adimassu et al. 2012, Amsalu and De Graaff 2006, De Graaff et al. 2008, Kassie et al. 2008, Shiferaw and Holden 2000). The identified factors included the characteristics of households (e.g., gender, education, experience, etc.), characteristics of plots (e.g., size, slope, fertility condition, etc.), and policies and institutional support (e.g., land tenure, access to training, etc.). However, the results were often inconsistent, while much evidence remains undocumented.

Concrete evidence is needed to guide and facilitate a design of informed policies. This chapter attempts to present a comprehensive synthesis of evidence on the factors that affect farmers' investments in CSLM practices in Ethiopia by reviewing study reports and other sources. This chapter proposes to classify these factors into three major categories: incentive to invest, capacity to invest, and external factors (Figure 16.1), which could enhance adoption of CSLM technologies and practices in Ethiopia.

16.2 Incentives to Invest in Climate-Smart Land Management

For farm households to invest in CSLM, they need to have incentives, such as economic benefits from the investment. Incentives, specific to the households' investment, depend on net returns/profitability of investments, relative returns, riskiness, the households-specific discount rate, and the biophysical environment (Reardon and Vosti 1995, Reardon et al. 1996, Clay et al. 1998), which will be reviewed and discussed respectively.

16.2.1 Net returns

Net return is one of the most important factors governing investments in land management technologies (Pampel and van Es 1977, Ervin and Ervin 1982). If the costs of land management practices exceed the short- and long-term benefits, then farmers have no incentive to adopt the technologies (Camboni and Napier 1994, Cary 1994). Net return of a given investment depends on the yield and input requirements per unit of output and the prices of inputs and outputs. Leaving aside the question of capacity constraints, the better the net return of a potential investment in land management technology, the greater the probability of farmers to invest in the technology (Adimassu et al. 2018, Adimassu et al. 2012). As farmers in Ethiopia are sensitive to net returns, they implicitly compare the expected costs and benefits and then invest in options that offer the highest net returns, either in terms of income or reduced risk (Shiferaw et al. 2007, Zainab and Folmer 2000). Moreover, farmers' decisions to invest in land management are affected by the (perceived) profitability of a technology (Napier 1991, Napier et al. 1998, Kelly et al. 2003, Langyintuo and Dogbe 2005, Crook and Decker 2006, Diagana 2007, Getnet 2008). This is substantiated by studies in Tanzania and Ethiopia on adoption and continuous use of stone terraces, which revealed that farmers' investments are highly influenced by the (perceived) profitability of the technologies (Tenge et al. 2004, Amsalu and De Graaff 2006, De Graaff et al. 2008).

16.2.2 Relative returns

Farmers may consider investing in a technology (relative to alternative farm and non-farm investments) when the investment is likely to be profitable, although it may not be sufficiently attractive to motivate them to invest. Some studies reported that the availability of off-farm income has negative impacts on farmers' investments in land management technologies (Pender and Kerr 1998, Shiferaw and Holden 1998, Mbaga-Semgalawe and Folmer 2000, Gebremedhin and Swinton 2003, Holden et al. 2004, Tenge et al. 2004, Amsalu and De Graaff 2006, Mduma 2007). The studies argued that the negative impacts of off-farm activities on investment in land management technologies are because of two reasons. The first reason is that available off-farm activities provide opportunities for household workers to choose to allocate their family labor toward off-farm activities, where it fetches higher returns than on-farm land management. The second reason is that off-farm employment often directly overlaps with the slack season, when land-management activities are undertaken, and this reduces the labor available for land-management practices. However, the result of this variable (relative return) is not consistent. For example, there are conditions in which off-farm earnings are reinvested in land management technologies (Reardon and Kelly 1989, Clay and Reardon 1995, Clay et al. 1995, Kelly et al. 1995). The cash generated from off-farm income can be used to

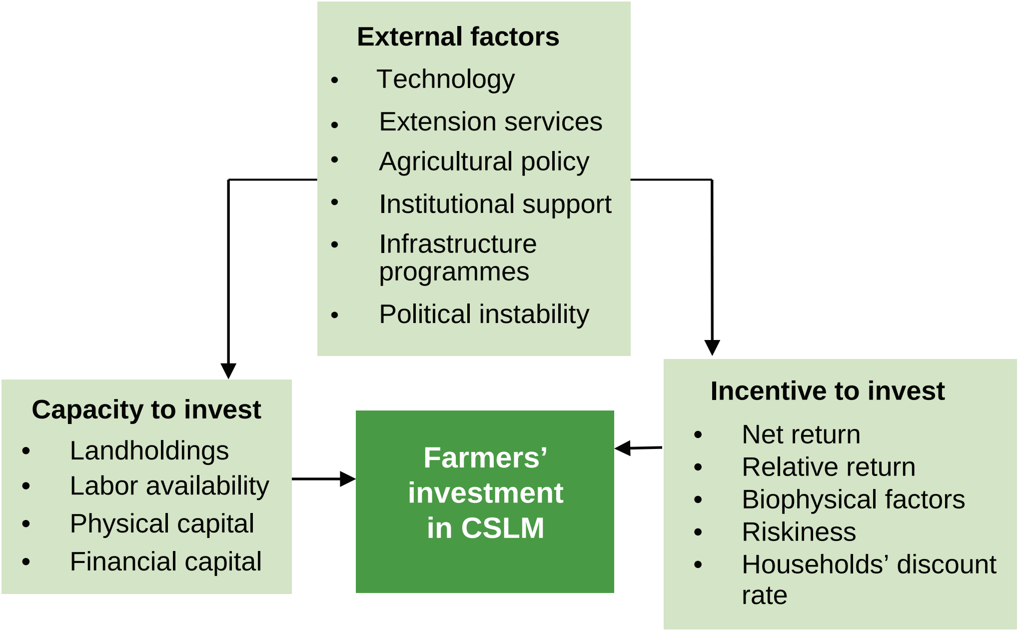

Figure 16.1 Schematic presentation of the key factors affecting farmers' investment in climate-smart land management (CSLM). (Adapted from Reardon et al. 1996.)

purchase chemical fertilizer and improved seeds as well as agricultural tools, which could be used for land preparation and other land management practices.

16.2.3 Riskiness

Another important factor affecting farmers' incentives to invest in land management is risk. Agricultural production under smallholder farming systems involves risk and uncertainty in SSA in general, and in Ethiopia in particular. . Investments in CSLM become risky and incentives decline if farmers are not sure that they will be able to get full benefits by recovering their investment costs. Some studies showed that investment in CSLM can significantly reduce production risks caused, for example, by rainfall variability in SSA (Reijntjes et al. 1992, Alfoldi et al. 2002, Scialabba and Hattam 2002, Mäder et al. 2002) and in Ethiopia (Hengsdijk et al. 2005, Shiferaw and Holden 1998). However, there are circumstances in which some interventions may increase risks (Shiferaw and Holden 1998). Such risks may arise from price and yield variability and land tenure security (Scialabba and Hattam 2002, Shiferaw et al. 2007).

(i) Price variability

The market for agricultural inputs and outputs in Ethiopia is poorly developed and contributes to an unfavorable relationship between input and output prices in the country (Aune and Bationo 2008). As the prices of agricultural products are unknown at the time of planning, they create uncertainties in the price and availability of inputs. Uncertainty in output market outlets also plagued several promising technologies in Africa (Kelly et al. 1995, Abdoulaye and Sanders 2006). Moreover, prices of inputs and outputs are influenced by demand and supply of inputs and outputs (Hill et al. 2006) as well as by limited access to market and market information (Markelova et al. 2009, Tang 2009).

(ii) Yield variability

Crop yields in Ethiopia are generally low and highly variable (Harris and Kennedy 1999). Studies have clearly demonstrated that rainfall is the predominant factor influencing yield variability in the region (Singh and Byerlee 1990, Howard et al. 2003). The increase in extreme weather events, such as spells of high temperatures and droughts, also increases yield variability and reduces average yield (Tittonell et al. 2008, Sinebo 2005). Yield variability also affects the technology choices of farmers due to risk aversion (Graves et al. 2004). Because of this uncertainty, farmers in Ethiopia show logical reluctance to invest in potentially more productive and economically rewarding practices when the outcomes and returns seem so uncertain from year to year (Howard et al. 2003).

(iii) Land tenure security

Secure and transferable land rights have long been identified as key elements to bringing about higher levels of long-term investments (Gebremedhin and Swinton 2003, Deininger and Jin 2006). Most empirical studies indicated that security of tenure is important for long-term investment and is positively correlated with long-term land management practices (Roth et al. 1994, Besley 1995, Gavian and Fafchamps 1996, Shiferaw and Holden 1998, Gebremedhin and Swinton 2001, Place and Otsuka 2002, Gebremedhin and Swinton 2003, Otsuka et al. 2003, Asrat et al. 2004, Kabubo-Mariara 2007, Nyangena 2008). Although insecurity in land tenure would be a disincentive for investment, paradoxically, it actually increases incentive because investment by itself can increase land security. In other words, investment is necessary to facilitate land security (Sjaastad and Bromley 1997). However, the role of land tenure security in SSA in providing incentives for land-related investment is inconsistent and complicated (Sjaastad and Bromley 1997, Place and Swallow 2000, Deininger and Jin 2006). Accordingly, land tenure security has no significant effect on investment in land management (e.g., Migot-Adholla et al. 1994, Migot-Adholla et al. 1991, Place and Hazell 1993, Pinckney and Kimuyu 1994, Place and Otsuka 2002, Gavian and Fafchamps 1996, Sjaastad and Bromley 1997, Brasselle et al. 2002). The mixed reports on land tenure security on investments in land management could be caused because of inconsistencies in methodologies and definitions of land tenure security used in the different studies (Kabubo-Mariara 2007).

16.2.4 The household-specific "discount rate"

The household-specific "discount rate" is the time value of money, and it reflects how future costs and benefits are weighed, relative to immediate costs and benefits (Pender 1996). Most land-management investments require heavy initial investments (either in cash or in-kind) although the benefits are delivered in many years in the future (Shiferaw et al. 2007). Investments in land management, for example, in agroforestry and terracing, typically have delayed payoffs, and a household with a high discount rate might be less inclined to make this type of investment (Gardner and Barrows 1985, Reardon et al. 1996). The capital budgeting analysis in Ethiopia suggests that returns from investment in stone terraces are highly sensitive to discount rate (Barrett et al. 2002). It is generally accepted that an individual's discount rate is influenced by a number of personal factors, such as wealth and income profiles, level of education, age, and state of health. Wealthier, healthier, younger and well-educated individuals have lower discount rates than their poorer, older, less healthy, and less educated counterparts (Lumley 1997, Shiferaw et al. 2007).

16.2.5 Biophysical environment

Through their effect on profitability and riskiness, biophysical factors, such as natural fertility of soils, rainfall, topography, temperature, diseases, and pests determine the technical feasibility of investments. Among the biophysical factors, rainfall variability is the most important cause for year-to-year variability of crop production, and the high insecurity it produces may consequently affect farmers' willingness to invest in rain-fed agricultural activities (Shiferaw et al. 2007).

Studies in Ethiopia indicated that farmers with steep slope plots invest in land management techniques such as stone terraces (Pender and Kerr 1998, Shiferaw and Holden 1998, Bekele and Drake 2003, Asrat et al. 2004, Amsalu and De Graaff 2006). This can be attributed to the positive relationship between slope and levels of soil erosion severity. Plots perceived to have greater erosion severity receive more investment in land management. The soil fertility status of plots is also an important factor in land management investment. Farmers invest more in fertile plots than infertile ones (Bekele and Drake 2003). This could be attributed to marginal productivity loss due to erosion from plots with fertile topsoil, which is higher than that of plots with less fertile topsoil, and such plots are expected to yield a greater return as compared to infertile plots. Generally, areas with good soil fertility and relatively abundant rainfall may have good agricultural profits, which farmers then reinvest in land management (Gebremedhin and Swinton 2003, Joshi et al. 2005). In spite of this, some studies indicated that farmers invest more in infertile plots than in fertile ones (Amsalu and De Graaff 2006, Benin and Pender 2001) due to a lack of perception on the effects of soil erosion and soil nutrient depletion.

16.3 Capacities to Invest in Climate-Smart Land Management

Farmers' capacity to invest in land management depends on the household's landholdings, labor availability, and physical and financial capital (Reardon et al. 1996).

16.3.1 Landholdings

Land is the major source of wealth and livelihood in SSA. Quantity and quality of land affect the types and intensity of investments that are technically feasible and profitable. Mostly, it is hypothesized that farmers with large plots and farms are more capable of undertaking investments because they can spare part of their land for terracing, fallow, and trees, while still keeping large portions under cultivation (Hayes et al. 1997, Asrat et al. 2004, Smith 2004). In spite of this, empirical studies in Ethiopia showed mixed results. For example, small farms may have strong incentives for intensification and land-enhancing investments because their owners depend more on these small landholdings (Kassie et al. 2008, Byiringiro and Reardon 1996). However, small farmers often face stiff constraints, for example, in obtaining credit and physical capital which could enhance investment in land management (Clay et al. 1995).

On the other hand, some empirical studies in Ethiopia suggest that farmers who hold large farms are more likely to invest in land management (Hayes et al. 1997, Asrat et al. 2004, Smith 2004, Tenge et al. 2004, Amsalu and De Graaff 2006, De Graaff et al. 2008). This could be attributed to farmers with large landholdings who take the risk of investing in land management, which then may help them survive crop failures due to drought, pests, hailstones, or excess rainfall (Nowak 1987, Reardon et al. 1996).

16.3.2 Labor availability

Labor availability, in terms of quantity and quality, is critically important in land management. The quantity aspect of labor is important when labor is considered as an input in labor-intensive land management activities, such as construction of stone terraces. Empirical studies in SSA, including in Ethiopia, showed that large family size and an economically active population have positive and significant effects on labor-intensive investments in land management practices (Pender and Kerr 1998, Mbaga-Semgalawe and Folmer 2000, Gebremedhin and Swinton 2003, Bewket 2007).

16.3.3 Education/knowledge level and capability

The quality of labor, which includes the worker's education level and technical knowledge, is also important to the farmer's ability to make appropriate investment decisions (Smith 2004). Education level of households is also considered as a proxy influencing household head's capacity for understanding technical aspects related to land management (Jumbe and Angelsen 2007). Most studies indicated that higher education levels are associated with more access to information on land degradation problems and improved land management measures (Adimassu et al. 2015, Hagos and Holden 2006). Similarly, education of a household head leads to an increased ability to assess information, better understanding of new technologies, and strengthening of his/her analytical capabilities with new technologies (Swinton and Quiroz 2003). Studies also reported that education has a positive impact on investments in improved land-management technologies in SSA (McDowell and Sparts 1989, Abeygunawardena 1990, Mbaga-Semgalawe and Folmer 2000).

16.3.4 Physical capital

Physical capital to invest in land-management practices includes infrastructure and other physical characteristics of plots. To adopt less erosive forms of land use in steeper plots, which are more susceptible to erosion, there is high incentive to invest in land management practices (Clay et al. 1998). The greater the land degradation in a village, the more likely resident farmers are to invest in land management (Clay et al. 1998, Gebremedhin and Swinton 2003). Empirical studies in Ethiopia also revealed that distance from homesteads to farmers' fields affects the type and intensity of land-management investment (Pender and Gebremedhin 2007, Pender et al. 2004, Gebremedhin and Swinton 2003). Because transportation options for transporting inputs to distant plots were lacking or limited, farmers were more likely to invest in land management practices (e.g., application of compost/farm yard manure) on plots closer to their residence (Clay et al. 1998, Nkonya et al. 2004, Nkonya et al. 2005).

16.3.5 Financial capital

Financial capital consists not only of cash, but also liquefiable assets, such as livestock and crop sales that can be used to finance an investment in land management. The main sources of cash for Ethiopian farmers include livestock and crop sales, off-farm activities, and credits (Pender and Gebremedhin 2007). Because it provides cash income, livestock husbandry, for example, is a boon to farm investments (Hayes et al. 1997). Like other factors, the effect of livestock on investment in land management is mixed. For example, some studies in Ethiopia indicated that large livestock size discourages investment in conservation practices (Amsalu and de Graaff 2006, De Graaff et al. 2008). Due to livestock's relative profitability, households may focus more on livestock than on crop production. By contrast, other studies reported that large livestock ownership is associated with greater use of land-management practices, which is likely because income generated from livestock products helps farmers to purchase agricultural inputs (Hayes et al. 1997, Pender and Gebremedhin 2007). Availability of credit is another financial factor that influences farmers' capacity for investing in land management. Research on the adoption of land-management technologies indicates that there is a positive relationship between adoption levels and the availability of credit in the region (Shiferaw and Holden 1998, Benin and Pender 2001, Pattanayak et al. 2003, Yirga 2007).

16.3.6 Collective action

Collective action is crucial for the success of land-management practices in Ethiopia (Adimassu et al. 2011). This can be explained in two ways. First, most physical land-management practices, such as construction of stone bunds, soil bunds, and cut-off drains, require huge amounts of labor and cannot be implemented by individual farmers. Second, spatial interlinkages related to the flow of water and nutrients are inherent in watersheds. While conservation measures in the upstream may benefit downstream use, soil erosion in the upstream may harm downstream uses of both land and water. In both cases, collective action enhances farmers' capacities to invest in land management and enables fair distribution of costs and benefits from land management. Studies in the northern part of Ethiopia showed that collective action-based land management methods, including use of grazing lands, are effective and sustainable (Gebremedhin et al. 2004, Benin and Pender 2006). Similarly, collective actions in the Gununo watershed of the southern part of Ethiopia increased the effectiveness of land-management practices such as *fanya juu* and soil bunds (Mazengia and Mowo 2012). In the highlands of Kenya, collective actions also determined farmers' investments in land-management practices (Nyangena 2008).

16.4 External Factors

External factors are constraints that are beyond the control of farmers and are more relevant to policy and institutions. These factors affect investments in land management through their effect in influencing farmers' incentives and capacities to invest. External factors common to all households in a particular agro-climatic/policy context include lack of (appropriate) technologies, limited extension services, poor agricultural policies, weak institutional collaboration, poor infrastructure programs, and political instability (Reardon and Vosti 1995).

16.4.1 Lack of (appropriate) technologies

Technology development and transfer is essential for increasing productivity and enhancing land resources management (Reilly et al. 2000). Lack of (appropriate) technology on land management may limit farmers' investment in land management by reducing profitability and increasing riskiness of a particular investment (Vallaeys et al. 1987). If it is difficult for farmers to obtain capital and dry season labor, for example, although the available land management technologies require these resources, then the technology may not be appropriate. Studies in Ethiopia reported that available technologies are not appropriate because they often fail to take proper account of biophysical, socioeconomic, and policy factors (Ehui and Poison 1993, Crane and Traore 2005). Lack of access to technologies is also another main constraint in SSA (Nederlof and Dangbegnon 2007).

16.4.2 Limited extension services

Extension services promote technology adoption and may also cut the cost of using new land-management technologies (Reardon 1996). Studies in Ethiopia revealed that farmers who have close access to extension services adopt more land-management technologies than do those with less or no access at all (Wale 2008, Barrett et al. 2002). The numbers of visits to farmers by extension agents also affected farmers' investment in land management positively and significantly (Clay and Reardon 1995, Benin and Pender 2001, Wale 2008). Unfortunately, there is very limited access to extension services and poor research-extension-farmer linkages in most SSA countries (Mowo et al. 2010).

16.4.3 Weak institutional support

The effectiveness of land management practices depends on how efficiently institutions can work together in providing technical support to farmers (Hoffmann et al. 2007). However, imperfect institutional arrangements; lack of transparency, accountability, and capacity; and limited access to information and networking, are the main features of most institutions in SSA countries, including Ethiopia (Ribot 2002).

16.4.4 Poor infrastructure programmes

Mainly due to inadequate physical infrastructure, agricultural growth in SSA has been constrained by a number of factors, including inefficient agricultural output markets and input supply systems (Gunvant et al. 1987, Katungi et al. 2008). Most farmers in SSA have insufficient access to markets because agricultural outputs are either produced in remote areas or access roads are bad or non-existent (Lindner et al. 1992, Spencer 1996, Neill and Lee 2001). The quality and quantity of roads affect transaction costs, risks, and price fluctuations of farm products and non-farm activities. Transport and communication infrastructure determines the availability of information and access to markets as well as costs and returns of investments. By increasing output-to-input price ratios, better access to roads and markets can increase labor and/or capital intensity of investments on land management practices (Binswanger and McIntire 1987, Osbahr et al. 2008). Better access to roads and markets also promotes higher income per capita by providing greater economic opportunities to rural households who, in turn, invest in land management practices (Tiffen et al. 1994). On the contrary, poor infrastructure raises the price of inputs and reduces agricultural outputs, which further diminishes the profitability of land management technologies (Shiferaw et al. 2007). A price increase in agricultural products may make certain land management interventions profitable or attractive to farmers. Accordingly, some studies reported a positive relationship between increases in prices of agricultural products and the adoption of land-management technologies (Shiferaw and Holden 2000, Lee 2005). Some studies, however, reported that better infrastructure could instead increase non-farm rather than farm opportunities, which may, thus, reduce intensities of land management technologies (Tschirley and Benfica 2001, Grothmanna and Patt 2005).

16.4.5 Political instability

Political instability appears to be the most important obstacle to agricultural development (Muleya et al. 1987, Nwilene et al. 2008). Political instability can, thus, influence investments in land-management technologies in SSA, including in Ethiopia (Blackie 1987). Political instability interrupts input distribution and output marketing, and may lead farmers to keep their savings in liquid assets, such as jewels or livestock, rather than investing them in long-term land improvement activities (Nwilene et al. 2008).

16.4.6 Poor agricultural policies

Policy plays a pivotal role in land management practices by creating an enabling environment for investment in land management. Macro- and micro-policies directly and indirectly affect output and input prices and, therefore, net and relative returns on investments. Price and credit policies in Ethiopia are changing dramatically and frequently, and farmers do not know how to plan; thus, they shy away from on-farm investments (Baye 2017).

16.5 Conclusions

The principal part of this chapter is the documentation of key factors influencing farmers' investments in CSLM. The investment in CSLM by smallholder farmers is constrained by an array of biophysical, social, economic, institutional, and policy factors. In this chapter, the most important factors that affect farmers' investments in CSLM are grouped into three categories: incentives, capacities, and external factors. While we identify these factors that affect farmers' investments in CSLM, there are good lessons to be learned from Ethiopia, where CSLM practices are successful mainly in the Amhara and Tigray regions (Adimassu et al. 2018). Farmers are able to constrain these factors by enhancing their capacities to invest in CSLM and increase incentives for the investments they make. The success behind these case studies is due to the fact that CSLM land practices are implemented using the landscape approach. The landscape approach employs collective action to constrain the three key factors that affect farmers' investments in CSLM. This implies that a landscape approach is crucial for the adoption of CSLM in Ethiopia. Due to differences in social, economic, cultural, and biophysical characteristics, however, the influence of these factors varies from place to place within in the country. This suggests that a blueprint (one-size-fits-all) approach of CSLM practiced in lowland areas of Ethiopia may not be useful in the highland areas. Based on local biophysical, social, cultural, and farmers' contexts, CSLM strategies should be designed and adapted at micro- and macro-levels.

Although this chapter reviews the key determinants of farmers' decisions to invest in CSLM, further meta-analysis and synthesis may be required to better understand the impacts of CSLM practices on farmers' livelihoods and the environment.

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17. Weather Index Crop Insurance as a Climate-Smart Approach for the Vulnerable Groups: The Case of Adiha, Northern Ethiopia

Ataklti Techane Teame[a]* and Fitsum Hagos[b]*

Summary

Smallholder farmers in Ethiopia face recurrent droughts and consequent low agricultural productivity, among other issues, due to inadequate use of farm inputs. Thus, the need to develop risk-transfer mechanisms and the use of modern agricultural inputs becomes an important task, although one that is challenging for farmers and policy makers to implement. To observe the relationship between new technologies and productivity under smallholder conditions, this study explores the impact of weather index insurance on farm input investments using 182 randomly sampled households in *Adiha tabia* (village) of Tigray, northern Ethiopia. The main task of this chapter was to explore whether there were any differences in farm input uses between farm households that were participating in a weather index insurance (WII) and households that were not. The second task was to quantify the differences in per-capita input costs (cost estimated per *tsimdi*) among participant and nonparticipant households. To analyze the data, we used propensity score matching with three matching algorithms. The average treatment effect for the treated results revealed that participants in WII had higher and more significant per-capita input costs than did their counterparts. Using three different matching algorithms, nearest neighborhood, kernel, and calliper matching, the results indicated that input costs for households who participated in WII were higher and more significant than those of their counterparts. The study concluded that WII could catalyze risk taking behavior of households towards using yield-enhancing technologies and accessing credit, among other financial services.

Keywords: crop insurance, PSM, input cost per capita, WII

17.1 Introduction

Risk is inherent in many production systems, including agriculture. Farmers face a variety of market and production risks that make their incomes unstable and unpredictable from year to year (Barret et al. 2007). For example, input prices may increase out of reach, crops may be destroyed by drought or pest outbreaks, selling prices may plummet, and harvests may rot in poor storage facilities. Assets and lives may also be lost due to severe droughts, hurricanes, earthquakes, and floods. The type and severity of the risks confronting farmers, particularly small-scale farmers, are burdensome in the developing world. Unless they are adequately managed, agricultural risks could contribute to slow economic development, hamper poverty reduction efforts, and consequently, lead to humanitarian crises (Hazell et al. 2010).

Low-income households are much more vulnerable to various risks and to economic and weather shocks than are households with risk management options such as savings and access to credit. The high vulnerability to risk is especially challenging for poor households in developing countries (Levin and Reinhard 2007), where the threat of shocks can make households reluctant to access credit markets because they fear the consequences of an inability to repay debts (Hill et al. 2011). In addition to the anthropogenic risks, the performance of agricultural production is also highly influenced by the conditions of the natural environment. In particular, fluctuations in climatic and weather conditions impact agricultural production, especially in developing countries where unfavorable conditions can easily and severely affect the overall wellbeing of households in a region or even an entire country (Fuchs

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[a] Mekelle University, Department of Agricultural Resource Economics, Mekelle, Ethiopia. Email: aticheck@gmail.com; ataklt_techane@yahoo.com

[b] International Water Management Institute (WMI), East Africa and Nile Basin sub-regional office, Addis Ababa, Ethiopia. Email: F.Hagos@cgiar.org

* Corresponding author

and Wolff 2010). Furthermore, risks arising in agriculture and the ways used to manage such risks—by farmers, rural communities, financial institutions, farm input suppliers, private insurers, and relief agencies—are often challenged by the difficulties and costs that covariate risks pose, especially those involved in catastrophic losses (Hess and Hazell 2009). Accordingly, more protection, in the form of *ex-ante* insurance and post-shock safety nets, would have substantial returns, not just in terms of short-run welfare gains, but also in terms of subsequent growth (Dercon 2004).

Among the many risks, unfavorable weather conditions constitute the single most important risk faced by the hundreds of millions of poor rural households around the world. To address this risk, index-based agricultural insurance, such as weather index insurance (WII), has come to be viewed as a viable risk-management tool for low-income farmers, especially in developing countries. Weather index products and related derivatives have also been used by other sectors to hedge against weather-related risks because index insurance is perceived to be substantially less costly to operate and manage than yield-based insurance (Smith and Watts 2011). These weather index insurances use local rainfall indexes that are closely correlated with yields in the region where the farmers live. When the index falls below a certain level, farmers automatically get a payment, with no requirement to estimate the costs of their potential yield losses and no need to address moral hazards. Although the provision of index insurance on a small scale has been observed in a number of countries (Giné and Yang 2009, Cole et al. 2009, Hess and Hazell 2009), including in Ethiopia (Meherette 2009), it has not yet been used on a large scale (Binswanger-Mkhize 2010).

While WII offers potential benefits to millions of poor rural households, there is still work to be done in perfecting its design—in particular, in reducing basis risks and improving understanding in reducing the cost of insurance provisions. Once established, index insurance can be less expensive to administer than traditional agricultural insurance because there is no need to perform on-site inspections or make individual loss assessments (Hazell et al. 2010). Moreover, transaction costs are low, making it workable under real market conditions; index insurance is both financially viable for private-sector insurers and affordable to small-scale farmers (Barrett et al. 2007). In spite of this, index insurance is expensive to launch. It requires significant resources and technical expertise to conduct the initial research and development, build the capacity of local insurers and others in the delivery channel, effectively raise awareness of potential clients and market the product, and, in some cases, access the data (Hazell et al. 2010).

Although most of the studies (including case studies and reviews of existing program history) contain overviews of the concept behind weather insurance, few contain results focusing on its impact on the people who use it. Thus, there is an urgent need for the evaluation of the impact of this product in order to understand the circumstances under which poor farmers in Ethiopia and other developing countries are likely to purchase weather insurance. Despite the substantial welfare benefits that could arise from improved agricultural risk management, the voluntary purchase of these products has been much lower than anticipated. Despite the potential for welfare gains, WII has not been well adopted (Binswanger-Mkhize 2010). In this regard, Cole et al. (2009) and Karlan and Morduch (2009) suggest that this low demand indicates a need for further investigation, especially given the substantial benefits WII offers. Although the impact of insurance can be assessed by its low and insufficient uptake, both in the number of people accessing it and in the level of insurance purchased (Cole et al. 2009), this chapter focuses on the impact of insurance on investment decisions, particularly, on input cost (e.g., fertilizer, improved seeds, and labor day value) per *tsimdi*.[1] Input cost was chosen because WII is believed to avoid moral hazard and adverse selection, while helping farmers to use improved technologies. Moreover, the input cost was chosen based on the findings of the study on Horn of Africa Risk Transfer for Adaptation (HARITA) (Oxfam America 2011), which reported that changes or differences were observed among the participant farmers due to the input costs.

As formal weather insurance products have only recently begun to spread throughout the developing world, and taking into account the lag time in publishing, the body of published peer-reviewed journal articles and other literature focusing on the impacts and issues associated with WII is quite limited (Cole et al. 2012). In fact, very few articles in peer-reviewed journals have investigated the impact of weather index-based crop insurance in developing or transition countries, though these do include Berg et al. (2009) in Burkina Faso; Breustedt et al. (2008) in Ukraine; Chantarat et al. (2008) in Kenya; Molini et al. (2008) in Ghana; and Zant (2008) in India. Moreover, ex-post insurance studies are also quite limited (Cole et al.

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[1] One *tsimdi* is equivalent to 0.25 ha.

2009, Giné and Yang 2009, Hill et al. 2009). In tandem, the relative importance of ex-post evaluation and the relative dearth of attention given to it by researchers and policy makers underscore the need for conducting high priority research on the untapped potential of insurance, which could provide improved local risk management in developing countries. The aim of the chapter is, therefore, to examine the extent of investment on farm inputs among WII participating and non-participating households.

17.2 Methodology

17.2.1 Description of the case study area

The study was conducted in Adiha *tabia* (an administrative unit), Kolla Tembien, central Tigray zone, northern Ethiopia, between February and August 2012. The altitude of the area ranges from 1,573 to 2,299 m.a.s.l. The area is characterized by erratic rainfall, which occurs mainly between June and August, although it can sometimes vary, for example, starting in May and stopping early or starting late and continuing until September. Seven years of rainfall data, measured at the Adiha weather station, indicate that annual rainfall ranges from 436–700 mm, with a mean annual rainfall of about 600 mm. Except for during the wettest months (July and August), the area is characterized by hot temperatures. The maximum and minimum temperatures of the area are 27 °C and 18 °C, respectively. The soil texture of the area is predominantly sandy.

An annual report of the Kola-Tembien Bureau of Agriculture and Rural Development (2008) indicates that Adiha is the largest *tabia* (sub district) in the *woreda* (district) with a land size of 10,920. It has four *kueshets* (villages) with 1,783 households engaged in rainfed and irrigated agriculture. The total population of the tabia was 8,494 (3,910 males and 4,584 females). Of the households in the site, 613 were dependent on irrigation and 1,170 on rainfall agriculture practices. The site also has about 283 landless households.

Among other pilot sites in Ethiopia, an index insurance pilot was implemented in Adiha in 2006 through a partnership between the World Food Programme (WFP) and the government. The main objective was to insure against the risk of a national drought catastrophe on the international financial market, i.e., to connect it with a re-insurer. The insurance targeted a group of 5 million people who experienced transient food insecurity and who would be directly affected if drought occurred. In 2006, the WFP took out insurance on behalf of the Ethiopian government for part of its emergency assistance exposure. In 2008, WFP and partners sought to scale up the pilot to a livelihood risk financing package of $US 300 million to cover up to 6.7 million people through a safety net, with around $US 50 million of the package covered by insurance. This is an example of a "crisis safety net" funded through index insurance (Barrett et al. 2007).

17.2.2 Method of data collection

During the 2012 rainfed agricultural season, primary data required for this study was collected, using a structured questionnaire, from sample households who were participants and non-participants in the weather index-based crop insurance program. Interviewers for this survey were recruited from the district of Mekelle. A four-day training program was organized for the enumerators on methods of data collection, approaching the farmers, and the overall contents of the questionnaire. Relevant secondary data was also drawn from the Dedebit Credit and Saving Institute (DECSI) micro-finance and the Relief Society of Tigray (REST) local NGO.

17.2.3 Sample size and sampling techniques

The Adiha site in Tigray was specially selected for the weather index-based crop insurance pilot program. Its major crop, teff (*Eragrostis tef*) was the pioneer crop insured by WII, and teff-producing farmers were selected for the study.

Teff has a short growing season, and can be sown towards the latter part of the rainy season. When there is a season with a low and early-ending rainfall, farmers frequently shift towards sowing teff as a last resort. In spite of this, teff is labor intensive and requires expensive inputs that farmers must often purchase through loans (Dinku et al. 2009). Because of its high demand in both domestic and international markets, teff is common crop not only in Adiha but also in many parts of Ethiopia.

In order to select sample respondents, first, households in the *tabia* were identified and placed into two strata, namely, WII participants and non-participants during the 2012 rainfed agricultural season. Finally, a total sample of 182 households, of which 90 were participating in WII and 92 were not participating, was selected.

To capture risk preference, a dummy variable was included that took a value of 1 if the respondent preferred risky business. It was hypothesized that engaging in these activities proxies a greater willingness to undertake risk, ceteris paribus. To elicit/measure the risk preference, respondents were asked the following question (which touches on the adoption of new technologies):

"Assume that someone in your village has received a gift of some money. Does he/she own enough to buy an ox or some lemon trees? If he/she buys the ox, he/she will be able to increase his/her tef harvest and sell the surplus for about 100 Birr per year. If he/she buys lemon trees, he/she knows that there is a 50 percent chance that pests will affect most of his/her lemon trees and he/she will only earn 50 Birr per year from sales of the lemon. If there is a 50% chance that there will be no pests and he/she will be able to sell the lemon for 200 birr per year. What would you do? (A) Buy the ox and get the extra 100 birr per year with certainty or (B) Buy lemon trees and take the 50-50 chance of getting either 50 birr or 200 birr?"

17.2.4 Data analysis

Descriptive statistics, mainly mean and standard deviation, were used to see whether the participating households in the program were characteristically different from non-participating households.

The impact of the WII on participating households' farm inputs investment was analyzed using a propensity score matching (PSM) model. Matching econometrics provides a promising tool to find comparable groups of treated and control groups and to combine (match) treated and control groups of households that are similar in terms of their observable characteristics (Ravallion 2003, Khandker et al. 2010). PSM estimators aim to estimate the effect of participation as the difference in the mean value of an outcome variable, i.e., farm input investment per *tsimdi*.

Matching is a method widely used in the estimation of the average treatment effects (ATT) of binary treatments (Khandker et al. 2010) on a continuous scalar outcome. To construct the counterfactual under the assumption of a selection of observables, it uses non-parametric regression methods. Households who bought the insurance product were considered the treatment group and non-user households were considered the control group, while input cost per-capita was considered an outcome variable. The observable household characteristics used in this study included education level, sex, age, land size, and total asset value, all of which may influence the choice of participation in the intervention (e.g., choice of insurance), but are not necessarily influenced by the intervention.

The ATT were only determined in the region of common support. Common Support (Overlap), which means that for any value of the confounding variables X, a unit i can be potentially observed with treatment (D = 1) and without treatment (D = 0). To ensure maximum comparability of the participating and non-participating households in WII, the samples used for matching were restricted for those households who were within the common support region. Further, to see the robustness of the ATT estimate, nearest neighborhood, kernel, and radius calliper matching algorithms were used for ATT estimation.

Sensitivity analysis was also undertaken using the critical levels of gamma (Γ), called the Rosenbaum test, using Γ bounds command in STATA 11. The Rosenbaum test was used to examine whether the causal inference about the impact of WII on the outcome variable would be altered by unobservable factors that affect both treatment and outcome variables. The p-critical values represent the upper bound of the p-value. Given that the estimated treatment effect was positive, the lower bounds, under the assumption that the true treatment effect has been underestimated, were less interesting (Becker and Caliendo 2007).

17.3 Results and Discussion

17.3.1 Demographic and socioeconomic variables

The study revealed that the average household size was 5 members, and that about 60% and 40% of the respondents were male and female, respectively. The mean age of the head of household was about 40 years. In addition, the average years of schooling was about four, and 32% of respondents were illiterate, with a mean land-holding size of 5 *tsimdi* (1.25 ha). Furthermore, the study indicated that 73% of respondents had borrowed money from DECSI, whereas the remaining 27% had not. The results showed that 78% of the respondents—91% and 65% of the participants and nonparticipants, respectively—were well informed about the product. The average spending of a household over six months for food, clothing, education, health, and ceremonial purposes was 4,151 Birr (218.9 USD). Among the households in the study area, about 47% and 53% were risk takers and risk averse, respectively, as determined with the "dummy variable" question used as a measure for willingness to take risks (i.e., whether to buy an ox or lemon trees).

The mean total asset value of a household was estimated to be 9329.69 Birr (*491.86 USD*). The asset value included livestock holdings and productive assets value (such as hoe, hammer, plough materials). Using a mean separation test, the outcome showed how the result (input cost per tsimdi) variable fluctuates among participating and non-participating households (Table 17.1).

The t-statistic of input cost per *tsimdi* was 2.5979 with 175 degrees of freedom, whereas the corresponding two-tailed *p*-value was 0.0102, which is less than 0.05—which justifies that input use by WII participating households was higher than for the non-participating ones. Input per-capita cost was, therefore, 1192.79 Birr (*62.9 USD*) and 957.13 Birr (*50.48 USD*) for participating and non-participating households, respectively. This finding suggests that WII might contribute to improving input use or technology adoption by smallholder farmers. However, given that participation in WII is endogenous, a simple comparison of the input per-capita cost of participating and non-participating households has no casual interpretation. The difference in input per-capita cost may not be a result of participation in WII. Instead, this might be related to other factors, such as differences in household characteristics and endowments. Hence, this result calls for conducting a careful multivariate analysis to manage this econometric problem and to test the impact of participation in WII on input cost per *tsimdi*.

17.3.2 Propensity score estimation results for impact of WII

Although a detailed interpretation of the propensity score estimates was not undertaken, the study examined the impacts of WII participating households on farm input investment. However, the results of the propensity score indicated that most of the variables included in the estimators showed the expected signs; for instance, household size had a negative effect on participation in WII, and education level of the household head had a positive effect.

The propensity score has a probability value in the range of 0 to 1, whereas the estimated propensity scores had a range of 0.1285148 to 0.9995037 with a mean of 0.5982939 for participating households, and between 0.0336743 and 0.8512942, with a mean value of 0.3878101 for non-participating households (Table 17.2). Based on the minima and maxima criteria, the common support region would then lie between 0.0336743 and 0.9995037. In other words, households with propensity scores estimated as less than 0.0336743 and greater than 0.9995037 were not considered for the matching analysis. The density distribution of the propensity score for participating and non-participating households in the WII showed a good overlap, which suggests that the common support condition was satisfied.

Table 17.1 also shows how the matching analysis restricted the control sample in order to increase the similarity of the sub-sample of control cases that were directly compared

Table 17.1 Mean separation test of participants and non-participants in WII.

	Households that did participate in WII		Households that did not participate in WII		
Variable name	Mean	Std. Dev.	Mean	Std. Dev.	*P*-value
HH size	5.08	0.198	5.45	0.195	0.19
Sex	0.53	0.053	0.67	0.049	0.05
Age	39	1.06	41.5	1.33	0.16
Education	4.4	0.41	3.9	0.39	0.348
Total expenditure	4717	384.359	3596.935	179.78	0.0085
Awareness to WII	0.91	0.03	0.65	0.05	0.0000
Distance to station	39.24	4.6	48.04	3.1	0.113
Total number of ha	4.6	0.32	5.3	0.32	0.1238
Per capita input cost	1192.795	78.57	957.132	45.84	0.0102
Risk preferences	0.52	0.053	0.423	0.051	0.1861
Credit	0.756	0.0455	0.6956	0.048	0.3681
Total asset value	9729.77	1093.523	8938.33	1057.25	0.6034

Note: HH refers Household

Source: Survey, 2012.

Table 17.2 Estimated propensity score by participation status.

Participation status	Observation	Mean	SD	Min.	Max.
Participant HHs	90	0.5982939	0.1845608	0.1285148	0.9995037
Nonparticipant HHs	92	0.3878101	0.2331273	0.0336743	0.8512942
Total	182	0.4918955	0.2349661	0.0336743	0.9995037

Source: Survey, 2012.

to the treated cases and to estimate the consequences of the treatment. Additionally, Table 17.1 presents the balancing information, before and after matching, for the propensity scores and for each covariate. In many cases, it was found that sample differences in the unmatched data significantly exceeded the sample difference in the matched cases. The process of matching, thus, creates a high degree of covariate balance between the treatment (i.e., the participating households in WII) and the control groups (non-participating). The imbalances between the treatment and the control samples in terms of the propensity score were more than 33% before matching, as shown in Table 17.1. This bias was, however, significantly reduced, to a level of 8.6%, after matching. Furthermore, Table 17.1 shows that several variables exhibited statistically significant differences before matching, although the covariates were balanced after matching.

The low pseudo R^2 and the (not significant) likelihood ratio tests also support the hypothesis that both groups had the same distribution in covariates after matching. These results clearly showed that the matching procedure is able to balance the characteristics of the treated and the matched comparison groups. Therefore, these results were used to evaluate the impact of WII on farm input investment among groups of households having similar observed characteristics.

17.3.3 The average treatment effects (ATT)

In the results from the three matching algorithms taking all observations within the common support region, the result from nearest neighborhood, kernel, and radius calliper revealed that 0 (0 for control and 0 for treatment groups), 9 (0 for control and 9 for treatment groups) and 25 observations (0 for control and 25 for treatment group) were discarded from the estimation of ATT, respectively. As shown in Table 17.3 the estimated ATT indicated that participation in WII exerts a positive and significant effect on farm input investment. For example, results from nearest neighborhood matching revealed that farm households in the treatment group had, on average, 229 Ethiopian Birr, i.e., a higher per-capita farm input investment per *tsimdi* than non-participating households. Likewise, Hill and Viceisza (2009) reported that households in Ethiopia who were offered a hypothetical insurance product had increased their capacity to purchase more fertilizer (i.e. 29% more). In addition, the study revealed that general insurance provision would increase the average farmers' return by 21.8%. Thus, promoting weather index-based crop insurance enhances climate-smart agriculture, which in turn contributes to food security and poverty alleviation of poor rural households through increasing investment farm inputs (Steenwerth et al. 2014).

Similarly, Horowitz and Lichtenberg (1993) reported that farmers in the developed nations, such as in the U.S. Midwest, who purchased insurance were able to apply more agrochemicals per ha than those who did not purchase insurance. Goodwin et al. (2004) also found that an increased participation in crop insurance programs lead to statistically significant results in farm input use. The critical levels of gamma (Γ) test showed that the positive effect of WII was not sensitive to selection bias due to unobserved variables even allowing for a difference of as much as 25% between the participating and non-participating households in terms of unobserved covariate. However, Becker and Caliendo (2002) argued that these sensitivity results are a worst-case scenario. The overall critical values clearly indicated that even unobserved heterogeneity would not alter the influence of the treatment effects. This suggests that the findings were generally not sensitive to hidden bias. Additionally, the treatment effects presented in Table 17.3 could be considered a pure effect of WII.

Table 17.3 ATT estimates of per capita input cost.

Matching algorithms	Variable	Sample	Treated	Controls	Difference	*P*-value
Nearest neighborhood	Per input cost	Unmatched	1192.795	957.132	235.662	0.013
		ATT	1192.795	963.714	229.080	
Kernel	Per input cost	Unmatched	1192.795	957.132	235.662	0.012
		ATT	1166.652	956.214	210.437	
Radius calliper	Per input cost	Unmatched	1192.795	957.132	235.662	0.008
		ATT	1132.261	930.373	201.888	

Source: Survey, 2012.

17.4 Conclusions and Recommendations

The benefits of WII encourage participating smallholders to use risk transfer mechanisms and modern agricultural inputs. The study investigated how participation in WII affects farm investments, as measured by per-capita input cost per *tsimdi*. To this end, we used PSM with nearest neighborhood, kernel, and radius matching. The ATT results suggest a positive and significant effect of WII on farm input investment. These findings were generally consistent across all of the matching algorithms used in the study. For example, the mean average per-capita input cost per *tsimdi* of participating households in WII was higher than for non-participating households by 229, 210, and 201 Birr for the nearest neighborhood, kernel, and radius caliper matching algorithms, respectively. This finding also showed that participating households who were offered a hypothetical insurance product increased their purchasing capacity of fertilizer. WII increases the incentive to use more intensive production, which, in turn, has an implication for poverty reduction and for achieving food security, which is the priority of the Ethiopian government. Expanding the insurance coverage to many poor and vulnerable smallholder farmers in the district is important.

It is clear from this study that an appropriately designed WII would certainly be of significant economic interest to smallholder farmers in the study area. For example, WII increases the incentive to use more intensive production, which in turn has implications for poverty reduction and for achieving full self-sufficiency, which is the priority of the Ethiopian government. Given this, the policy implications of this study are as follows:

First, more emphasis should be given by the government, NGOs, and other stakeholders in the region to scaling up the existing WII pilot program to similar areas in the region as well as in the country at large.

Second, insurance marketing should concentrate on educating households on the limitations of existing coping mechanisms and on the advantages of WII as ex-ante sources of risk mitigation. For example, if insurance is not commonly available in the countryside, general education about insurance and risk management may be necessary. Index insurance policies are typically much simpler and easier to understand than traditional farm-level insurance policies. However, potential users may need help in evaluating how well the index insurance works for their individual risks.

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18. Building Gender-Sensitive Climate-Smart Agriculture Approaches for Sustainable Food-Energy Systems

Mastewal Yami[a]*, Edom Haddis[b], Emiru Birhane[c], and Gidey Kidu[d]

Summary

Climate change influences agricultural production and threatens the livelihoods of farming households in Africa. The impacts of climate change have been more severe for poor and marginalized peoples, especially women, than they have been for other groups in the society, due to their disadvantaged access to technologies, resources, information, and power. Conventional agriculture technology interventions aiming at improving productivity and income often do not consider social disparities and fail to enhance equitable benefit sharing among men and women. Similarly, climate-smart agriculture (CSA) approaches often fail to take into account the differences in men's and women's needs and capabilities for adapting to climate change and instead have an implicit male bias that privileges male needs, interests, and priorities in the distribution of opportunities and resources. The poor representation and involvement of women in decision-making processes in the agricultural sector has limited their contributions to addressing the adverse effects of climate change, energy shortages, food insecurity, and poverty. This chapter, by drawing on lessons from past and current agricultural interventions across Africa, especially Ethiopia, aims to foster understanding of the various roles and responsibilities of women in designing and implementing gender-sensitive CSA interventions to achieve a sustainable food-energy system.

Keywords: climate change, food-energy system, gender, governance, women, livelihood

18.1 Introduction

Climate change, in the form of unreliable rainfall availability and increased incidence of droughts and flooding, influences agricultural production and threatens the livelihoods of farming households. Agricultural production in Africa has not increased to meet the demand of the growing population due to climate change and other socio-cultural and environmental constraints (Rosegrant et al. 2008). The negative impact of climate change in Africa on the environmental, economic, and social aspects of smallholder agriculture has become explicit. For example, in the central highlands of Ethiopia, climate change negatively influences agricultural production, income, and the livelihoods of farmers through shortening the length of the crop growing period, increasing crop damage by insects and pests, and increasing the severity of weed infestation (Bewket 2012).

Poor and marginalized peoples are especially vulnerable to adverse impacts of climate change primarily because of their reliance on climate sensitive sectors, including farming and fisheries, and their limited human, institutional, and financial capacities to adapt to the negative impacts of climate change (Lambrou and Nelson 2010). In response to this, in Ethiopia, addressing climate change has been mainstreamed into various national policies, strategies, and programs, such as the Climate Resilient Green Economy (CRGE) initiative supported by the Green Economic Strategy (GES) and the Climate Resilience Strategy (CRS), which focuses on improving crop and livestock production practices for greater food security and better income for farmers, while reducing emissions (Woolf et al. 2018).

However, climate change still disproportionately affects women and girls because of their greater vulnerability to

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[a] International Institute of Tropical Agriculture (IITA), P.O. Box. 7878, Kampala, Uganda (email: mastewalyami@yahoo.com)

[b] Addis Ababa Universities, Department of Environmental Sciences, Addis Ababa, Ethiopia (email: edom.haddis@gmail.com)

[c] Department of Land Resource Management and Environmental Protection (LaRMEP), Mekelle University, P.O. Box 231, Mekelle, Ethiopia (email: emiru.birhane@mu.edu.et)

[d] Department of Agricultural and Resource Economics, Mekelle University, P.O. Box 231, Mekelle, Ethiopia (email: gideykidu2005@gmail.com)

* *Correspondence:* Mastewal Yami (email: mastewalyami@yahoo.com)

extreme weather-related events, such as droughts and floods. In Sub-Saharan Africa, about two-thirds of women work in subsistence agriculture, rely on rainfed farming, and have less access to productive assets and services, such as land, labor, and technology; climate change could exacerbate gender inequalities (World Bank 2008). Climate change affects the factors most essential to women's means of subsistence – food, water, and energy supply (Woolf et al. 2018). In Africa in general, and in Ethiopia in particular, women are the responsible actors for collecting fuelwood, hauling water, cooking foods, looking after children, and performing other home-related work. Their role in the farming practice, particularly in weeding and other farming activities, is notable. Women's lives in rural areas are characterized by overwork, low productivity, and little access to credit, land, training, or use of rudimentary technology. The diminishing capacity of agriculture to provide for household subsistence has increased the workload shouldered by women as men withdraw their labor from the agriculture sector (Labintan 2010).

Gender disparities related to the effect of climate change are attributed to the social position and roles of women within families and communities. The adaptive capacity of women can often depend on their access to land, credit, security of land tenure, and active involvement in decision-making on land and water resources (among other factors). Women are unable to voice their specific needs even though climate change affects women and men differently. Although women are responsible for feeding their families and are therefore more dependent on natural resources such as land, wood, and water, their access to these resources is limited. They are also denied full access to loans, education, and information (Bäthge 2010). Their extreme vulnerability to climate change emanates from the gendered roles in society; for instance, due to common restrictions on their mobility, women are less likely to receive emergency information in time to act upon it (ADB 2013).

Therefore, putting in place strategies and measures that compensate for women's historical and social disadvantages, which otherwise prevent women and men from operating on a level playing field, is important for enhancing fairness (CARE International 2009). Gaps in gender equity influence how men and women contribute, respond, and adapt to climate change (Jost et al. 2014). Thus, understanding these gaps enables the development of strategies that both address them and gain buy-in from both men and women.

Inclusion of gender disparities in climate smart agriculture (CSA) approaches could enhance the adaptive capacity of women and girls while sustainably increasing productivity, building farmers' resilience, and reducing the release of greenhouse gases (GHG) (Murage et al. 2015). Therefore, addressing the equity and justice issues in smallholder agriculture by understanding the different needs and priorities of men and women in agriculture and landscape management is important for effective strategies for adapting to and mitigating the impacts of climate change (Karlsson et al. 2018). Although some studies have examined the relevance of addressing gender issues in climate change (Lambrou and Nelson 2010, ADB 2013), concrete evidence is lacking regarding how gender equity can contribute to addressing the negative impacts of climate change and sustaining the positive outcomes of CSA approaches. This is unfortunate because such evidence would be useful for developing strategies that consider the different needs of men and women in adapting to the negative impacts of climate change.

This chapter aims to contribute to filling the knowledge gap by examining how inclusion of gender disparities in CSA approaches can contribute to achieving improved agricultural productivity, food security, and livelihoods. The chapter reviews how conventional agricultural technological interventions and CSA approaches are often gender-insensitive, with unintended negative welfare consequences for women. The chapter is based on a literature review and on authors' experiences in gender-related research and development projects.

18.2 Conventional Technological Interventions and Gender

Many efforts have been made to empower women's decision-making abilities on household resources and increase their access to modern agricultural inputs. Consequently, more opportunities have been created for women to ensure their equitable participation in society (USAID/IUCN 2019). For instance, in Ethiopia, women's participation in social and economic aspects, such as their access to education, health, and economic opportunities, has reached 91%. However, their access to modern agricultural inputs and other agricultural technologies is still minimal. New technologies that have been introduced are benefiting men while leaving most rural women in poverty and vulnerable to climate change (Doss 2001). Agricultural productivity has been negatively affected by unsustainable practices and gender inequality, which create high losses for local economies and for governments as a whole (Okwaro 2018). The new agricultural technologies introduced to improve productivity and income often overlook social disparities and fail to enhance equitable benefit sharing among men and women (Beuchelt and Badstue 2013). The poor access to credit and agricultural technologies used for enhancing women's agricultural productivity is among the known constraints to equitable benefit sharing. This finding is consistent with the study by UNDP (2017), indicating that the number of women who have access to agricultural extension services does not exceed 5%. This difference can be attributed to women's involvement in producing subsistence food crops with low potential for generating higher incomes. Their poor access to markets, finance, and technical advice also restricts them from participating in high-value cash crops farming (Byerlee et al. 2009). Moreover, the lack of gender equity also challenges the implementation of technologies that enhance the productive use of water and land resources. In Ethiopia, for example, domestic workloads of women increased with the development of "modern" irrigation schemes, such as micro-dams, river diversion, spring water use, shallow well increase the workload of women by creating an additional task necessary for working on an irrigable plot, which consequently limits their participation in water-user association committees (Yami 2013). Thus, in designing and focusing on interventions, such as irrigation development, it is useful to understand the various roles and responsibilities of women so that such interventions do not increase the demand on women's labor.

The interventions that aim to increase agricultural production through the expansion of improved agricultural practices also result in unintended consequences in gender equity. Often, the practice requires intensive use of hand weeding, which is mainly performed by women, and might therefore contribute to an unacceptable increase in the burden of labor on women in Sub-Saharan Africa (Giller et al. 2009). Beuchelt and Badstue (2013) also pointed out that women's labor burden can increase with new technologies when women take on additional tasks and when current tasks become more burdensome to women, such as when applying fertilizer leads to more weeding or more output process.

Therefore, failure to consider gender disparities and the different needs and priorities of men and women in agriculture has resulted in limited contribution of new technologies to agricultural production and income generation. Thus, it is critical to develop gender-responsive technologies and practices through ensuring the active participation of women in planning, designing, and implementing interventions that could enhance agricultural production, income, and livelihood diversification. It is essential to improve women's access to climate smart labor-saving technologies for agricultural production, as well as for household use in order to save labor in unpaid care and domestic work, such as through improved access to water and energy (Okwaro 2018). It is also indicated that gender-responsive climate-smart agricultural extension services are vital for increasing agricultural productivity. Empowering women to have access to and control over land and other resources is vital, as they are central to the household economy and to the welfare of their families (African Development Bank Group 2015). Moreover, the participation of women in CSA technologies enables them to improve the food security of the household (Meron and Gebermedihin 2018). Women are not necessarily victims of climate change, but they can be crucial actors in finding solutions on how to cope with climate change (FAO 2016).

18.3 CSA Approaches and Gender

A gender-responsive approach to CSA means that the particular needs, priorities, and realities of men and women are recognized and adequately addressed in the design and application of CSA so that men and women can both benefit equally (Nelson and Huyer 2016). It reflects the inclusion of women in improving the integration of agriculture development and climate responsiveness in order to achieve food security and broader development goals under a changing climate and with increasing food demand (Aweke 2017). CSA initiatives are playing a vital role in the economy through enhancing resilience and reducing/removing GHG. Evidence also reveals that CSA efforts have made efficient, productive, and resilient technologies, practices, and approaches more available (Mersha and Van Laerhoven 2016). CSA interventions have resulted in increased yields, diversified crops, improved soil fertility, saved labor, and other benefits (Sterrett 2011).

Despite these benefits, CSA approaches often fail to take into account the differences in men's and women's needs and capabilities in adapting to climate change, and instead have an implicit male bias that privileges male needs, interests, and priorities in the distribution of opportunities and resources (Skinner 2011). The achievement of positive outcomes through interventions should depend on whether the measures have considered gender dimensions of climate-change adaptation. For instance, understanding the cultural construction underlying the crop choices made by female and male farmers is important in devising gender-sensitive experimentation to help identify crops with high resistance to the adverse impacts of climate change. A study by Mersha and Van Laerhoven (2016) indicated that petty trade, hairdressing, and the sale of local drinks, spices, firewood, and charcoal, as well as working as a daily laborer, were all widely used climate-adaptive measures employed by female household heads. Carpentry work and the sale of charcoal and firewood were the preferred adaptive measures taken by male household heads. This implies that it is essential to consider disparities in gender during the implementation of CSA approaches for mitigating climate change and increasing productivity. Understanding how men and women respond to low agricultural production resulting from climate change is important to finding effective entry points for building resilience and for sustainable development. For example, men often respond to the effects of climate change by investing in cash crops and increasing their incomes, while women respond by producing low-value subsistence crops to meet the food demands of the family (Perez et al. 2015). Furthermore, women are assigned multiple roles related to the reproductive and productive aspects of their lives. The varied roles they play in society can enable them to switch between their different identities and adapt to the adverse impacts of climate change (Marshall et al. 2010, Perez et al. 2015). Failure to consider such differences in climate change adaptation and mitigation interventions contributes towards further aggravating gender inequity in terms of income and livelihoods.

Women's access to land and water resources also influences their involvement in decision-making processes such as investing in the restoration of degraded grazing and agricultural lands. For instance, women in northern Ethiopia, with access to land and water resources, have contributed to sustainable watershed management interventions, including the construction of stone bunds and other soil and water conservation practices and in land rehabilitation efforts for degraded communal grazing lands through the establishment of exclosures (Mengistu et al. 2005). Such interventions have resulted in positive outcomes, such as lowering soil erosion, increasing biodiversity, and increasing groundwater recharge, all of which contribute to increased agricultural production and greater resilience of the farming systems (Mekuria et al. 2007). Yet, women's participation in decision-making processes, particularly in establishing and managing exclosures, has been limited by the general assumptions of villagers that men are more assertive than women and because of the decision-making bodies' use of informal get-togethers to make major decisions regarding the management of exclosures (Yami et al. 2013). The lack of inclusiveness in decision making has, therefore, limited the desired positive outcomes of watershed management practices, including adaptation to climate change and building resilience of rural communities to the adverse impacts of climate change. Women's high labor input, if accompanied by a more inclusive decision-making process, would maximize the positive outcomes of the interventions (Nedessa et al. 2005, Yami et al. 2013).

Thus, the active involvement of women in decision-making processes and interventions is important to formulating and implementing gender-sensitive CSA policies, which could facilitate the implementation and scaling-up of productive, sustainable and resilient production systems, while reducing rural poverty, improving rural livelihoods, and contributing to climate change adaptation and mitigation. CSA technologies used for mitigating the adverse impacts of climate change on agriculture must consider the need for women's involvement and contributions in decision-making processes.

18.4 Energy and Gender

For most of the developing countries, biomass collected from natural forests and crop residues is the major source of household fuel consumption. The heavy dependence on these natural resources results in forest degradation and low agricultural productivity. This shows that there is a close relationship between agriculture and energy demand. Agriculture, through providing bioenergy, is becoming a source of energy, while fossil fuels have become a major input in modern agricultural production (FAO 2013). With the focus on increasing agricultural productivity, agricultural practices are highly dependent on the use of energy, and this necessity is now more apparent than ever. Despite high demand, the gap between energy needs and actual access to energy is widening, however. This energy demand gap, in turn, increases the burden on women and girls, since they are the actors responsible for collecting fuel for use in households. Hence, to empower women and build capacity for responding to climate change, there is a need to develop energy efficient technologies, practices, and approaches that can minimize the burden faced by women and girls (Khatri-Chhetri et al. 2017).

Employing energy-smart activities (i.e., activities that enable efficient use of energy) is important for achieving increased productivity, sustainability, and resilience of production systems and livelihoods. Moreover, promoting energy-smart food chains, which improve access to modern energy services and can increase energy diversity, can strengthen resilience capacity of women and households. For instance, in Ethiopia, engaging women in promoting multipurpose trees, which can serve as both an energy source and as a means of improving soil fertility, could be an essential instrument for enhancing their responsiveness to climate change. Tailoring such approaches could thus enhance the adaptive measures taken by women toward climate change (Kiptot and Franzel 2012). This is because energy, for women, is a means of carrying out household duties, like heating and cooking, and is also a means of income generation, through the sale of fuelwood and charcoal. Energy is required for women to carry out all of these duties and it has a pivotal role in their livelihoods. Thus, shortages in the availability of and access to energy increase women's vulnerability (Murray et al. 2016).

However, one of the major issues in gender equity and energy use is women's limited access to affordable and appropriate choices of energy (Woroniuk and Schalkwyk 1998, FAO 2013). Quite often, women with improved access to alternative energy sources have a better chance of directly supporting and improving their households' agricultural productivity. For example, the practice of using animal manure as fertilizer can be an effective means of increasing productivity, although manure (dung) is also sometimes needed as fuel. If women gain access to alternative energy, however, the manure can then be used to enhance soil fertility, and consequently, increase agricultural productivity (FAO 2010).

According to Murphy (2001), the major problems in gender equity and energy use include a lack of addressing women's total energy needs for reproductive and productive purposes; the lack of recognition of the economic value of women's work, by making their labor contributions invisible at all levels of the energy system; gender disparity in ownership of land, trees, and other productive assets required to access and control energy services; and gender-inequitable decision making at all levels in the energy system.

Women's minimal power in making domestic financial decisions plays a big role in reducing their access to modern energy. Because of the diminished control women have over household income, financial decisions fall under the control of men, which prohibits women from purchasing new and preferable energy products and services or financing energy-related community projects (Berhe et al. 2017). Investments to improve stoves, kitchens, and cooking fuels tend to be considered as marginal items when men make the decisions about household purchases (Murray et al. 2016). Women interested in acquiring new energy equipment may lack the capital to buy it or be unable to obtain the money (Lambrou and Piana 2006). This, coupled with their reduced ability to secure loans and credits from different institutions, curtails women's ability to gain access to various alternative energy sources. For example, women rarely decide upon whether to purchase a biogas digester (Farnworth et al. 2013). Biogas-purchasing households are typically male-headed, and ownership is vested on male household heads because the purchase of energy and other key resources is traditionally seen as a male task. This impediment makes women less productive and more vulnerable (Berhe et al. 2017).

Lack of access to various alternative forms of energy has devastating consequences for women. Women must travel long distances and spend several hours a day collecting fuelwood as well as work long hours doing household chores under unsafe conditions. Being deprived of basic energy services denies women many opportunities (Murray et al. 2016, Berhe et al. 2017). They are, therefore, less likely to be involved in other income earning activities, such as agriculture or trade, which could diversify their livelihoods; less likely to be economically independent; and less likely to have improved resilience to the impacts of different shocks, including those arising from climate change (Asfaw and Maggio 2016). Therefore, providing women with alternative energy sources could simplify their burden and strengthen their responsiveness to climate change

To reduce the excessive reliance of households on biomass energy and decrease GHG emissions, different alternative energy options have been employed in Ethiopia and other Sub-Saharan African countries. Investing in hydropower energy, geothermal energy, wind energy; the distribution of cook stoves and biogas; and the expansion of agroforestry are all among the various alternative energy interventions in Ethiopia. However, these alternative energy interventions still lack the involvement of women. Women are not getting adequate benefits from these energy-related development interventions. Inequitable sharing of benefits undermines the realization of the development goals of the climate smart approach, as there is a direct relationship between energy and agriculture. Hence, a holistic approach, which integrates sustainable energy use and agricultural production, is necessary to enhance the livelihoods of women and strengthen their responsiveness to climate-related shocks. Integration can also greatly reduce the pressure on natural resources and minimize the need for external inputs (e.g., energy, chemical fertilizers, and pesticides). In order for CSA to have an all-around and better chance of success, it should be gender-sensitive and inclusive of women. Involving women in the production of on-farm renewable energy sources, like agroforestry, would be a feasible approach for achieving CSA objectives. The introduction of multipurpose trees on farms, for example, can enable farmers to sustainably increase income through

Case Study 18.1 Fuel-Efficient Stove Production in Yeku Watershed, Amhara Region, Ethiopia

Background information

A very large number of women in Ethiopia use traditional open-wood fires for cooking and heating. This mechanism of obtaining energy is highly inefficient and is harmful for health. The use of improved stoves for cooking is highly beneficial to curbing the adverse impacts of the traditional open-wood fire system. This is the rationale behind the fuel-efficient stove production project in Yeku Watershed, which is part of the AMAREW (Amhara Micro-enterprise Development, Agricultural Research, Extension and Watershed Management) project funded by USAID.

Approach

In 2004, a total of 10 women were trained by the project in the production of fuel-efficient stoves and then supplied with the required molds to start off their venture. The women contributed their own money as capital to initiate stove production. Currently, the women have reached a stage of being registered as a cooperative by the Cooperatives Promotion Bureau.

Impact

Of the various benefits of fuel-efficient stoves, one is the reduced fuelwood consumption. Through the use of fuel-efficient stoves, it is possible to maintain local vegetation cover by reducing deforestation. Fuelwood consumption per capita is estimated at 1 m^3 of dry wood per annum, and, taking the household size of Yeku Watershed to be 220 households, the equivalent amount of dry wood is required for the annual incremental yield from the vegetation cover of the watershed. Because of the 50% fuel efficiency of the improved stoves to be produced, it is possible to reduce deforestation rate by 50%. Moreover, the increased fuel efficiency reduces fuelwood requirement for households. This opportunity eases the various problems related to collecting fuelwood; thus, the women will have enough time and can devote the effort required to be productive in other activities like farming and going to school. In addition to these positive impacts, the women can gain economic benefits through selling the stoves to local markets. The women of Yeku Watershed began the production of fuel-efficient stoves with an initial capital of 500 Birr, and they currently have managed to raise this amount to over 7,000 Birr. Within a year of production, each member of the association received a 500-birr dividend, in addition to setting aside 2,000 birr as working capital. The involvement of the women in off-farm income generating activities such as this is very important in building their adaptive capacity. It is important mention the health benefits that comes from using energy efficient stoves beyond the income generated.

Policy implication

This project supports Ethiopia's energy policy, which has the objective of improving the energy supply and efficiency of energy utilization and ensuring a reliable supply of energy at the right time and at affordable prices, particularly to support the country's agricultural and industrial development.

To find out more see: Kidane Georgis. 2009. *Integrated watershed management for improved resource management and agricultural production in the semi-arid regions of Ethiopia.* Addis Ababa, Ethiopia, 64 p.

diversifying agricultural production, as well as sustainably meet their energy demands (FAO 2013). In addition, women involved in on-farm renewable energy production, such as agroforestry, will have less demand for fuelwood, which in turn eases the pressure put on local forest resources (FAO 2010). Thus, implementing CSA approaches should also ensure gender sensitivity and equity, and this inclusiveness must be integrated into rural development policies and strategies (Shikuku et al. 2017, Karlsson et al. 2018).

With all of the multifaceted energy problems women face today, their chances of becoming productive and resilient to climate change and other shocks are slim to none. Fortunately, these problems can be resolved, and their impacts curbed, if gender equity is assured in energy use. Understanding and mainstreaming energy-smart production into CSA and ensuring that this energy-smart approach is gender sensitive will be instrumental in realizing the goals set forth in accomplishing CSA objectives.

18.5 Conclusions

Climate smart agriculture approaches that include and address gender disparity and enhance and enforce technologies, practices, and strategies for achieving gender equity can result in fair benefit sharing among men and women. This, in turn, contributes to more ownership of the outcomes of interventions, such as livelihood improvement and prevention of land degradation. Nevertheless, the failure to ensure gender equity has challenged technology and development interventions in achieving CSA objectives. Gender inequity in accessing agricultural technologies and farm inputs, and the lack of devising gender-responsive technologies with the active involvement of both female and male farmers in designing, planning, and implementation of the technologies will constrain the achievement of increased agricultural production and improved incomes. Moreover, women's poor access to land and water resources has influenced their adaptive capacity and their contribution to building resilient farming systems through watershed management and other sustainable land-management practices. Gender inequity in the use of energy resources also results in poor outcomes, due to sociocultural and political factors that lower women's access to energy-efficient technologies and practices.

To sum up, the lack of inclusive decision-making processes in agricultural production, land- and water-resources management, and energy use have lowered the effectiveness of the interventions for achieving sustainable CSA outcomes. The findings imply that addressing gender inequity, beginning at the onset of technological and development interventions, by involving both men and women in decision-making processes, is important for sustaining the positive outcomes of CSA approaches. Moreover, understanding the different needs and capabilities of men and women in adapting to the negative impacts of climate change, as well as the similar and varied effects of the technologies and practices, on both women and men, should be considered in gender-sensitive, equitable, and women-inclusive CSA approaches.

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19. Climate-Smart Approaches for Strengthening Livelihood Resilience in Ethiopia

Tewodros Tadesse*

Summary

Ethiopia's farming community is identified as among the most vulnerable to climate change because of its dependence on agriculture for its livelihood. In the face of climate change, Ethiopia's largely rural and agrarian population is directly experiencing adverse effects on their livelihoods and on the environment. The country's limited capacity in economic, institutional, infrastructural, technological, and knowledge-base aspects adds to the fact that the population remains vulnerable to climate change. Climate-smart approaches for strengthening livelihood resilience appear to be the only viable options for reducing poverty and vulnerability in the face of climate change. The challenge is that, while a great majority of the population perceives ongoing climate change, many are slow to adapt to climate change due to deep-rooted poverty. Current macroeconomic policies in the country adopt strategies and development approaches that contribute toward adaptation to climate change by expanding livelihood opportunities and reducing vulnerability. At the same time, there is evidence of the emergence of a platform for better adaptive capacity across different regions in Ethiopia. This chapter discusses the importance of policies for improved economic performance in order to reduce poverty and build farmers' wealth, assets, and access to institutional services, which is fundamental in enabling farming communities to adopt climate-smart approaches for strengthening livelihoods.

Keywords: livelihood, climate change, poverty, vulnerability, resilience, Ethiopia

19.1 Introduction

The world is facing degraded environmental quality both in clean air and water and of ecosystem services (Stern et al. 1996, Pearce et al. 2013). The favorable climatic conditions and environmental landscapes we used to take for granted are either no longer available or are dwindling. In terms of socioeconomic manifestations, the qualities, opportunities, and choices that people used to enjoy are either disappearing or getting more and more constrained. Although the impacts of climate change are global in nature, it is the developing countries[1] that are, by and large, more likely to be affected by the vagaries of "natural disequilibrium" in which climate change is one of the special forms of natural imbalance (Stern 2006, UNFCCC 2007, IPCC 2007). The peculiar susceptibility of developing countries to the effects of climate change emanates from the fact that a large proportion of their populations depend mainly on agriculture[2] and natural resources that are highly susceptible to climate change and environmental degradation. The susceptibility of the agricultural sector to climate change exacerbates the vulnerability of the population in developing countries that depends on it for food and livelihoods. Amidst the growing populations of these countries and better economic opportunities now available, food production and supply

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* Mekelle University, Department of Agricultural and Resource Economics, Mekelle, Ethiopia
Correspondence email: tewodros.tadesse@mu.edu.et

[1] In our contemporary world, the accepted terminology—"developing countries"—may, at times, give rise to misleading conclusions or interpretation. For instance, the so-called BRICS countries (Brazil, Russia, India, China and South Africa) may be considered as developing countries. While they may have a large population that depends on agriculture, the vulnerability to climate change of this important sector (i.e., agriculture) in the BRICS may not be as severe as the developing countries from Africa and southeast Asia. Thus, the arguments we make in relation to climate change-nexus-livelihood (or, climate change versus vulnerability and resilience) are more of contextual and/or country-specific.

[2] As an economic sector, general agriculture mainly includes livelihood strategies in crop farming, animal husbandry, forestry and fishing.

may not be able to meet the estimated 60% increase in food demand[3] by 2050 if constrained by the vagaries of nature and climate change (FAO 2013). In other words, unless climate-smart approaches are pursued, future climate change may severely limit our ability to feed the growing population by 2050 (FAO 2013).

Many reports, notably including Stern (2006) and IPCC (2007), confirm that climate change is largely caused by anthropogenic activities. The field of economics describes climate change as a unique form of negative externality. The emission of greenhouse gases (GHG) through production and consumption processes, largely by the developed world, leaves the developing countries with much to ponder. Unless this negative by-product is taken care of unilaterally or cooperatively, it is going to continue presenting daunting challenges for humanity.

Climate-smart approaches have much to provide toward addressing the challenges of climate change, whether by improving food production, economic growth, or development, yet with fewer unintended consequences than other approaches (World Bank 2012). The very essence of the climate-smart approach strikes one clear message: the realization of sustainable agricultural production through the process of building adaptive capacity and resilience to climate change while combating the rise of GHG emissions (FAO 2013).

Political commitment, economic policies, and international cooperation may all play major roles if efforts to meet the goals of ensuring sustainable development while keeping climate change at bay are to be realized. First, political commitments for mutual benefit and compromise are vital in the implementation of economic policies designed to tackle climate change while creating an environment conducive to climate-smart approaches. Second, sustainable economic approaches can be promoted by designing green economy policies. Establishing mechanisms and investing in technologies that may help increase resilience to and adaptive capacity for climate change (and that generally promote climate-friendly and climate-resilient economic polices) contribute to sustainable development. Hence, by embracing political commitments as well as by adopting climate-resilient economic approaches, a win-win outcome could prevail from both the societal and environmental perspectives.

In this chapter, we discuss the urgent need to implement climate-smart approaches for strengthening livelihood resilience in the context of Ethiopia, based on the review of different relevant studies conducted in Ethiopia, in particular, and in eastern Africa, in general. This chapter is organized as follows. Section 19.2 describes Ethiopia's contemporary socioeconomic and environmental conditions and reviews climate change impacts on the agriculture sector and its consequences on livelihoods. Sections 19.3 and 19.4 describe the political commitments for as well as community practices of climate-smart approaches; the conclusions follow, in Section 19.5.

19.2 Climate Change Impacts on Agriculture and Livelihoods in Ethiopia

Agriculture is the mainstay of Ethiopia's economy. While agriculture's share of the gross domestic product (GDP) is declining, it is still the largest, at about 46% (CIA 2013), as compared to the other sectors. The country earns most of its foreign exchange (MoFED 2012) primarily from the export of agricultural products. About 80% of Ethiopia's population is employed in the agriculture sector, which is mostly characterized by subsistence farming (MoFED 2010). Therefore, the fate of the Ethiopian economy (and the livelihoods of the majority of the population) depends on the performance of its agriculture sector. When agriculture performs well in any fiscal year, the overall economy does the same; when the agricultural harvest suffers, the whole economy follows suit. In general, agriculture is "a make or break" sector in the Ethiopian economy, at least for the foreseeable future.

As a country located in the Eastern Africa region, where most climate change models predict there will be increased variability in precipitation levels (rainfall), unforeseen changes in Ethiopia pose yet greater threats to the agriculture sector and livelihoods of smallholder farmers by affecting food and water security, natural resources, and biodiversity (McCarthy et al. 2001). Over the years, climate change in Ethiopia has manifested itself in various biophysical and socioeconomic phenomena. Irregular and uneven distribution of rains, decreasing river flows, expanding desertification, increasing temperatures, declining yields, and the occurrence of extreme weather (such as droughts and floods) are some of these manifestations (Aragie 2013, Simane et al. 2016). Since most of Ethiopia's agriculture is rainfed, the agricultural sector's vulnerability to climate change and environmental disaster could result in dire consequences if the status quo remains. Given this, it is imperative to give due attention to and study multifaceted

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[3] Over the last decade, developing countries have achieved respectable economic growth. It is also observed and projected that growth will continue to create economic opportunities in the long future, which raises the choice in food type and quality.

impacts of climate change on livelihood outcomes in an effort to design agricultural practices and policies that help ensure sustainable development.

A study by Yesuf et al. (2008) found that about two-thirds of the farm households perceived a decrease in rainfall and a rise in temperature over the last 20 years. A similar study by Deressa et al. (2008b) reported that about 83% of the surveyed farm households perceived changes in precipitation and temperature. Deressa et al. (2008a) indicated that no region is spared and that all regions in Ethiopia are vulnerable, to varying degrees, to climate change. However, the farm households in the relatively marginalized, semi-arid and arid regions of Afar and Somali in particular that are projected to be highly vulnerable. Even the Oromia region—widely known for its agricultural potential—has vulnerable highland and midland areas, which are often hit by recurrent droughts. In Ethiopia, crop farming is typically correlated with climatic variability, and when rain fails, crop harvest follows suit. Different studies (Conway et al. 2011, Di Falco et al. 2012, Kassie 2014) have found that climate change has had a significant impact on both farm productivity and farm net revenues. Kassie (2014), for example, estimated that maize yield will decrease, on average, by 20% through the 2050s as a result of climate change, if business as usual continues. Furthermore, Kahsai et al. (2017) estimated that business-as-usual climate fluctuations would reduce net returns of wheat-producing farm households between 8% and 12.7% through 2050. They add that if this occurs, the poverty rate would increase between 11.2% and 30% in the same period. More generally, Deressa and Hassan (2009) estimated that net crop revenue by 2050 and 2100 would decrease as a result of climate change and that the reduction in 2100 would be much higher than the reduction in 2050.

Given that agricultural production constitutes the single largest source of rural-household income in Ethiopia, the adaptation of the predominantly rainfed agricultural sector to climate change is absolutely critical in order to protect the livelihoods of the rural poor and further improve food security (Deressa et al. 2008a). As a measure of adaptation and reducing the risk of vulnerability to climate change, Deressa et al. (2008a) suggest the promotion of tailor-made interventions to support the livelihoods of farmers. For example, in regions with high agricultural potential, promoting irrigation and relevant infrastructure, institutionalizing effective early-warning systems to help farm households better cope in times of drought, and promoting the adoption and production of drought-tolerant crop cultivars and livestock all can contribute to adaptation and reduce farmers' vulnerability to climate change. For the lowland pastoralists, who rely on livestock for their livelihoods, the practice of grazing animals in certain areas, but moving to reserved sites during dry seasons (i.e., valley bottoms and hilltops), is a means of adaptation that reduces the risk of livestock loss. This risk management practice allows land to recover from grazing, similar to shifting cultivation within agricultural communities (Orindi and Murray 2005). Moreover, migration, often to neighboring areas (although sometimes to more distant locations), in search of pasture and water has been an important livelihood strategy among pastoralist communities in the lowlands of Ethiopia.

Studies (Yesuf et al. 2008, Deressa et al. 2008b) have observed, however, that there were a large number of farm households (42-58%) that perceived changes in temperature and precipitation, yet continued with their business-as-usual livelihood strategies (i.e., doing nothing to combat climate change). Instead, when times get difficult, desperate farmers often take a "last resort" or short-term risk management solution, such as the sale of assets, like livestock. This leaves them uninsured against sudden and extreme shocks, thus leaving them even more exposed to long-term risks emanating from climate variability and change. Among the Ethiopian farm households, the most commonly cited barriers to adopting some form of adaptation strategies include lack of information, lack of money, shortage of labor, shortage of land, and poor irrigation schemes (Yesuf et al. 2008, Deressa et al. 2008b).

The inability of farmers to adopt climate-smart approaches is effectively a recipe for disaster because the occurrence of extreme weather at any time would increase the vulnerability of farm households to shocks and long-term changes in precipitation and temperature. This, in turn, may lead to the loss of livelihood activities, many of which are at the behest of nature (most notably, agricultural activities).

As reported in case studies in Ethiopia and South Africa by Bryan et al. (2009), assets, wealth, and institutional services are key for adaptation to and reducing vulnerability of rural farm households to climate change. However, official records (MoFED 2012) have shown that about 29.6% of Ethiopia's population lives below the international poverty line of USD 1.25 per day, while UNICEF (2013) puts the proportion of people living below the poverty line at 39% (for the period 2006–2011). This huge chunk of the population living in poverty reflects the big challenge that lies ahead in facing climate change: the constraints that limit farmers' ability to accumulate assets and wealth or to access institutional services necessary to adopt climate-smart approaches. Ethiopia's limited capacity in economic, institutional, infrastructure, technology, and knowledge-based assets adds to the fact that the population remains vulnerable to climate change.

19.3 Enabling Policies for Climate-Smart Approaches

Political commitment to decent economic performance over the years and in the long run is fundamental to enabling farming communities to adopt climate-smart approaches. In the last two decades, Ethiopia's federal government's economic policy has revolved around the Agricultural Development-Led Industrialization (ADLI) policy, in which agriculture and rural development take center stage. While this policy has made progress in terms of lifting millions out of poverty (MoFED 2010), success has always been at the behest of climatic conditions. Building on the ADLI strategy, which has guided the country's economic approach over much of the last two decades, the Growth and Transformational Plans (GTP I and GTP II) envision transforming Ethiopia into a lower-middle-income country by 2025 through agricultural development (MoFED 2010, NPC 2016). The GTP plans integrate climate smart strategies of generating clean and sustainable energy, promoting sustainable agriculture (both crop and livestock), and promoting sustainable use and management of land and forests. The ultimate goal of the GTP plans is about not only eradicating poverty in Ethiopia well beyond 2025, but also ensuring equity among its diverse population in choices, services, resources, and production during the process, through sustaining the current rapid and equitable economic growth (MoFED 2010, NPC 2016). In the face of climate change, GTP I projected that the agricultural growth rate would be as large as 8% per annum (MoFED 2010). This agricultural growth was envisioned to be achieved by improving crop and livestock production practices through agricultural intensification via improved inputs and better residue management, as well as the introduction of low-emission agricultural techniques, ranging from the use of carbon- and nitrogen-efficient crop cultivars to the promotion of organic fertilizers (FDRE 2011).

Ethiopia's Climate Resilient Green Economy (CRGE) strategy document (FDRE 2011) more specifically states that the government's priority is to avert unsustainable agriculture by reducing land and soil degradation, which may exacerbate vulnerability to drought and floods. The green economy strategy outlines two pillars of the sustainable development approaches, which include the adoption of agricultural and land-use efficiency measures, as well as protecting and re-establishing forests for their economic and ecosystem services, based on experiences drawn from community practices in different countries, as reviewed in the following section (FDRE 2011, Edwards et al. 2013). Nationwide, afforestation and restoration of forest programs have practiced at a large scale. Outcomes suggest this is already leading to rehabilitated landscapes that can perform vital ecosystem services. In the process, this approach is believed to reverse deforestation and forest degradation and support the continued provision of ecosystem services. The impact of this will be significant, since more than 80% of Ethiopian households' energy supply today—particularly in rural areas—comes from fuelwood. Equally important, the share of the forestry sector in the GDP (which currently stands at an estimated 4%) will rise through the production of honey, forest coffee, and timber (FDRE 2011). These approaches will continue to play significant roles in reducing shocks and vulnerability, create opportunities for adaptation to climate change, enhance resilience through income diversification, and increase availability of animal feeds.

Naess (2012) singles out Ethiopia as one of the few countries in the world to embrace the essence of climate-smart agriculture and to begin to account for climate change in agricultural policy frameworks. Ethiopia's commitment to follow climate-resilient agricultural approaches and its quest for sustainable energy are also clearly documented in the GTP plans as well as in the CRGE strategy (MoFED 2010, FDRE 2011). These policy and strategy documents clearly outline that sustainable development approaches can be pursued through sustainable agriculture, afforestation, and clean energy expansion in combination with resource efficient technologies in industries, all of which would ultimately contribute to poverty reduction and increase overall resilience and adaptive capacity to climate change (NPC 2016).

19.4 Examples of Climate-Smart Community Practices

As reviewed in Section 19.2, studies (Deressa et al. 2008a, Deressa et al. 2008b, Bryan et al. 2009, FDRE 2011, FAO 2013) have revealed that while the great majority of farm households understand the on-going impacts of climate change, a significant proportion are still unable to utilize adaptation strategies for dealing with the consequences of climate change, such as drought, global warming, and flooding. This is partly due to limited technology options.

In turn, some farm households in Ethiopia, either individually or collectively, have started creating platforms for better adaptive capacity. Notable examples that conform to climate-smart approaches include farm households that actively restore biodiversity and conserve soil and water resources, such as those in Tigray; farmers that practice conservation agriculture in Konso (Southern Nations, Nationalities and Peoples' Region or SNNPR); and the forest rehabilitation union farmers in Humbo (again, in SNNPR).

In Tigray, for example, large-scale soil and water conservation activities have been conducted through governmental agencies and NGOs alike that have led to remarkably rehabilitated areas; the Abreha we Atsbeha area is a notable case. In the Konso of SNNPR, conservation agriculture is being practiced on a wider scale and is a worthy example of sustainable agriculture that could be scaled up. The most notable example, in this case, is the Humbo Natural Forest Regeneration and Rehabilitation Program in the Wolayita zone, SNNPR. This forest rehabilitation initiative, primarily administered by the farmers' union (cooperatives), is playing a significant role in helping farmers to combat vulnerability and increase resilience through diversifying income and increasing access to animal feed. The Humbo natural forest rehabilitation program is also playing a bigger role in increasing the adaptive capacity of the member farmers to climate change by creating wealth and assets that serve as insurance mechanisms that can be invoked in times of distress caused by climate variability. Furthermore, the Humbo forest restoration scheme is a pioneer in carbon trading, from which farmers in the cooperative generate a lot of income (personal communication, 2014; Tefera 2012). In 2011 and 2012, respectively, the cooperative farmers generated carbon revenues of about USD 34,184 and USD 48,915, respectively. The stock of GHG sequestrated by the project in 2011 alone was estimated to be about 73,000 tons of CO_2 equivalents, although this amount has not yet been verified (Tefera 2012). In effect, the Humbo natural forest regeneration program provides vital ecosystem services that lead to increased societal and ecosystem resilience (Tefera 2012).

The farm households who did make use of adaptation measures were observed to use a mix of alternative adaptation strategies in an effort to reduce vulnerability and boost resilience. Among the major adaptation measures in farm households in Ethiopia were changing the crop varieties, adopting soil and water conservation measures, harvesting and storing rain water, planting trees, and changing planting and harvesting periods (Yesuf et al. 2008, Deressa et al. 2008b). Such climate-smart activities contribute to reduced vulnerability for agricultural production and also create mechanisms for adaptation in the forms of conserved moisture and improved soil fertility. The resulting higher yields and the prospect of ensuring their sustainability ultimately lead to improved resilience in the farming community (Araya et al. 2011).

Although these adaptation measures were applied in order to shift agricultural practices, farm households also invariably exploited risk management strategies by diversifying livelihood activities into farm and non-farm ventures. For example, agroforestry practices most commonly pursued in the SNNPR and in some parts of Amhara, Oromia, and Tigray (such as integrating trees into farming systems in order to increase agricultural productivity and ameliorate soil fertility, control erosion, and conserve biodiversity) are greatly contributing to the diversification of income sources for households, while also assisting in developing their adaptive capacities and reducing their vulnerability to climate change (Neufeldt et al. 2013). For instance, Abdelkadir and Assefa (2013) documented, in a case study of Gedeo's agroforestry system, that the livelihood opportunities presented from such agroforestry practices are diverse in nature, which ultimately contributes to creating adaptive capacity and developing farm households' resilience to climate change.

Other potentially innovative climate-smart approaches include bio-farm practices, including the production of energy such as biogas (Edwards et al. 2013). In SNNP and Oromia, for instance, the agroforestry practice that farmers pursue simultaneously encourage households to exploit the opportunities presented by the bio-farm through engaging in "cleaner" and more sustainable forms of energy production. This practice not only helps to improve health (through less exposure to smoke) and nutrition, but also performs significant indirect ecosystem services as a result of less deforestation and lower emissions (Garrity et al. 2010, Neufeldt et al. 2013).

So far, as seen in a number of experimental studies conducted by governmental agencies and NGOs, the use of crop and livestock insurance has been observed to be limited among farm households in Ethiopia. Some private banks have started to offer insurance schemes as part of risk management for livestock loss or crop failure. Insurance as a risk management strategy is still at a grass-roots level, not to mention farmers' reluctance to take on calculated risks. Nevertheless, insurance is becoming more important for providing essential shock-absorbing options in the event of natural disasters, and it is one of the ways through which governments may transfer risk to other agencies and spread the financial cost of recovery over time.

19.5 Conclusions

Overall, Ethiopia's farming community has been identified as among the most vulnerable to climate change because of its dependence on agriculture for its livelihood. Due to climate change, Ethiopia's largely rural and agrarian population faces adverse effects on their livelihoods and the environment. The country's limited capacity in economic, institutional, infrastructural, technological, and knowledge-base aspects adds to the vulnerability of the population to climate change

At the macro level, strategies and development approaches that contribute toward climate change adaptation are taking place. The promotion of afforestation and forest rehabilitation programs not only contributes to climate-smart approaches, but also to sustainable development. In many ways, these approaches expand livelihood opportunities and reduce vulnerability. However, significant challenges still remain at the micro level. In the Ethiopian experience, while a great majority of the population perceives ongoing climate change, some studies have revealed that many farm households have been slow to adapt to it. Such business-as-usual approaches can increase the vulnerability of farm households to shocks and long-term changes in precipitation and temperature. This, in turn, can lead to loss of livelihood activities, many of which are at the behest of nature (most notably, agricultural activities). On the other hand, there is also increasing evidence that farm households, either individually or collectively, have begun to create platforms for better adaptive capacity across different regions in Ethiopia. Some farmers are reportedly using a mix of alternative adaptation strategies in an effort to reduce vulnerability and boost resilience, while others have adopted risk management strategies by diversifying livelihood activities. Lessons learned from these activities may be used to guide scale-up strategies.

In many respects, the sound development trajectory Ethiopia currently pursues is the best form of adaptation to climate change: sustainable and equitable economic growth. This type of growth will build the wealth and assets of farmers, as well as enhance institutional services through improving institutions and expanding the infrastructure necessary for quality education and health care services needed to help people adopt climate-smart approaches.

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20. Enabling Policies, Strategies, and Programs to Scale-Up Climate-Smart Agriculture in Ethiopia

Alemayehu N. Ayana[a]* and Kidane Georgis[b]*

Summary

Agriculture has been and is still the dominant economic sector in Ethiopia,-and consequently, it has been one of the policy priorities of successive regimes. The past two regimes and the incumbent government in Ethiopia pursued quite different agricultural policy paths and implemented programs that fit their political agendas. The past two regimes' approaches rather failed due to the high costs of implementation, ignorance concerning the experiences of smallholder farmers, and the lack of an enabling environment under unfavorable land tenure, poor markets, and lack of infrastructure. The current government has taken prudent measures to transform the agricultural sector and the rural economy of the country through the formulation of overarching agriculture and rural-oriented policies emphasizing market orientation and productivity enhancement, along with the mobilization of huge financial and human resources to implement them. Consequently, the country has achieved remarkable economic growth over the last 10 years, with agriculture being the major contributor to the economic progress. Common understanding of the latest policy environment is critical for all of the stakeholders to endeavor to achieve political goals through the wide-scale adoption of climate-smart agricultural approaches. With this in mind, this chapter synthesizes relevant and recent national policies, strategies, and programs related to agriculture, climate change, and sustainable natural resource management in Ethiopia. It also highlights global conventions and initiatives that Ethiopia has adopted to support agricultural development and sustainable natural resource management.

Keywords: policy, strategies, climate change, green economy, natural resource management, Ethiopia

20.1 Introduction

Agriculture has been one of the policy priorities of successive Ethiopian regimes because of its dominant role in the economy and sources of livelihoods for the large majority of the population. Agriculture still provides employment to 80% of the population, contributes 65% to total exports, and accounts for 42% of GDP. For quite a long time, Ethiopia has been experiencing multiple challenges in using and managing its environmental resources and addressing food insecurity. These challenges include considerable loss of the country's forest cover, topsoil, and biodiversity, as well as a decline in agricultural productivity due to intense and unsustainable human use of natural resources, coupled with environmental disasters, such as recurrent drought (Tadesse 2001, Yeraswork 2000).

Successive Ethiopian governments have put in place several policies, programs, and measures over the last half century to tackle the enduring challenges related to environmental management and addressing food insecurity (Kassahun 2012). The past two regimes and the incumbent government in Ethiopia pursued quite different agricultural policy paths and implemented programs that fit their political agendas (Kassahun 2012). The past two regimes' approaches rather failed due to the high costs of implementation, ignorance concerning the experiences of smallholder farmers, and the lack of an enabling environment under unfavorable land tenure, poor markets, and a lack of infrastructure. With this in mind, the current government has taken prudent measures to transform the agricultural sector and the rural economy of the country through the formulation of overarching agriculture and rural-oriented policies emphasizing market orientation and productivity

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[a] Ethiopian Environment and Forest Research Institute, P.O. Box 30708, Addis Ababa, Ethiopia. Email: yeroongari@gmail.com

[b] Ethiopian Institute of Agricultural Research, Addis Ababa, Ethiopia. Email: kidanegeorgis@yahoo.com

** Corresponding author*

enhancement, along with the mobilization of huge financial and human resources to implement them. As a result, the country has achieved remarkable economic growth over the last 10 years, with agriculture being the major contributor to the economic progress.

Common understanding of the latest policy environment is critical for all of the stakeholders to endeavor to achieve political goals through wide-scale adoption of climate-smart agricultural approaches. This chapter reviews and synthesizes relevant national policies, strategies, and programs related to agriculture, climate change, and sustainable natural resource management in Ethiopia. The next section reviews changing ideologies and approaches under the previous vs. incumbent regimes, followed by supporting policies and strategies as well as programs and measures derived from such processes in recent years. The chapter also highlights global conventions and initiatives that Ethiopia has adopted and implemented to support agricultural development, sustainable natural resource management, and adaptation to climate change.

20.2 Changing Ideologies and Approaches under the Previous vs. Incumbent Regimes

20.2.1 Five-Year Plans under the previous two regimes

The first official agricultural policy objectives were stipulated in Ethiopia in the imperial government's first two Five-Year Plans (i.e., 1957-1962 and 1962-1967). These two consecutive plans were in favor of large-scale commercial farms for mainly export purposes. The Third Five Year-Plan Period (i.e., 1968-1973) emphasized the modernization of smallholder agriculture and introduced Comprehensive and Minimum Package program for some parts of the country. It was reported that the success of all these plans was very minimal because of factors associated with high input costs, unfavorable land tenure, poor markets and infrastructure, and failure to draw on the experiences of smallholder farmers (Kassahun 2012).

The socialist military regime that stepped into power in 1974 also took various policy measures to enhance agricultural productivity and transform the rural economy. Some of those measures were the implementation of radical land reform, introduction of a new village-level government structure, organization of smallholder farmers into producers' cooperatives (i.e., collectivization program), the establishment of state farms, and the clustering of small and scattered villages into mega villages (villagization and resettlement programs). Despite the installation of all of these policies, agricultural production declined for many years mainly due to recurrent droughts as well as the unwillingness of the public to implement the unfavorable policies (Brune 1990, Dessalegn 2008, Habtemariam 2008).

20.2.2 Approaches under the incumbent government – from Agriculture Development Led Industrialization (ADLI) to Growth and Transformation Plan (GTP)

Cognizant of the growing challenges of addressing national food production, the incumbent Ethiopian government has adopted Agriculture Development-Led Industrialization (ADLI) as the centerpiece of its development policy since the early 1990s. ADLI places agriculture at the hub of economic development endeavors. The government envisages ADLI as a means to enhance agricultural productivity of smallholder farmers and to improve food security in both rural and urban areas. Consequently, it emphasizes market orientation, productivity enhancement, and sector development programs as a means of strengthening the provision of social services such as basic health and education, as well as infrastructure, which have a direct bearing on addressing poverty (Dessalegn 2008). The key features of the ADLI strategy include (1) commercialization of smallholder agriculture through product diversification; (2) a shift to higher-value crops; (3) promotion of niche high-value export crops; (4) support for the development of large-scale commercial agriculture; (5) effective integration of farmers with domestic and external markets; and (6) tailoring interventions to address the specific needs of the country's varied agro-ecological zones.

Proponents of the ADLI strategy argue that agriculture should be the starting point for initiating the structural transformation of the economy, and that smallholder farmers constitute the cornerstone of economic growth. The ADLI framework presupposes productivity enhancement of smallholder agriculture and agriculture-based industrial development, using domestic raw materials and labor-intensive technology. Although the government strongly believes that ADLI is the fastest way to ensure economic development, critics doubt its effectiveness, arguing that it tends to disregard labor productivity by focusing on land productivity. Moreover, those critics argue that smallholder agriculture cannot shoulder the responsibility of transforming the performance of agriculture in a manner that could enable it to play a pivotal role in boosting Ethiopia's development efforts, as expected, because of its fragmented nature and the small size of per-capita land holdings.

Ethiopia had the Plan for Accelerated and Sustained Development to End Poverty *(*PASDEP) over the period of 2006–2010. More recently, with the vision to propel Ethiopia into middle-income country status by 2025, the Ethiopian government launched the Growth and Transformation Plan (GTP-1) for the period 2010/11–2014/15. It emphasized the central role of agriculture as a major source of economic growth, as well as gradually creating favorable conditions for industry to play a key role in the economy as well. The four major goals in GTP-1 were (FDRE 2010b): (1) sustaining faster and more equitable economic growth; (2) maintaining agriculture as a major source of economic growth; (3) creating favorable conditions for industry to play a key role in the economy; and (4) building capacity and advancing good governance. It was envisaged that the achievement of this plan would enable the country to meet the Millennium Development Goal vested on the country. In order to implement the aforementioned GTP goals, the government envisaged new programs and institutions, such as the Agricultural Growth Program (AGP) and the Ethiopian Agricultural Transformation Agency (ATA). The AGP is a comprehensive program focused on increasing sustainable agricultural growth in Ethiopia that has three major components: (1) agricultural production and commercialization; (2) small-scale rural infrastructure, to improve productivity and increase the efficiency of key value chains through improved access to market development and management; and (3) management and monitoring to support effective coordination of the AGP at all levels of implementation.

For enhancing the agricultural productivity under GTP-1, the emphasis given included scaling up models of smallholder farmer practices, expansion of small and medium scale irrigation, development of rural infrastructure both all-weather roads and access to markets, and the promotion of commercial farming. In addition, efforts to conserve natural resources and mitigate and adapt to climate change were emphasized. Departing from the initial ADLI strategy, which gives very limited attention to natural resource conservation and environmental management, the GTP document focused on maximizing the synergy between agriculture, the environment, and other similar sectors. It recognizes that sustainable development in Ethiopia can be achieved if development programs are pursued in the social, economic, and environmental sectors in a balanced way during the plan period. It also calls for the equitable distribution of benefits accrued from the implementation of the GTP-1 development programs. Various measures have been taken during this planning period to address sustainable natural resource management and climate change issues in Ethiopia. These measures include strengthening tenure security by expanding the ongoing land certification project, building capacity in community-based approaches to watershed management, scaling up successful models for watershed management, and strengthening natural resource information management, such as evaluation, synthesis, and dissemination of best management practices and innovations, in sustainable land management.

Building on the positive achievements of GTP-1 and lesson drawn from its implementation, the Government of Ethiopia (GoE) has formulated the Second Growth and Transformation Plan (GTP-2). Moreover, in formulating GTP-2, the government considered the existing national and sectoral policies, strategies, and programs, as well as its commitment to Sustainable Development Goals (SDGs) and regional and international economic collaboration initiatives. The major objective of GTP-2 is to serve as a springboard towards realizing the national vision of becoming a low middle-income country by 2025, through sustaining rapid, broad-based, and inclusive economic growth, which accelerates economic transformation and the journey towards the country's renascence (FDRE 2016).

20.3 National Policies and Strategies

20.3.1 The Conservation Strategy of Ethiopia

The Conservation Strategy of Ethiopia (CSE), which was issued in 1997, is the foundation for most environment- and natural resource-related policies in Ethiopia (EPA 1997a,b). It evolved from the 1994 National Conservation Strategy (NCS) document (IUCN 1990). The CSE document constitutes 11 sectoral and 11 cross-sectoral issues and presents the state of natural resources and the causes of environmental degradation and lays out a policy and strategy framework for sustainable use and management of natural resources (EPA 1997a). The document provides 19 guiding principles upon which the federal natural resources and environmental policy are based.

The overall policy goal on natural resources and environment is to "improve and enhance the health and quality of life of all Ethiopians and to promote sustainable social and economic development through the sound management and use of natural, human-made and cultural resources and the environment as a whole so as to meet the needs of the present generation without compromising the ability of future generations to meet their own needs" (EPA 1997a,b). The document also stipulates policy objectives for both sectoral and cross-sectoral issues. Compared to many other similar documents, the CSE is well-organized and comprehensive, and it provided an umbrella strategic framework for the management of natural resources and the environment of the country (Melaku 2008). Despite the strength of the document, insufficient resources and human capacity were mobilized to impact the formal policy arrangement, and its programs were weakly implemented at both federal and regional state levels (Hoben 1995).

20.3.2 The Environment Policy of Ethiopia (EPE)

The Environmental Policy of Ethiopia (EPE) was formulated in April 1997 as a direct output of the CSE, particularly based on the second volume (EPA 1997b). The legal base for the environmental policy is also stipulated in the Constitution of the Federal Democratic Republic of Ethiopia (FDRE) (Proc. 1/1995), where the concepts of sustainable development and environmental rights are enshrined. The overall policy goal of EPE is to improve and enhance the health and quality of life of all Ethiopians and to promote sustainable social and economic development through the sound management and use of natural, human-made, and cultural resources and the environment as a whole, so as to meet the needs of the present generation without compromising the ability of future generations to meet their own needs (EPA 1997b). The Environmental Policy of Ethiopia has drawn from international initiatives, such as the Rio Agenda 21 and the Program for Further Implementation of this Agenda, and the IUCN's principles for caring for the Earth. It has, however, made a commendable attempt to adopt the international principles to Ethiopian conditions (Alemayehu et al. 2013).

Departing from the conventional type of goal setting, which focuses on preserving the environment, EPE emphasizes the improvement and enhancement of the health and quality of life of all Ethiopians and the need to ensure social equity in resource use. It articulates the requirement for integrating environment and development at policy, planning, and management levels for improved decision-making. The sectoral policy of EPE includes Soil Husbandry and Sustainable Agriculture; Forest, Woodland and Tree Resources; Genetics, Species and Ecosystem Biodiversity; Water Resources; Energy Resources; Mineral Resources; Human Settlement, Urban Environment and Environmental Health; Control of Hazardous Materials and Pollution from Industrial Waste; Atmospheric Pollution and Climate Change; and Cultural and Natural Heritage. The Environmental Policy of Ethiopia also addresses the following cross-sectoral policies: Population and the Environment; Community Participation and the Environment; Tenure and Access Rights to Land and Natural Resources; Land Use Plan; Social and Gender Issues; Environmental Economics; Environmental Information System; Environmental Research; Environmental Education and Awareness; and Environmental Impact Assessment (EIA).

20.3.3 Rural Development Policy and Strategies (RDPS) and the Food Security Strategy (FSS)

The Rural Development Policy and Strategy (RDPS) document, which was drafted in the mid-1990s and issued in 2001, was one of such documents disclosing the government's plans and strategies concerning agricultural and rural development, including sound natural resource management approaches. The pillar of the RDPS document is the ADLI strategy, which details the government's commitment toward accelerated economic growth and agriculture as a centerpiece of its development policy.

The Ethiopian government also adopted the Food Security Strategy (FSS) in 2002 under the umbrella Plan for Accelerated and Sustained Development to End Poverty (PASDEP, 2005/06-2009/10). It is derived from the country's RDPS and aims to increase domestic food production, ensure access to food for food-deficit households, and strengthen emergency response capabilities. This strategy gives due consideration to the problems of environmental degradation and the importance of natural resource conservation, rehabilitation, and restoration of degraded lands in order to combat drought and famine, which are induced by poor environmental management. The Productive Safety Net Program (PSNP) was initiated in 2005 as an operational program of FSS. This program was designed to assist the food-insecure population in chronically food-insecure districts in order to prevent asset depletion at the household level and create a favorable environment for future productivity improvement in rural communities.

20.3.4 The Energy Policy

The first Energy Policy of Ethiopia was issued in May 1994, following several attempts to formulate a comprehensive national energy policy with the goal of addressing the problem of energy supply and its utilization. The preamble to this policy presents the crucial role of energy in development and also details the modern energy regime in Ethiopia, which is heavily reliant on traditional biomass sources (which meet 94% of total energy requirements), such as fuelwood, charcoal, branches, dung cakes, and agricultural residues. Only 6% of the energy demand is met by commercial energy sources, such as electricity and petroleum. The Energy Policy is intended to enhance and foster the ADLI strategy and is consistent with other sector polices, such as RDPS and the environmental policy. For example, the general energy sector policy stipulates the need to promote and strengthen agroforestry programs; provide alternative energy sources for the household, industry, agriculture, transport, and other sectors; and ensure the compatibility of energy resources development and utilization with ecologically and environmentally sound practices. The policy also places high priority on hydropower resource development, a gradual transition from traditional energy fuels to modern fuels, and close attention to ecological and environmental issues during the development of energy projects. For traditional fuels development, the policy provides provisions on a countrywide afforestation program and measures to reduce the negative effects of agri-residue use for energy on soil fertility by modernizing and increasing the efficiency of the utilization of agri-residue as an energy source.

A revised national energy policy was formulated in 2013 by updating the old version. The goal of the new policy is to ensure the availability, accessibility, affordability, safety, and reliability of energy services to support accelerated and sustainable social and economic development and transformation of the country. This policy was also translated into a legal provision (Proclamation 810/2013) in order to reinforce the government's commitment to sustainable development practices as outlined in the GTP and Climate Resilient Green Economy Strategy.

As part of its plans to enhance the development of renewable energy sources, Ethiopia has started establishing wind, solar, and geothermal electric power generating plants in different parts of the country. Ethiopia has a huge potential for wind resources, with velocities ranging from 7 to 9 m/s. Its wind energy potential is estimated to be 10,000 MW. Currently, the Ashegoda and Adama wind farms are operational in north and central Ethiopia, respectively. Ethiopia receives a solar irradiation of 5000–7000 Wh/m^2 (depending on the region and season) and has great potential for solar energy production. The amount of off-grid solar power in the country is estimated to be about 5 MW, most of which currently used for telecommunications, village well pumps, health care, and school lighting. Ethiopia has also begun constructing a geothermal electric power plant in the Rift Valley, which will be completed in two phases (2018 and 2021) and will generate about 1,000 MW per year when it is complete in 2021. Much of these renewable energy strategies are integrated into the Climate Resilient and Green Economy Strategy to achieve improved access to sustainable and affordable clean energy for all by 2030.

20.3.5 Ethiopian Biodiversity Strategy and Action Plan

Ethiopia issued its National Biodiversity Strategy and Action Plan (NBSAP) in December 2005, following Article 6 of the United Nations Convention on Biological Diversity (CBD), which demands the preparation of a plan by each signatory country. This document defines the current status of, pressures on, options for, and priority action to ensure the conservation, sustainable use, and equitable share of benefits accrued from the use of biological diversity in Ethiopia. It serves as a roadmap for supporting the environmental component of Ethiopia's journey to sustainable development. The goal of the Ethiopian Biodiversity Strategy and Action Plan has been formulated as follows: "Effective systems are established that ensure the conservation and sustainable use of Ethiopia's biodiversity, that provide for the equitable sharing of the costs and benefits arising therefrom, and that contribute to the well-being and security of the nation."

The NBSAP document calls on the Federal Government of Ethiopia to find the ways and means to achieve the following: (a) develop an effectively managed protected-areas network that covers the full range of ecosystems; (b) bring the natural areas outside of the PA network under sustainable use; (c) strengthen the policy framework for biodiversity conservation; (d) develop effective legislation for biodiversity conservation; (e) build capacity in research and training; (f) undertake public education and awareness raising; (g) develop environmental impact assessments in support of biodiversity conservation; (h) develop policies and laws to regulate access to genetic resources and to ensure equitable sharing of benefits; (i) ensure effective exchange of information; (j) develop the financial resources needed; (k) and build biotechnology capacity and enhance technology transfer.

20.3.6 Forest Conservation and Utilization Policy and Strategy

The general objectives of the 2007 Forest Conservation and Utilization policy of Ethiopia read: *"to meet public demand in forest products and foster the contribution of forests in enhancing the economy of the country through appropriately conserving and developing forest resources."* The specific components that this policy and strategy document addresses include promoting private forest development and conservation, promoting forest development technologies, strengthening forest product markets, administrating and managing state forests, preventing deforestation, and establishing an up-to-date information system.

This policy and its companion forest proclamation (Proc. No. 542/2007) emphasize *economic forestry,* which focuses on how to meet the forest product demands of society and increase the contribution of forest resources to the national economy and to household livelihoods. It pays special attention to encouraging the engagement of the private sector in forest production and industrial development. However, the much desired involvement of the private sector in forest development, particularly large and medium level investment in forestry, has remained insignificant more than 10 years after the implementation of this policy. On the other hand, although tree plantations and forest products marketing by smallholder farmers have significantly increased in the last two decades, the official statistics often underestimate the contribution of the forestry sector to the national economy and rural livelihoods, primarily due to the lack of reliable data and to methodological limitations (Ensermu and Abenet 2011). The 2007 forest law also clarified the powers and duties of federal and regional states. Article 18 of this proclamation vested regional states with the power to administer all types of forests in their region, including the authority to set the royalty rate and collect and utilize revenue from forest products (FDRE 2007a). A parliament approved a new forest proclamation in December 2017 that repealed Proclamation No. 542/2007. This new law, among other things, recognized community forests as a third separate property-rights regime and included articles that clarify carbon rights. The new forest law also classifies Ethiopian forests into "productive," "protected," and "absolutely protected" forests based on their environmental, social, and economic significance.

20.3.7 The Climate-Resilient Green Economy (CRGE) Strategy of Ethiopia

The CRGE strategy of Ethiopia was formulated in 2011 to improve the synergy between different economic sectors and build a green economy. It focuses on four pillars: improving crop and livestock production practices for higher food security and farmer income regions, while reducing emissions; protecting and re-establishing forests for their economic and ecosystem services, including as carbon stocks; expanding electricity generation from renewable sources of energy for domestic and regional markets; and transforming to modern and energy-efficient technologies in transport, industrial sectors, and buildings. The CRGE initiative assessed 150 potential green economy initiatives across seven sectors to prioritize those that can form a green economy program for Ethiopia. By implementing those initiatives, the GoE aims to overcome the effects of climate change and achieve middle-income status by 2025 following a green development pathway (FDRE 2011a).

Agriculture and forestry sectors have been identified as having the largest abatement potential, since about 37% and 50% of the current GHG emissions in Ethiopia come from forestry and agriculture, respectively (FDRE 2011a). The CRGE document acknowledges that the current agricultural development practices, which have resulted mainly in a spatial expansion of land under cultivation at the expense of forest and woodlands, and the energy consumption patterns, which heavily depend on traditional biomass fuels, must be reversed in order to bring about a significant positive impact on the country's economic development and the wellbeing of its people. For this reason, the CRGE document stipulated measures that could help to intensify the productivity of farmland and livestock, resulting in a decreased requirement for additional agricultural land or cattle head count. The document also planned to reduce fuelwood demand via the dissemination and usage of fuel-efficient stoves and/or alternative fuel cooking and baking techniques (such as electric, LPG, or biogas stoves). Therefore, the CRGE strategy aims to foster fast economic growth and support adaptation to climate change by limiting emissions of greenhouse gases (GHG).

20.3.8 Science, Technology and Innovation Policy

The GoE introduced its Science, Technology and Innovation Policy in 2012. The objectives of this policy, inter alia, include building the national capability to generate, select, import, develop, disseminate, and apply appropriate technologies for the realization of the country's socioeconomic development objectives and to rationally conserve and utilize its natural and human resources (FDRE 2012). This policy recognizes environmental protection and natural resource management as a crucial issue for maintaining continual and sustainable economic growth. It explains that desertification, deforestation and soil erosion, lack of solid waste disposal, and poor sewerage systems are critical environmental challenges in Ethiopia. It recommends that appropriate technologies be applied in the course of natural resource utilization and implementation of various development activities in order to address these environmental problems. The major strategies devised and the priority areas identified in the Science, Technology and Innovation Policy include the following:

- Strengthening the technologies that would help to follow up changes in the environment and to forecast, prevent, and minimize the effects of natural disasters.
- Supporting the techniques that would help the search and use of alternative and renewable sources of energy.
- Formulating and implementing the science, technology, and innovation plans, programs, and projects to accelerate the country's socioeconomic development.

- Self-sufficiency in food production and satisfying the need for other basic necessities, with due attention to environmental protection.
- Applying the S and T for awareness and control of environmental conditions and for the conservation and rational use of the natural resources of the country.
- Developing the capacity and the mechanism to search, choose, negotiate, procure, adapt, and exchange technologies that are appropriate and environmentally sound to the Ethiopian socioeconomic conditions
- Facilitating the research and development (R&D) programs that would help to discover, popularize, and develop fast growing, drought-resistant and multi-purpose tree species, so as to rehabilitate and develop degraded environments.
- Encouraging and supporting the strategies for efficient and economical use of energy in all sectors.
- Establishing a system that allows technology importation, adaptation, utilization, and disposal activities without polluting the environment and creating local capabilities to learn about, adapt and adopt green technologies.

All of these science, technology, and innovation policy aspects are relevant to climate change and have been further elaborated upon in the sectoral S and T policies, which are envisaged to be implemented through the various institutions of the socioeconomic sectors.

20.4 National Programs and Measures

20.4.1 Productive Safety Net Program (PSNP) and Sustainable Land Management (SLM)

PSNP was initiated in 2005 as an operational program of the Food Security Strategy (Woolf et al. 2015.). This program was designed to assist those in the chronically food-insecure districts in order to prevent asset depletion at the household level and to create a favorable environment for future productivity improvement in rural communities. This program consists of two components (i.e., public works and direct support). Public works are labor-intensive activities that are carried out on community land and resources, such as activities undertaken to solve problems of soil erosion, deforestation, water shortage, and infrastructure. Direct support, on the other hand, is the provision of direct or unconditional transfer of cash or food to vulnerable households that have no active members who can participate in public works. One of the challenges in the implementation of PSNP is that the ownership of community assets that are created by public works were not clearly defined (Dessalegn 2008).

The Ethiopian government also launched the SLM project in October 2008 to combat the ever-increasing land degradation problems in the country. The SLM project was envisioned to contribute to the United Nations Convention for Combating Desertification (UNCCD) and global action against climate change. The SLM project aims at reducing land degradation in agricultural landscapes, improving the agricultural productivity of smallholder farmers, restoring ecosystem functions, and increasing diversity in agricultural landscapes (FDRE 2010a). The project consists of three main components: (1) the rural land certification and administration component, which is targeted at expanding the coverage and enhancing the government's land certification program, with the aim of strengthening land tenure security for smallholder farmers; (2) the project management component, which details the project implementation procedures, using the existing institutional arrangement at the federal, regional and district levels; (3) and the watershed management component, which is designed to support the scaling-up of the best land management practices and technologies for smallholder farmers in the “high potential” / “food secure” areas that are increasingly becoming vulnerable to land degradation and food insecurity. The SLM projects are implemented by using the existing institutional arrangement at the federal, regional, and woreda levels (Woolf et al. 2015).

The second phase of SLM project was started in 2013 with more or less similar objectives with the first phase. These objectives included scaling up best practices in watershed management, strengthening land tenure through land certification, and knowledge management. In addition to those objectives, the second phase of the SLM project aims to address climate-related issues and includes measures to reduce GHG by achieving the goals set in both the GTP and CRGE strategies.

20.4.2 Measures related to public sector research and extension system

The GoE is determined to support the agricultural development endeavors with up-to-date technologies and information generated through research. As a result, besides reorganizing and strengthening federal research institutions, which focus on conducting strategic research of national importance, regional agricultural research institutes (RARIs) were established to conduct research of regional importance. Higher-learning institutions were strengthened and developed to train the necessary human power for conducting basic and applied research of national importance.

Extension services are reoriented in an entirely new direction, from the previous top-down approach to a more participatory approach. Since the early 1990s, the reorientations of the research and extension services have taken place side by side with a reallocation of public expenditure in favor of these two activities. In the extension system, the number of development agents was increased drastically to assist farmers and pastoralists in disseminating improved technologies through training and demonstration. For facilitating this, the Ministry of Agriculture established Farmers Training Centers over most parts of the country and assigned three development agents (DAs): one each for crops, livestock, and natural resources.

20.4.3 Ethiopia's Program of Adaptation to Climate Change (EPACC)

The Environmental Protection Authority (EPA) of Ethiopia developed a program for action on adaptation to climate change by updating the national adaptation program of action (NAPA) in 2010. This program document connects climate-change adaptation with the economic and physical survival of the country and identifies key climate-change adaptation measures and strategic priorities and intervention areas to address the adverse effects of climate change. The main objective of EPACC is to create the foundation for a carbon-neutral and climate-resilient path towards sustainable development in the country (FDRE 2011b). The program states that most of the solutions to climate change will be implemented by communities and farmers at local and district levels; thus, the role of federal institutions will be primarily to initiate, facilitate, and monitor activities. EPACC is closely interlinked with the Climate Resilient Green Economy (CRGE) Strategy.

EPACC identifies 20 climate-change risks and the institutions responsible for countering and mitigating each of the identified risks. The risks identified are broadly in the areas of human, animal, and crop diseases; land degradation; loss of biodiversity; decline in agricultural production; dwindling water supply; social inequality; urban waste accumulation; and displacement due to environmental stress and insecurity (FDRE 2011b). In addition, climate change risk identified adaptation strategies and options in the various socioeconomic sectors, including cloud seeding, crop and livestock insurance mechanisms, grain storage, societal reorganization, renewable energy, gender equality, factoring disability, climate-change adaptation education, capacity building, research and development, and enhancing institutional capacity and political momentum.

EPACC adequately captures the growing threat of climate change in Ethiopia and clearly spells out the need to mainstream climate change concerns in all spheres of development policy making and planning and at all phases and stages of the planning and implementation process. The program clearly states the urgency of taking practical adaptation and mitigation actions in the various social and economic sectors. However, the program is compiled from contributions made by different government ministries, implying that the climate-change adaptation issue is being addressed in a less coherent manner (FDRE 2011b). Moreover, the role of non-state actors in the planning, design, and implementation of activities mentioned in the work program is not clearly spelled out. Support and concerted effort, in the form of funding, technical assistance, training, and technology transfer, is extremely important in order to adequately implement EPACC targets.

20.5 Global Conventions

Ethiopia has adopted several global treaties and conventions that can support agricultural development and sustainable natural resource management. The country is also actively engaged in implementing international initiatives related to climate change mitigation and adaptation strategies, such as the United Nations Framework Convention on Climate Change (UNFCCC), Reducing Emissions from Deforestation and Forest Degradation (REDD+), and the UN Clean Development Mechanism (CDM).

20.5.1 United Nation Framework Convention on Climate Change (UNFCCC)

UNFCCC was adopted at the Rio Earth Summit in 1992 and entered into force in March of 1994. Since then, 195 countries have ratified the convention. The ultimate objective of UNFCCC is the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference in the climate system." The convention sets an overall framework for intergovernmental efforts to tackle the challenge posed by climate change. The Kyoto Protocol is an active international package of measures to address climate change, negotiated by UNFCCC parties in Kyoto, Japan in 1997 (UNFCC 2006).

As a signatory to the UNFCCC, Ethiopia is obliged by the treaty of the convention to address climate change through the preparation of a national adaptation document and the integration of climate change into its sectoral development policies and plans. Accordingly, Ethiopia ratified the UNFCCC (1994) and its related instrument, the Kyoto Protocol (2005), and submitted its initial national communications in 2001 and National Adaptation Program of Action (NAPA) in 2007 (FDRE 2007b).

The Bali Action Plan identified forest-based mitigation, particularly REDD, as a viable mechanism for reducing GHG emissions in 2007. Within a framework of sustainable forest management (SFM), increasing the forest area through afforestation and reforestation, restoring degraded forests, and substituting carbon-intensive materials with wood-based biofuels are also viable strategies for climate-change mitigation (FDRE 2011a). All such strategies can generate increased revenues and employment, thereby providing economic alternatives to forest conversion.

20.5.2 The Convention on Biological Diversity (CBD)

The CBD was signed in 1992 in Rio de Janeiro, and about 187 parties have already ratified the convention. The convention's three main goals are the conservation of biodiversity, sustainable use of biodiversity, and the fair and equitable sharing of benefits arising from the commercial and other utilization of genetic resources. Ethiopia signed the CBD in 1993 and ratified it in May 1994 (Proc. 98/1994).

To meet the planning requirements of the convention, as well as national biodiversity conservation goals, Ethiopia developed its NBSAP in 2005. Ethiopia has been involved in many aspects of biodiversity conservation, including national park planning and in-situ and ex situ conservation of biodiversity. The Ethiopian Government has put in place policies and strategies for sustainable natural resource management, including biodiversity conservation and sustainable development.

20.5.3 United Nations Convention to Combat Desertification (UNCCD)

UNCCD is the only legally binding international agreement on the conservation of natural resources in dryland areas. Its goal is to combat land degradation and promote sustainable development in dryland areas. It was adopted in Rio de Janeiro in 1992, together with the UNFCCC and CBD. Since 1996, 195 states have ratified the convention, thus affirming their commitment to take coordinated global action on desertification and guarantee long-term support to the affected countries. The Government of Ethiopia signed the UNCCD in October 1994 and ratified it in June 1997. Countries affected by desertification are implementing the convention by developing and carrying out national, sub-regional, and regional action programs. The government of Ethiopia designated EPA as a focal point for coordinating the implementation of the Convention. To execute this mandate, the EPA established a National Steering Committee (NSC) for the formulation of the National Action Programme (NAP) to Combat Desertification and Mitigating the Effects of Drought, as well as formed a task force for the formulation of a National Desertification Fund (NDF).

20.5.4 Other climate change-related initiatives in Ethiopia

The GoE has recently started to implement several initiatives, such as REDD+ and CDM, to reduce GHG emissions by adopting a sustainable natural resource management approach and reducing deforestation and forest degradation. REDD is a scheme that was introduced at the 2007 UNFCCC Conference of the Parties (COP 13) in Bali. It was further developed into REDD+ with the additional goals of sustainable forest management, conservation, and increasing forest carbon stocks using economic incentives in a cost-effective manner. The implementation of the REDD+ initiative requires effective policies and legal frameworks as well as more stable resource property rights regimes. In recent years, the Ethiopian government has taken prudent actions in terms of reforming policy and institutional frameworks that are conducive to the implementation of the REDD+ initiative. These include the establishment of the new Federal Ministry of Environment, Forest and Climate Change (MEFCC) and the ongoing revision of the federal forest laws and regulations that incorporate provisions on forest carbon, forest carbon sequestration, and carbon trade arrangements. The adoption of a participatory forest management (PFM) approach and the CRGE strategy aimed at building a green economy are additional positive steps towards addressing climate change issues and sustainable natural resource management in Ethiopia.

The CDM of the Kyoto Protocol of the UNFCCC allows a country that emits carbon above the agreed emission limits to purchase carbon offset from an entity that uses biological means to absorb or reduce GHG in the atmosphere. The CDM is a suitable market mechanism for both developing and industrialized nations. Ethiopia initiated the Humbo Community-Managed Forestry project in 2005 with the support of World Vision Australia (WVA) and World Vision (WV) Ethiopia. The general objective of the project was to sequester carbon dioxide through the restoration of degraded forests, thereby contributing to the alleviation of poverty through the sale of certified emission reduction (CER) credits and forest and non-forest benefits.

20.6 Conclusion

This chapter synthesized relevant national policies, programs, and measures implemented by the Ethiopian government, as well as global conventions adopted to facilitate agricultural development and sustainable natural resources management. Despite the increasing impacts of climate change, Ethiopia has achieved remarkable economic growth over the last 10 years, with agriculture being the major contributor to the country's GDP growth. This growth is in one way or another attributed to the favorable policies, programs, and measures that the country has pursued over the last two decades to support agricultural development and sustainable natural resources management.

Besides formulating and implementing policies and programs, the government's commitment and political will towards environment and natural resource management has been improving over the last few years. This is witnessed, for example, in GTP and CRGE documents that strongly interlink agricultural development, natural resource management, environmental conservation, and climate change issues. It is recognized in the CRGE and GTP documents that addressing issues related to agriculture and environment in a holistic manner will have a significant impact on transforming the Ethiopian economy to the status of a middle-income country within the coming decade.

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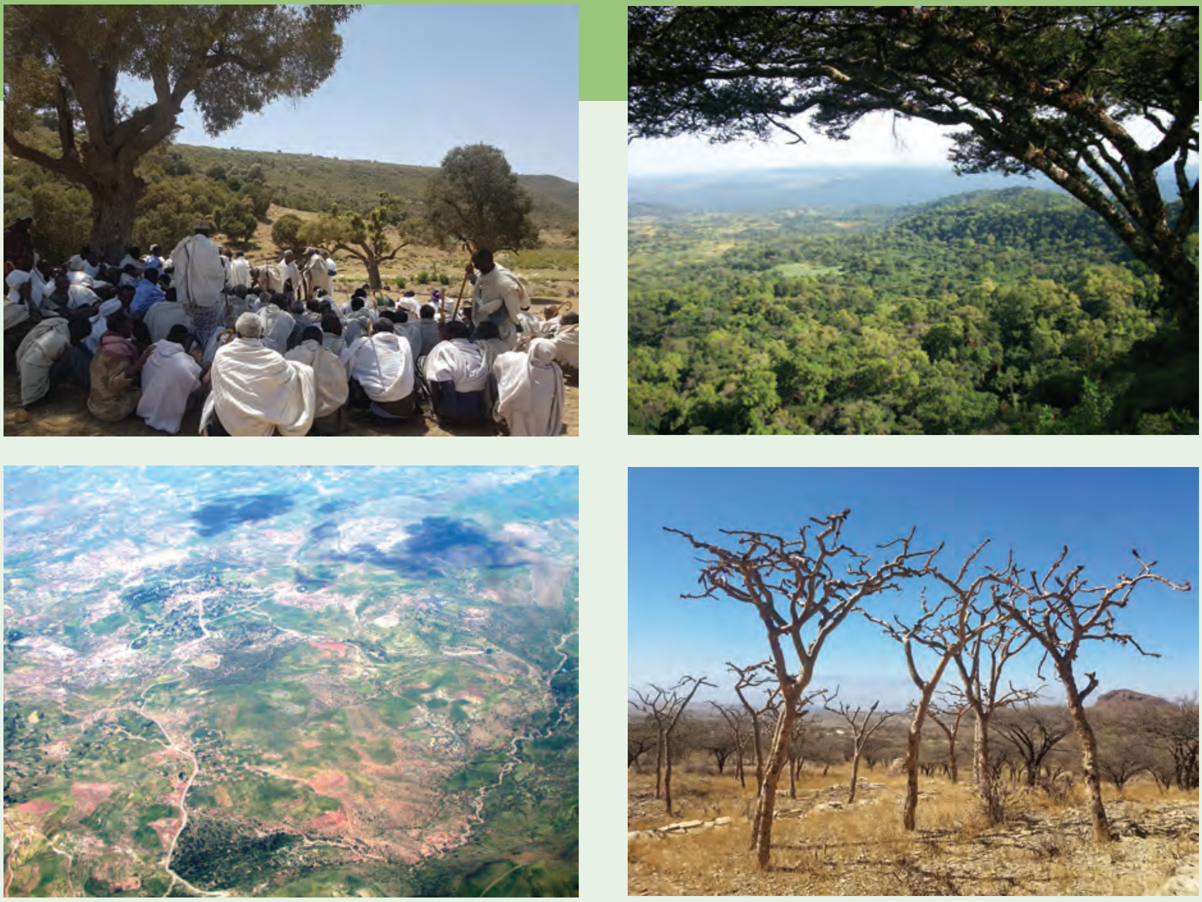
PART VI. Facilitating Decision-Making



Photos (clockwise, from top left): community in the process of conflict resolution for cross border natural resources management and utilization, Afar and Tigray border, Ethiopia (by Aklilu Negussie); protected forest, Southwestern Ethiopia (by Emiru Birhane); dryland forest dominated by Boswellia papyrifera (Frankincense), central Tigray Region (by Aklilu Negussie); and aerial view of landscapes in central Ethiopia (by Miyuki Iiyama).

21. Remote Sensing and Climate Data for Targeting Landscape Restoration in Africa

Lulseged Tamene[a]*, Quang Bao Le[b], Gudeta W. Sileshi[c], Ermias Aynekulu[d], Fred Kizito[e], Deborah Bossio[f], and Paul Vlek[f]

Summary

Tackling land degradation and restoring degraded landscapes require information on areas of priority intervention, since it is not economically and technically possible to manage all areas affected. Recent developments in data availability and improved computational power have enhanced our understanding of the major regional drivers of land degradation and possible remedial measures at different scales. In this study, we have used land degradation hotspots, which were identified using satellite and climate data covering the period of 1982–2003 (Vlek et al. 2010). We then simulated the potentials of different management measures in tackling land degradation in Sub-Saharan Africa (SSA). Scenario analysis results show that about 14 million people can benefit from the application of sustainable land management (e.g., integrated soil fertility management, conservation agriculture, and soil and water conservation) techniques targeted to improve the productivity of croplands. Fallowing degraded areas and allowing them to recover (e.g., through exclosures and agroforestry) could improve land productivity. However, this intervention requires appropriate and improved methods that can accommodate the needs of about 8.7 million people who utilize those "marginal" areas for crop production or livestock grazing. This chapter presents the benefits of utilizing long-term satellite data to analyze the potentials of targeted land management and restoration measures for improving land productivity in SSA. This approach and framework can also be used to design suitable land-use planning for the restoration of degraded areas and to perform detailed cost-benefit and trade-off analysis of various interventions.

Keywords: land degradation, NDVI, rainfall, restoration, sustainable land management options, sub-Saharan Africa (SSA)

21.1 Introduction

Recent trends show that pressures on land resources, due to natural and human-related processes, have increased and are leading to severe land degradation, thereby causing productivity decline (Eswaran et al. 2001, Lal 2010, Lal and Stewart 2011). Land degradation is the more challenging issue, as it generally leads to an interlinked, downward spiral of increasing poverty and diminishing potential productivity (Greenland et al. 1994). This cyclic process, the vicious feedback loop of land degradation→ productivity decline→ land degradation, is experienced mainly in poor societies that have limited options for coping, once degradation is aggravated and productivity has declined.

Sub-Saharan Africa (SSA) is often cited as most seriously affected by soil degradation, with huge implications for food security, economic development, and ecological integrity (Dregne and Chou 1992, Lal 1995, Scherr and Yadav 1996, Hountondji et al. 2006). Batjes (2001) reported that degraded soils account for about 494 million hectares in Africa. In addition, Oldeman et al. (1991) and Scherr (1999) estimated that 65% of SSA's agricultural land is degraded because of soil erosion and chemical and physical degradations. According to Sanchez et al. (2009), many landscapes in the region are characterized by a combination of poor soils, low crop yields, water scarcity, and poor livestock health, all of which contribute to poor human health and low levels of economic development. Considering the increasing population pressure, accompanied by low investments in land conservation, the future health of the land in SSA is in question (Vlek 2005). African smallholder farmers and pastoralists are caught in poverty traps that are also preventing the investments needed to maintain

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[a] International Centre for Tropical Agriculture (CIAT), Chitedze Agricultural Research Station, P.O. Box 1 58, Lilongwe, Malawi

[b] Natural and Social Science Interface (NSSI), Institute for Environmental Decisions (IED), ETH Zurich, Universitaestrasse 22, CH-8092, Switzerland

[c] Plot 1244, Ibex Meanwood, Lusaka, Zambia

[d] World Agroforestry (ICRAF), Nairobi, Kenya

[e] International Center for Tropical Agriculture (CIAT) c/o ICIPE Duduville Complex, Off Kasarani Road P.O. Box 823-00621, Nairobi, Kenya

[f] University of Bonn, Center for Development Research (ZEF), Walter-Flex-Str. 3, 53113 Bonn, Germany

* *Correspondence:* Lulseged Tamene (email: lt.desta@cgiar.org)

soil resources, and are thus likely to cause further losses in agricultural productivity and a decline in the provision of ecosystem services (Sanchez et al. 2009).

In light of the severity of resources degradation in SSA, and to fulfil some of the targets of some of the sustainable development goals, investments in preventing further degradation and restoring degraded landscapes should be given priority. The availability of information on land degradation hotspots and major drivers of degradation can help guide management and investment plans (Vlek et al. 2008, Sanchez et al. 2009). With improved data availability at global or regional scales and improved computational power, such as the use of remote sensing and geographical information systems, information on the extent, trend, and severity of land degradation is becoming increasingly more available at different scales (Bai et al. 2008, Hellden and Tottrup 2008, Vlek et al. 2008). This chapter attempts to identify land management options on hotspots areas of land degradation in Africa mapped by Vlek et al. (2008 & 2010). The hotspots were based on data derived from the long-term satellite Normalized Difference Vegetation Index (NDVI) of the Advanced Very High Resolution Radiometer (AVHRR) and climate data (Tucker et al. 1991, Prince et al. 1998, Milich and Weiss 2000, Weiss et al. 2001, Groten and Ocatre 2002, Thiam 2003, Evans and Geerken 2004, Herrmann et al. 2005, Vlek et al. 2008, and Le et al. 2012). Once the hotspot areas of land degradation were identified, the potential impacts of different land management options on improving the productivity of the concerned hotspots were analyzed.

21.2 Methodological Approach

21.2.1 Identifying land degradation hotspots in SSA

In this study we followed the approach used by Vlek et al. (2008 & 2010) to map hotspot areas of land degradation in SSA. The AVHRR NDVI, with a resolution of 64 km^2, has been analyzed for the period of 1982–2003 on a pixel-by-pixel basis to evaluate the temporal trend of vegetation productivity (Vlek et al. 2008 & 2010). This is based on the assumption that if the NDVI slope exhibits a statistically significant decrease over time, then the temporal trend in vegetation productivity is declining and the area imaged in that pixel is undergoing land degradation, and the vice versa (Weiss et al. 2001). The hotspot areas are then categorized into different climate zones, based on mean annual rainfall (MAR) received: *arid* (MAR <500 mm yr^{-1}), *semiarid* (500 mm yr^{-1}≤ MAR ≤ 800 mm yr^{-1}), *subhumid* (800 mm yr^{-1}≤ MAR ≤ 1300 mm yr^{-1}), and *humid* (MAR > 1300 mm yr^{-1}) as shown in Figure 21.1 (Vlek et al. 2010). The climatic zones were designated using MAR for the period 1981–2002 (Mitchell and Jones 2005).

In order to determine whether the observed land degradation is driven by climate- or human-related factors, the response of green biomass (NDVI) to inter-annual rainfall variability was analyzed using a correlation analysis (Vlek et al. 2008, 2010). The hypothesis is that a decline in vegetation greenness without a decline in precipitation can be interpreted as a decrease in the ability of the land to produce biomass, due to factors other than rainfall (Figure 21.2), as demonstrated in Propastin et al. (2008). According to Propastin et al. (2008) and Vlek et al. (2008), it is anticipated that if the upward/downward trends in NDVI and precipitation are synchronous (Figure 21.2a, b), an improving/declining vegetation cover would be observed due to increasing/declining precipitation amounts, and vice-versa. If the trends are asynchronous, meaning an increased NDVI for an observed decline in precipitation (Figure 21.2c), we can conclude that vegetation cover is recovering, despite declining rainfall (Propastin et al. 2008). This could be attributed to improving land management or diminishing human impact. In situations where the trends are more asynchronous, such that there is a decline in NDVI despite an observed improvement in precipitation (Figure 21.2d), we anticipate that the observed increase in precipitation did not cause improvement in vegetation productivity (Propastin et al. 2008). Such an observed negative trend in vegetation productivity, despite an increase in precipitation, would be due to human-induced decline in productivity.

Based on the correlation between NDVI and rainfall and its significance levels (Vlek et al. 2008, 2010, Le et al. 2012), the hotspot areas of SSA where significant level of degradation occurred were identified. According to Vlek et al. (2008 & 2010), around 2.13 million km^2 (i.e., 10% of SSA) inhabited by over 60 million people has been affected by land degradation over the observation period of 23 years. Of the 2.13 million km^2 in the degraded area, the majority (around 44%) is covered by woodland/shrubland, followed by cropland (13%) and grassland (12%). On the other hand, marginal areas, such as rock outcrops and barren land, cover about 5%. Of the hotspot areas, around 0.19 million km^2 is grassland, largely in the dry areas, which could be over-grazed. Woodlands/shrublands are widespread, predominantly in the sub-humid tropics and most are declining in extent, whereas forest/savannah and dense forests, in the humid area, are under risk of degradation. As much as 38% of the woodland/shrubland in the sub-humid

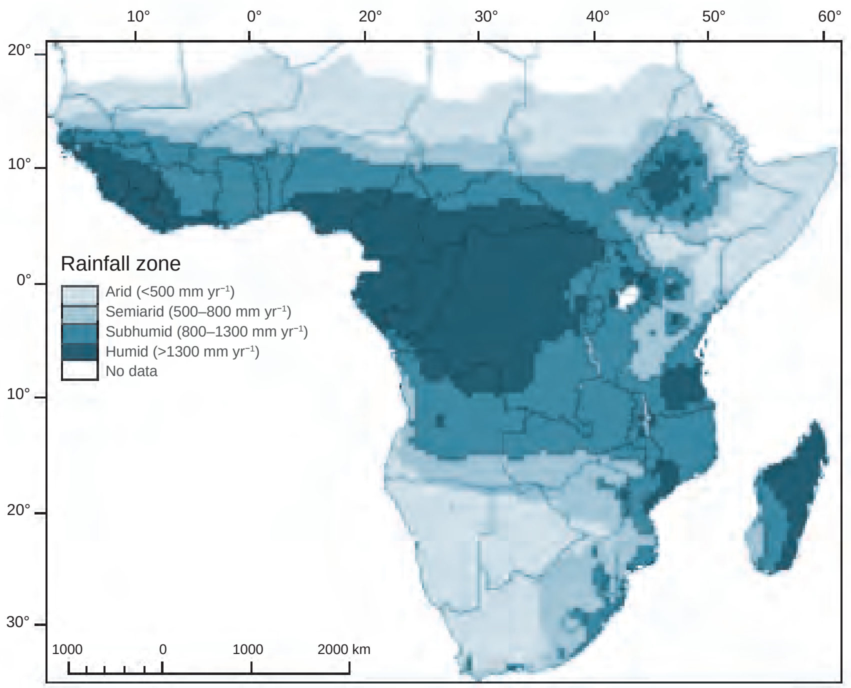

Figure 21.1 Precipitation zones classified using mean annual precipitation (MAP) for the period 1981–2002. MAP calculated based on monthly rainfall from the CRU TS 2.1 data (Source: Vlek et al. 2010).

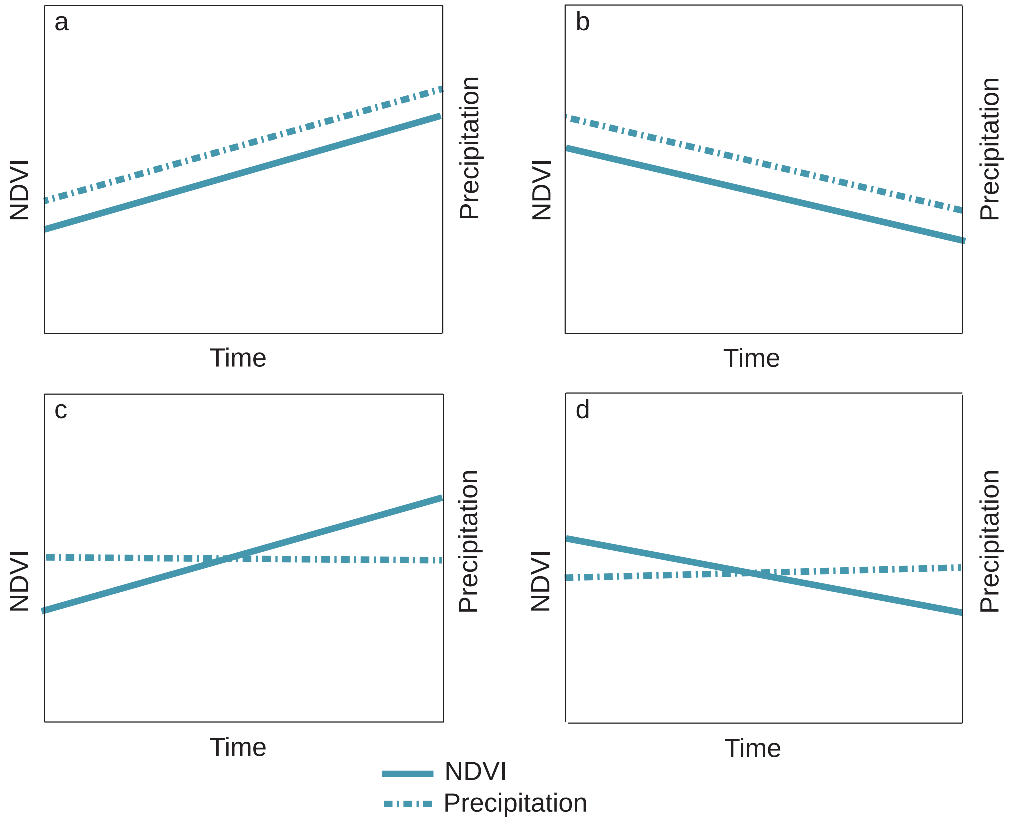

Figure 21.2 Scenarios of a possible long-term relationship between NDVI and precipitation: (a) improving NDVI due to increasing precipitation; (b) declining NDVI due to declining precipitation; (c) improving NDVI despite declining precipitation; (d) declining NDVI despite improving precipitation.

and humid areas is in a state of decline. For the densely forested regions, forest degradation amounts to 11%, most of which is located in the humid zone.

21.2.2 Characterizing the identified land degradation hotspots

In order to assess the possible management options to tackle land degradation, the hotspots (Figure 21.3) were characterized in terms of climatic zone, human population density, soil and terrain conditions, and land use/cover types. Average mean population densities for the years 1980, 1990, and 2000 were obtained from the Grid Population of the World Version 3 (GPWv3) dataset of the Center for International Earth Science Information Network at Columbia University and Centro Internacional de Agricultura Tropical (CIAT) (Balk and Yetman 2004). Each of the degrading pixels of the respective rainfall zones was differentiated according to three classes of human population density (less than the mean, more than twice the mean, and range between these two ends) to assess how human population is distributed within the degrading zones (Vlek et al. 2008). Soil classes were derived from the FAO classification of soil constraints (Fischer et al. 2002), according to the ratings of *good* for FAO classes of 1, 2, 3, or 4; *poor* for FAO classes of 5 or 6; and *unsuitable* for FAO class 7 or 8. Topographic Shuttle Radar Topography Mission (SRTM) elevation data obtained from the United States Geological Survey (USGS 2004), with a resolution of 90 m, was used to derive terrain constraints with respect to agricultural productivity. The slope and elevation data were delimited as given in the following categories: *good* for $0° \leq$ slope $\leq 15°$ and >0 elevation and ≤ 3500 m.a.s.l.; and *bad* for $15° <$ slope $\leq 25°$ and $0 >$ elevation ≤ 3500 m.a.s.l. Pixels with an elevation > 3500 m.a.s.l or surface slope >25° were considered not suitable for agriculture (Sheng 1990). The GLC2000 (Mayaux et al. 2004) map derived from Satellite Pour l'Observation de la Terre vegetation was used to differentiate the areas that are subjected to land degradation according to land-use/cover types (Vlek et al. 2008).

Each map was pre-processed, and the spatial resolution adjusted to be congruent to that of the NDVI (64 km^2). The land productivity decline map was then cross-referenced with the respective maps to understand the major attributes of the identified hotspots in terms of major biophysical and population attributes (Flugel 1997, Bull et al. 2003). This information can serve as a basis for understanding the major constraints of the degraded areas and for designing suitable management options.

21.2.3 Identifying suitable land management/restoration options

Ecological restoration of degraded landscapes is now regarded as an effective response to reducing the negative effects of habitat loss, degradation, and fragmentation on native biological diversity and ecological processes (Aerts et al. 2007). Optimal restoration of degraded lands, both in terms of resource endowment and recovery time, requires management options that are suited for the biophysical, socioeconomic, and political conditions of the targeted hotspots (Woodwell 1994, Parker 1997).

For a heavily degraded ecosystem to recover from a disturbance, the disturbing agent(s) must be removed, and/or inputs (conservation measures) that can enhance recovery or prevent further decline should be provided (Lamb 2000, Bussmann 2001, Suding et al. 2004). According to studies in different regions (Lamb and Gilmour 2003, WOCAT 2007, Twomlow et al. 2008, Gabathuler et al. 2009, Schwilch et al. 2012), some key land use and management options (alone or in combination) can be applied to reverse degradation and restore degraded areas and improve land productivity at a regional/continental scale. In this study, information from the literature, especially that compiled by World Overview of Conservation Approaches and Technologies (WOCAT) and Desertification Mitigation and Remediation of Land (DESIRE), have been used to define suitable management/restoration measures that can help alleviate land degradation in the hotspot areas identified at SSA scale (WOCAT 2007, Schwilch et al. 2012). Among the commonly recommended interventions, the potentials of exclosures (areas protected from direct human and livestock intervention), afforestation, agroforestry, biofuel plantations, and integrated soil fertility management (ISFM) in tackling land degradation were assessed. The importance and contributions of these technologies for halting land degradation and improving land productivity were discussed and documented in various publications (e.g., Fimbel et al. 1996, Nedessa et al. 2005, Vanlauwe et al. 2006, FAO 2008, Zomer et al. 2008, Mekuria et al. 2011, Schwilch et al. 2007, Yayneshet et al. 2009, Schwilch et al. 2012, Dosskey et al. 2012).

21.2.4 Assessing the environmental requirements for restoration options

The efficacy of interventions can be improved, not only if the interventions are targeted to a problem they can cure, but also if they are dedicated to locations where their requirements can be met. For instance, it would not be wise to introduce ISFM in locations where soil, terrain, climate

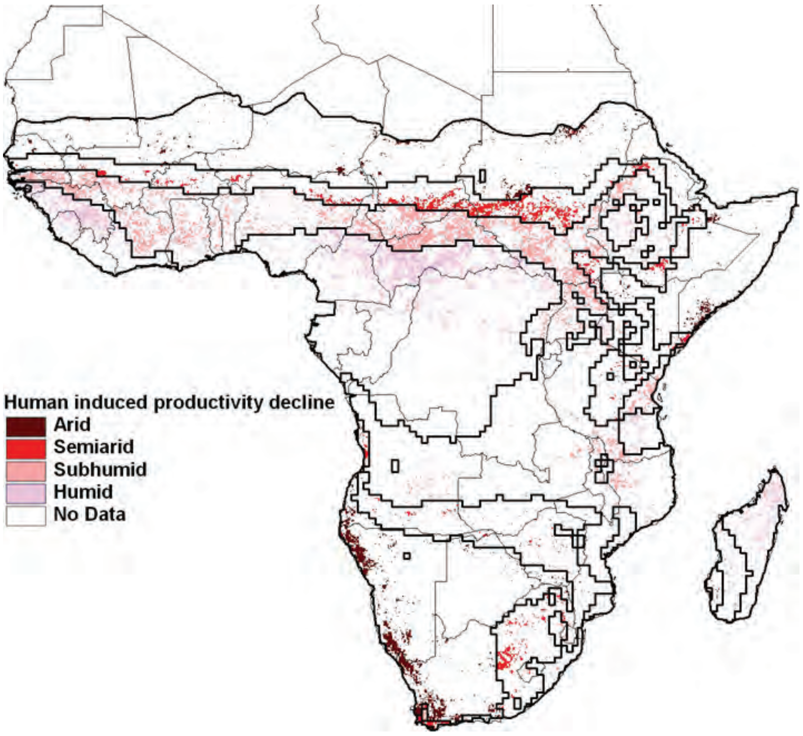

Figure 21.3 Hotspot areas of human-induced land productivity decline in SSA for different climate zones based on satellite and climate data for the period 1982–2003 (Reproduced based on Vlek et al. 2010). Note that the "contours" inside represent climate zones. No data category represents areas that do not suffer from "human inducted land degradation."

conditions, and socioeconomic realities do not support the system. It also may not be effective to introduce a system that cannot be adopted by locals, either because it is too expensive or because it is not culturally acceptable. The type of recommendation for different climatic zones and land classes also varies. For instance, it may not be feasible to recommend ISFM in arid areas where serious water limitations could prohibit meaningful agricultural practices (unless irrigated), nor may it always be acceptable to prescribe exclosures for a sub-humid environment characterized by high population density, good soils, and terrain. Although the latter option might be economically feasible, it may not be socially acceptable, if it directly competes with agricultural land. Adequate knowledge about the land requirements, cultural sensitivities, and potentials of the identified management interventions is therefore necessary in order to match options with context before land management practices are introduced.

Once the candidate techniques are identified among land restoration options, the next steps are assessing the limitations of each option (i.e., conditions where they cannot perform well based on their requirements); evaluating their tolerances (i.e., relative ability of each option to tolerate stress); and analyzing their susceptibilities (i.e., events or conditions to which they are vulnerable). The main aim here is to understand the specific biophysical requirements that must be satisfied in order for a given landscape restoration measure to be effective. This knowledge will help match restoration measures (with different sets of requirements) in the landscapes with land and soil conditions. Since this study is focused at a sub-continental scale, the choice of candidate restoration options mainly considers general requirements based on soils, terrain, climate, and existing land use/cover types.

21.2.5 Matching the problem to its potential solution

Once the conditions of the hotspots and the requirements of selected management options are determined, the next step will be matching the appropriate restoration option with the hotspots. In this case, the use of geographical information systems (GIS) can be helpful in order to easily manage geo-referenced data. GIS, coupled with multi-criteria evaluation (MCE), has been applied in a number of applications related to nature conservation, environmental planning, forest management, and the identification of rehabilitation and conservation priorities (Pereira and Duckstein 1993, Store and Kangas 2001, Ceballos-Silva and Lopez-Blanco 2003, Marjokorpi and Otsamo 2006, Zhang et al. 2010). In this chapter, a simple, rule-based, multi-criteria approach was employed in a GIS environment to identify hotspots and assign them suitable management options. The approach follows an iterative sequential process (Table 21.1) according to the general principle: *If an area experiences a significant productivity decline, and shows no or negative correlation with rainfall, then it can be considered as an area of concern; and if the area is a cropland with a suitable soil and terrain which is located in humid-sub-humid zone, then assign ISFM, ELSE proceed to the next step.*

The above example typically seeks to allocate a land management measure to a specified land degradation hotspot, considering the potentials and constraints of hotspots and the requirements of management options concerning a given land use. In areas where water limitation is expected (for instance, in arid areas), water harvesting is suggested as a "supplement" in order for a given management option to be successful. Most of the management measures can also be implemented along with soil and water conservation (SWC) practices.

In this example application, we restrict ourselves to demonstrating the procedure in crop and grasslands, considering that human influences are more pronounced on cultivated and grazing lands as compared to others land use types—although woodland and forest areas can also be affected, due to deforestation or selective logging.

21.3 Major Results and Highlights

21.3.1 Identified restoration options and their requirements

Table 21.2 highlights the main requirements of the identified restoration options and defines the corresponding hotspot for which those measures could be effective, provided that some conditions are met. This documentation is based on experiences gained in different regions, related to the site-specific effectiveness of the respective restoration measures (e.g., WOCAT 2007, Schwilch et al. 2007, Schwilch et al. 2012, Dosskey et al. 2012). Table 21.2 also illustrates cases where some policy and institutional arrangements should be in place for the successful implementation of some of the interventions, such as exclosures. Because the use of exclosures requires restriction against human and livestock interference, its applicability in areas of high population/livestock density can be questionable; hence, alternatives should be designed before implementing the option. In addition, suggestions for the exclosure of areas that are currently under cultivation or grazing should be accompanied by "compensation" or by the provision of options to change the current use—because the benefits from exclosures may not necessarily substitute for the benefits that were derived from using the area for cultivation or grazing, at least in the short term.

Another challenge in the implementation of biofuel plantations, such as jatropha, as land restoration options is the assumption that the introduced plant species are less "exploitative" and instead facilitate recovery without themselves requiring extensive input—the idea being that these species do not put too much stress on the land (Pimentel et al. 1994). Generally, it would be ideal to introduce biofuel plants with limited tradeoffs between their environmental demands vis-à-vis their potential as sources of energy.

21.3.2 Potential impacts of the restoration options targeted to specific hotspots

After the requirements of restoration options were matched with the landscape conditions and appropriate management measures were identified and implemented, the next step would be to analyze the possible impacts of those measures. This requires long-term and detailed monitoring and impact assessment. In this study, we provided a

Table 21.1 Framework employed to assigning management options to restore land degradation hotspots. Note that different combinations are possible, and only examples are shown in this table.

	Land use	Climate zone	Soil	Terrain	Population density	Do this (*Option*)
IF	Cropland	Semiarid-humid	Unsuitable	Unsuitable	Any	Set-aside/exclosure
	Cropland	Semiarid-subhumid	Poor$^+$	Altitude <2500m	Low-medium	Agroforestry/parkland
	Cropland	Subhumid-humid	Poor$^+$	Good	Low	Improved fallow
	Cultivated	Semiarid-humid	Poor$^-$	Good	Medium-high	ISFM
	Pasture/cultivated	Semiarid-subhumid	Poor$^-$	Good	Low-medium	Agroforestry/silvopastoral
	Non-cultivated	Semiarid-humid	Any	Any	Low	Reforestation/exclosure
	Non-cultivated	Arid-subhumid	Poor$^-$	Any	Low	Biofuel plants-Jatropha

Note: Poor$^+$ = very poor soil; Poor$^-$ = poor soil that requires input generalized picture of the potential impacts of the various interventions (Table 21.2).

Figure 21.4 shows the spatial distribution of the "rehabilitated areas" in relation to the "degraded ones" after restoration measures have been implemented. The application of the restoration options identified in this study helped to restore about 65% of the degraded landscapes. Targeting the "unsuitable land" would help to address problems over a wide geographical extent, compared to managing other areas, such as cultivated or grazing lands (Table 21.2). One of the interesting results of this analysis is that targeting croplands with unsuitable soil through the use of exclosures could restore a relatively large geographical region (i.e., 1,556 km^2) in SSA, and the outcome would likely be positive, because utilizing those areas with poor soil would not yield good agricultural productivity. In addition, local communities and the environment could benefit from the regenerated areas due to exclosures (including grass for livestock, selective tree cutting for construction, etc.). Similarly, introducing biofuel plantations in areas that are less suitable for cultivation due to soil and terrain constraints could restore and improve the productivity of about 0.12 million km^2 of land.

As croplands (about 0.30 million km^2 of land) are the second largest areas experiencing significant loss of productivity in SSA, ISFM should be the primary management option employed. ISFM can help improve land productivity and food security for about 14 million people in SSA. This intervention would mainly be suitable for hotspots that already have appropriate physical land requirements for ISFM, i.e., appropriate climate, soils, and terrain. It is, however, important to recognize that employing ISFM includes input use, such as fertilizer, which can be costly and risky for farmers to adopt. It also should be noted that supplemental irrigation water and soil and water conservation measures may need to be put in place for ISFM to be productive.

Out of the 1.4 million km^2 of degraded land for which different management measures have been recommended,

Table 21.2 Restoration options and their potential "applicability" to tackle land degradation in SSA.

Management option	Basic environmental requirements and conditions for the interventions to be efficient and effective
Exclosures	A range of environments and hillsides, but if gullied, may need physical soil and water conservation measures. Suitable for degraded areas with no or very low population density. Not attractive if area is already under cultivation or private grazing. Clear land tenure and public land use policy required to succeed.
Reforestation	Depends on which trees are identified – but generally soils and terrain should not be unsuitable; should be acceptable to farmers; should not compete with other benefits; should be in areas with very low population density; can be applied in all systems (excluding croplands) but if dry, water will be needed. High security of land tenure (e.g., clear state ownership or farmer's long-term land use right) is usually required.
Agroforestry	Relatively good soils and terrain to support "agronomic" crops. Choose acceptable system to society. If in arid and semi-arid, water harvesting needed. Not in areas with no or very low population density. High security of land tenure (e.g., clear land ownership or long-term land use right) is usually required.
Biofuel crops (e.g., *Jatropha curcas*)	Less suitable for cultivation, but terrain should not be unsuitable and should be no critical water limitation. Care should be given to avoid competition for land, and local community should understand its benefits. Difficult to implement if existing land use practice is cultivation or private grazing, may be as a hedge/live fence form. Species that don't necessarily exploit the soil need to be adopted.
ISFM including intercropping and conservation agriculture	Soils and terrain should not be unsuitable. Could be effective in environments where farmers have the ability to adopt the technology. Not attractive to communities in arid and semi-arid unless additional water is provided. Not in areas with no or very low population density. High security of land tenure (e.g., clear land ownership or long-term land use right) is usually required. Incentives such as credits and subsidies may need to be in place.
Physical and biological soil and water conservation measures	Terrain should not be unsuitable, or apply on proper landscape position. Effective in conditions where farmers are part of the system and show willingness to maintain. Land ownership security should be in place. Incentives are necessary to maintain interventions. Suitable biological options should be implemented.
Water harvesting	There should be adequate runoff to be harvested. Water development (e.g., shallow ground water, boreholes, river diversion) and proper management and sharing system (regulations, bylaws on water use) should be devised
Better mineral fertilizer access and use	The agricultural system in the degraded areas with good soil and suitable terrain is still the status quo, but farmers' access to fertilizer and their fertilizer use are improved to rebuild soil nutrient reserve. The measure is suitable in populated farming zones with a good physical access to market (i.e., high proximity to roads and towns)

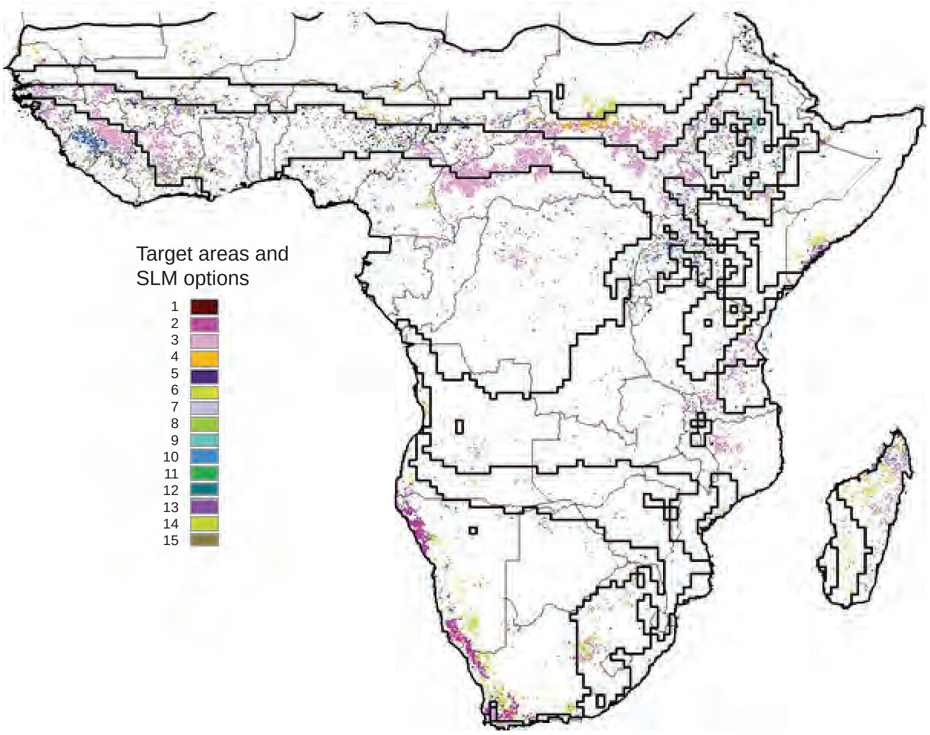

Figure 21.4 Spatial distribution of hotspots targeted with restoration measures in SSA. Note that the "Target areas and SLM options" legend corresponds to the restoration options designated to the respective land use/cover system, climate zone and land condition shown in Table 21.3.

Table 21.3 Restoration measures targeting hotspots in SSA and the potential extent of area affected.

SN	Target land use/cover	Climate zone	Land condition	Type of intervention	Extent targeted (km^2)
1	Unsuitable land	All	Bad terrain	Set-aside/exclosure	352,000
2	All types	Arid	Poor soil	Set-aside/exclosure	117,376
3	All type	All but arid	Poor soil	Set-aside/Water harvesting/Jatropha	10,394
4	Cropland	Arid and semiarid	Good terrain and good soil	SLM with water harvesting	806
5	Cropland	Sub-humid and humid	Good terrain and good soil	SLM	1,363
6	Cropland	Arid and semiarid	Good terrain with poor soil	Jatropha with water harvesting	142
7	Cropland	Semiarid	Good terrain with poor soil	ISFM with water harvesting	815
8	Cropland	Sub-humid and humid	Good terrain with poor soil	ISFM	1,569
9	Cropland	All	Bad terrain and poor soil	Improved fallow	437
10	Cropland	All	Unsuitable soil	Exclosure	1,556
12	Forest/cropland	Sub-humid and humid	Good terrain and good soil	Agroforestry or ISFM	432
13	Forest/cropland	All	Bad terrain and poor soil	Leave as forest or exclosure	62
14	Grassland	All	Good terrain and soil	Controlled grazing	1,923
15	Grassland	All	Bad terrain and poor soil	Exclosure	41
Total area conserved/restored					488,916

*Note that natural regeneration of vegetation cover and soils in arid areas may take relatively longer time compared to areas with favorable and more regular rainfall.

about 20% (0.29 million km^2 land) are assigned to be exclosures. This management option targets those areas with land characteristics (climate, soil terrain, or a combination of the two) that restrict the feasibility of other land management options, either because the physical implementation of management practices is not possible or because the economic returns of the interventions are not profitable. However, it is important to note that current cultivation or livestock grazing areas account for 46% of total land use, and that restricting their utilization will have negative social implications. If their use is restricted, planning will be required in order to find ways of accommodating the needs of about 8.7 million people who will be excluded from directly utilizing those areas. If the land condition allows, it would be more feasible and attractive to introduce agroforestry systems or fruit crops in the exclosed hotspots so that the benefits could be shared with the settlers and communities around the exclosures.

The results of this study demonstrate that targeted allocation of restoration measures might not only reverse land degradation, but also enhance land productivity and food security in SSA. Since free grazing can be a hindrance to the implementation of agroforestry and/or exclosure-related options, there is a need to design alternative options for the community when planning to implement land management practices across landscapes. Farmers' management-assisted regeneration, which has become a success story in the Sahel, could also be a useful intervention (Reij and Steeds 2003, Reij et al. 2005). It is also essential to note that careful analyses of the cost-benefits and trade-offs are necessary, and should be implemented before farmers and other concerned bodies are advised to employ the suggested management measures. In addition, it is essential to conduct a detailed analysis of processes and drivers, focusing on hotspots, in order to appropriately identify relevant restoration measures.

21.4 Conclusions

Land degradation is a serious problem in SSA that affects livelihoods and food security. The results of this study reveal that 8% of SSA is suffering from land degradation due to human-caused processes. Results also show that out of the 1.6 million km^2 of cropland with declining productivity, about 20% is located on good terrain, but with severely eroded soils; however, these soils could be restored with suitable management measures.

Analyses of the potential restoration measures targeted to serious problem areas showed that about 20% of the 1.4 million km^2 of degraded land is recommended to be protected from direct human and livestock intervention (exclosure). Of this amount, about 46% consists of cultivated and grazing lands. This means that the people using those lands need to be compensated, if the management option is to be accessible and successful.

Scenarios of preventive and restorative measures show that suitable land management measures can help prevent land degradation and restore degraded areas. However, the assessments presented above should be seen as a first approximation, and the maps and conclusions made here must be further verified in the field. It is strongly suggested that detailed data be utilized in order to get a sound picture of the processes involved. Considerable research efforts should be made to identify the immediate and proximate causes of land degradation and to develop more sustainable management and farming practices. Additionally, cost-benefit impact assessments and trade-off analyses are necessary to quantify the roles of those management interventions, including their positive and negative externalities (on society and nature).

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22. Lessons on Alien Biofuel Crops Invasiveness Risk Assessment: Based on Practical Experiences from *Jatropha curcas* L. in Southern and Western Africa

Aklilu Negussie[a]*, Lindsey Norgrove[b], Wouter Achten[c], Souleymane Nacro[d], Marc Kenis[e], Martin Hermy[f], and Bart Muys[f]

Summary

Invasion by newly introduced species is considered the second largest global threat to biodiversity after habitat destruction. Biofuel crops are increasingly promoted as economic solutions to satisfy global energy needs and as an alternative means to fight climate change and reduce greenhouse gas emissions. Some studies have warned about the risk of biological invasions and environmental damage in tropical habitats as a consequence of land conversion to biofuel crops. Once species escape and become invasive, they can have detrimental social, economic, and ecological effects and can threaten the transition to adaptive rural development. In this context, there is a need to develop ways to select and manage biofuel crops as components of resilient agro-ecosystems that balance economic profits and ecosystem wellbeing in the changing climate. This would necessitate addressing several issues, including the main biological traits and environmental circumstances associated with invasive behavior, consequences of long-term biofuel plantations and other unintentional changes in the rural landscape, the question of accountability for invasions and the consequent ecological damage, and the management and policy interventions needed to prevent invasions and respond to them if they occur. In this chapter, we reviewed the ecological fundamentals of invasiveness by analyzing the plant traits that potentially lead to invasive behavior. We applied a predictive invasiveness risk assessment model to *Jatropha curcas* L., a tropical biofuel crop of which the sustainability is heavily debated, and compared the outcomes with the current status of knowledge on its invasiveness. Then we showed effective methodologies on how to assess the invasiveness risk of biofuel crops in the field, based on our field experiences from southern and western Africa.

The chapter recommends carrying out risk assessments for exotic biofuel crops, such as *J. curcas* and others, using an *in situ* field experimental method, on top of predictive invasiveness risk evaluation models, as part of procedures to regulate their use at the national or local level. The advantage of the experimental approach is that it generates knowledge and experience useful for farmers and local communities in order to monitor, prevent, and manage potential invasive crops, and integrate their use with the overall adaptive rural development approach. Such an approach may be more successful at avoiding bio-invasions and promoting sustainable biofuel development in Africa.

Keywords: sustainability, transition, resilience, ecosystem, ecology, biological invasion

22.1 Introduction

There is increasing interest in agro-biofuel implementation globally, mainly because of environmental concerns and concerns over energy supply security (Lima et al. 2008). Biofuels may reduce our reliance on fossil fuels and lessen anthropogenic carbon emissions (Danielsen et al. 2009). However, any alternative energy must be technically feasible, economically competitive, environmentally safe, socially acceptable, and readily available (Lima et al. 2008). Ecosystems provide a wide range of services to humankind (Costanza et al. 1997). However, ecosystems undergo changes, some of which are induced anthropogenically, either intentionally or unintentionally. Biological invasions are a product of the ongoing and increasing human redistribution of species to support agriculture, forestry, horticulture, and recreation, as well as a result of accidental introductions (Santos et al. 2011, Van Wilgen et al. 2008). Invasive species can have severe effects. They can change an entire ecosystem balance by diminishing native plant or animal species that function as an important

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[a] WeForest, Ogentroostlaan 15, B-3090 Overijse, Belgium
[b] Bern University of Applied Sciences, Switzerland
[c] Institute for Environmental Management and Land Use Planning (IGEAT), Université Libre de Bruxelles (ULB), Avenue Antoine Depage 13, 1050 Brussels.
[d] Foundation Fasobiocarburant, BP 200 Le'o, Burkina Faso
[e] CABI, Rue des Grillons 1, CH-2800 Delémont, Switzerland
[f] Division Forest, Nature and Landscape; University of Leuven, Celestijnenlaan 200E-2411, Belgium
* *Correspondence:* Aklilu Negussie Mekuria (email: aklilumekuria@gmail.com / aklilumekuria@weforest.org)

resource for both natural ecosystems and human communities (Parker et al. 1999), thus, irreversibly destroying environmental resilience (Folke et al. 2004). The decrease in the resilience of one system may also affect the resilience of adjacent systems (Folke et al. 2004).

Although there is a general fear that the recently adopted biofuel plants may become invasive (Lake and Leishman 2004, DiTomaso et al. 2007, DiTomaso et al. 2010), most of the reviewed biofuel studies focused mainly on the positive aspects of the crops, while undermining their negative societal and ecological impacts. Very few studies have sought to determine the invasiveness potential of biofuel species in the tropics and sub-tropics (Dawson et al. 2009, Gordon et al. 2011, Negussie et al. 2013, Negussie 2013, Negussie et al. 2015b). It is, therefore, necessary to consider their biological attributes; the current development and production pathway; and the social, economic, and ecological risks before biofuel crops are extensively planted.

Biosecurity relies on ecological risk assessment to evaluate alternative technologies and regulations as well as to design adaptive management strategies and mitigations (Ives and Schellhorn 2011, Sheppard et al. 2011). Therefore, early screening and understanding of the invasiveness potential of new biofuel crops intended to be domesticated is valuable. This information would also be helpful in developing knowledge and tools to improve effective climate smart bioenergy technologies and management strategies in order to minimize unintended social and ecological risks in the farming communities of Africa.

22.2 Jatropha and Current Biofuel Sustainability Controversies

Jatropha curcas L. (family Euphorbiaceae) is a small tree with a life span of about 50 years. The center of origin of the species is Central America (Achten et al. 2010). Nowadays, it is widespread in Africa, Central and South America, the Caribbean, India, and Southeast Asia (Katembo and Gray 2007). The species has a high ecological adaptability and can tolerate a wide rainfall range of between 250 and 3000 mm (Foidl et al. 1996) and average temperatures of between 20 and 28 °C, but it is susceptible to frost (Heller 1996, Foidl et al. 1996, Achten et al. 2008). Because of its oily seeds and wide range of ecological adaptability, it was considered a good feedstock for biodiesel production, and, as such, it would have considerable promise for a bio-based economy (Achten et al. 2008, Chhetri et al. 2008, Makkar and Becker 2009, Corro et al. 2010). At present, however, expectations for Jatropha and other biofuel crops are low, and plantations have been abandoned, due to their poor agronomic performance and land use conflicts in Ethiopia (Wendimu 2016) and other African countries (von Maltitz and Setzkorn 2013, Negussie et al. 2016, Ahmed et al. 2018). It was previously claimed that Jatropha would grow in poor soils and wastelands that could not be used for food crops, although the yields were low (Trabucco et al. 2010, Negussie et al. 2016). Therefore, maximizing the yield of Jatropha was seen as a key variable in obtaining a positive energy balance and an economically profitable production. To achieve this, biofuel companies preferred to invest in large-scale Jatropha cultivation on irrigated fertile lands, rather than on degraded lands. To do so might provoke land competition with food crops or the conversion of valuable natural habitats (Makkar and Becker 2009). As such, the balance between food crops and biofuel production, as well as the climate change adaptation potential of Jatropha (and other biofuel crops), have been heavily debated in recent years, and there have been investment failure in many African countries (Trabucco et al. 2010, Jørgensen 2011, Negussie 2013, Wendimu 2016, von Maltitz and Setzkorn 2013, Ahmed et al. 2018). In central and southern Africa, the conversion of the Miombo woodlands into biofuel production with Jatropha caused serious environmental threats, including a large carbon debt (Romijn 2011). The high invasiveness risk of Jatropha when introduced into sensitive ecosystems, such as disturbed forests, was mentioned by DiTomaso et al. (2010). Some studies warned of biological invasions in tropical habitats as a consequence of the conversion of lands to biofuel crops (Cadotte and Lovett-Doust 2001, Lake and Leishman 2004), and then the abandonment of those lands (Negussie et al. 2013). Still, specific scientific information on the invasiveness and agronomic management of Jatropha and other biofuel crops is scarce (Negussie et al. 2013, Negussie et al. 2016). In addition, some countries, such as Australia and South Africa, have banned large scale plantations, based on the risk of Jatropha becoming invasive (FAO 2010). Similarly, other countries, such as the USA (Daehler et al. 2004, USDA-NRCS 2008), the Galapagos Islands of Ecuador (PIER 2008), and Fiji (PIER 2008) have classified Jatropha as a high-risk plant species and banned further plantations, based on semi-quantitative risk-assessment results and the invasiveness history of other species in the same genera (e.g., *Jatropha gossipifolia*). In Ethiopia, most large-scale Jatropha plantations have collapsed because of low productivity, lack of improved planting materials, and conflicts of interest among communities and stakeholders (Wendimu 2016). Similarly, Jatropha investment failure was reported in Tanzania, as a result of poor investment planning (Hashim 2014); in Kenya, as a result of low productivity (Iiyama et al. 2013) and conflict of interest among local stakeholders (Hunsberger 2010); in Ghana, mainly as a result of low productivity, weak business planning and community conflict over the land use (Ahmed et al. 2018); and in Zambia, because of low productivity and lack of market (Negussie 2013). As a result, the abandonment of large-scale Jatropha plantations may lead to environmental risk, such as invasiveness. Therefore, revisiting and assessing their invasiveness risk and developing management measures for any proposed exotic biofuel crop is imperative for avoiding ecological risks and other negative economic and social consequences.

22.3 Invasiveness Risk Evaluation Methods for Biofuel Crops

22.3.1 Semi–quantitative invasiveness risk assessment method

Three broad approaches have been adopted for the weed/ invasiveness risk assessment of plants: quantitative statistical models, semi-quantitative scoring (such as Australian and Hawaiian weed risk scoring), and qualitative expert experience-based assessments. The Australian weed risk assessment (A-WRA) (Pheloung et al. 1999) and its modified version, the Hawaiian weed risk assessment (H-WRA) (Daehler et al. 2004), are among the most widely used weed risk assessment approaches. They use a combination of predictive models, individual expert knowledge, and secondary information to assess the likelihood that a plant species will become an invasive. These approaches rely on questions related to the history of a plant's invasiveness elsewhere outside its native range, climate matching, environmental requirements, and biological attributes. The system consists of 49 questions, and a minimum of 10 questions must be answered for each species to be considered in the scoring procedure. In this subsection, the H-WRA was used for tropical and subtropical regions (Daehler et al. 2004) to evaluate the invasiveness risk of Jatropha in the tropical and subtropical regions of Africa. The questions cover a range of plant attributes in order to screen invasiveness of Jatropha. Then, the questions were divided into three sections: (1) biogeography, which encompasses the documented distribution, climate preference, history of cultivation, weediness, and invasiveness history of the plant or its congeneric; (2) the undesirable attributes of Jatropha, such as its toxicity to animals and humans; and (3) ecological traits, specifically the reproductive and dispersal mode of the species. In this invasiveness risk assessment, 38 questions were answered, based on secondary information and field observations in Zambia, Malawi, and Burkina Faso (see Table 22.1). The interpretation was made based on the final score, according to the answers to each question. The final scores were interpreted as accepted (score <1), rejected (score >6), or needs further assessment (1–6).

22.3.2 Semi-quantitative risk scoring result for Jatropha

To analyses the invasiveness risk of Jatropha, we used secondary information from different studies (Table 22.1) and field information from Malawi, Zambia, and Burkina Faso. Based on the semi-quantitative risk scoring method, Jatropha is considered to be a potentially highly invasive plant, with a score of 18 (Table 22.1). Daehler et al. (2004), PIER (2008), Crosti et al. (2010), and Gordon et al. (2011) reported the same results.

22.3.3 Invasiveness risk assessment of jatropha using field experiment

In this section, we reviewed the field assessments of jatropha invasiveness by Negussie et al. (2013) and Negussie et al. (2015a) from three years of field research and observations in Zambia and Burkina Faso and personal observation from Malawi. The tests included the occurrence of spontaneous regeneration, primary and post dispersal mechanisms, fruit and seed removal and predation by animals, natural and artificial seed germination, and early seedling survival. *In situ* ecological experiments, such as seed production, dispersal ability, and after-dispersal fate have shown important evidence for determining the future invasion risk of potential alien tropical biofuel crops (Cochard and Jackes 2005, Thompson and Davis 2011, Negussie et al. 2013 and 2015a, Flory et al. 2012).

22.3.3.1 Jatropha plantations' seeding risk to adjacent land ecosystems

The spontaneous regeneration assessment study in Zambia (Negussie et al. 2013) and Burkina Faso (Negussie et al. 2015b) revealed that, in these countries, the occurrence of Jatropha populations outside of plantation boundaries is very unlikely. No regeneration was observed in adjacent land uses (i.e., woodlands and open grasslands) in two study areas of Zambia, covering about 46 ha; similar results were also found in Burkina Faso (Table 22.2). Spontaneous regeneration was limited to within the bounds of Jatropha plantations. Fruit rain simulation (i.e., mimicking fruits dropped through gravity) experiments (Negussie et al. 2013) in Zambia showed that the dropped fruits landed predominantly under the canopy of the parent plant, within an average radius of 0.79 ±0.51 m from the parent stem. The studies showed that primary fruit and seed dispersal

Table 22.1 Invasiveness risk of *Jatropha curcas* **L. based on the Australian Weed Risk Assessment (A-WRA) modified after** the Hawaiian Weed Risk Assessment (H-WRA).

Questions			Answer	Score	Reference
Domestication/ cultivation	1.01	Is the species highly domesticated?	N	0	Achten et al. 2008, Ambrosi et al. 2010
	1.02	Has the species become naturalized where grown?	Y	Y	Raju and Ezradanam 2002
	1.03	Does the species have weedy races?	Y	Y	Bebawi and Campbell 2002
Climate and Distribution	2.01	Is the species suited to tropical and subtropical climates (0-low; 1-intermediate; 2-high)?	Y	2	Katembo and Gray 2007, Maes et al. 2009
	2.02	How does quality of climate match data (0-low; 1-intermediate; 2-high)?	High	2	Maes et al. 2009
	2.03	Is the climate suitable broadly (environmental versatility)?	Y	1	Heller 1996, Katembo and Gray 2007, Jimu and Nyakudya 2009, Maes et al. 2009, Trabucco et al. 2010
	2.04	Is the species native or naturalized in regions with tropical or subtropical climates?	Y	1	Sujatha et al. 2008, Sahoo et al. 2009
	2.05	Does the species have a history of repeated introductions outside its natural range?	Y	2	Heller 1996, Kumar et al. 2008, Maes et al. 2009, Meng Ye et al. 2009, Romijn 2011
Weed Elsewhere	3.01	Is the species naturalised beyond native range?	Y	1	Standley and Steyermark 1949, De Padua et al. 1999
	3.02	Does the species have garden/amenity/disturbance weed behaviour?	Y	1	No evidence
	3.03	Does the species have agricultural/forestry/horticultural weed behaviour?	?	?	
	3.04	Does the species have a history of environmental weed behaviour?	?	?	
	3.05	Does the species have a congeneric weed behaviour?	Y	2	Bebawi and Campbell 2002
Undesirable traits	4.01	Does the species produces spines, thorns or burns?	N	0	Heller 1996, Katembo and Gray 2007
	4.02	Does the species have allelopathic effect?	Y	1	No evidence
	4.03	Does the species have parasitic nature?	?	?	
	4.04	Is the species unpalatable to grazing animals?	Y	1	Heller 1996, Makkar and Becker 2009
	4.05	Is the species toxic to animals?	Y	1	Makkar et al. 1997, Makkar and Becker 2009
	4.06	Does the species have a behaviour of being a host for recognised pests and pathogens?	?	?	
	4.07	Does the species cause allergies or is otherwise toxic to humans?	Y	1	Kumar and Sharma 2008, Li et al. 2010
	4.08	Does the species create a fire hazard in natural ecosystems?	?	?	
	4.09	Is the species a shade tolerant plant at some stage of its life cycle?	N	0	Katembo and Gray 2007
	4.10	Does the species tolerate a wide range of soil conditions?	N	0	Campos et al. 2012, Díaz-López et al. 2012, Niu et al. 2012
	4.11	Does the species have a climbing or smothering growth habit?	N	0	Heller 1996, Katembo and Gray 2007
	4.12	Does the species form dense thickets?	Y	1	Hannan-Jones and Csurhes 2008
Plant type	5.01	Is the species an aquatic plant?	N	0	Heller 1996, Kumar and Sharma 2008, Sahoo et al. 2009, Subramanyam et al. 2010
	5.02	Is the species from grass family?	N	0	Heller 1996, Divakara et al. 2010
	5.03	Is the species a nitrogen fixing woody plant?	N	0	Heller 1996, Sahoo et al. 2009
	5.04	Is the species Geophyte?	N	0	Heller 1996

Table 22.1 *(continued)*

Questions			Answer	Score	Reference
Reproduction	6.01	Does the species have evidence of substantial reproductive failure in native habitat?	?	?	No evidence
	6.02	Does the species produce viable seed?	Y	1	Jimu and Nyakudya 2009
	6.03	Does the species hybridise naturally?	Y	1	Prabakaran and Sujatha 1999, Raju and Ezradanam 2002
	6.04	Is the species self-compatible or apomictic?	Y	1	Raju and Ezradanam 2002
	6.05	Does the species require specialist pollinators?	N	0	Raju and Ezradanam 2002, Vaknin 2011
	6.06	Does the species reproduce by vegetative fragmentation?	Y	1	Shrivastava and Banerjee 2008, Meng Ye et al. 2009
	6.07	How long is the minimum generative time (in years?)	1	1	Heller 1996, Prueksakorn et al. 2010, Islam et al. 2011
Dispersal mechanisms	7.01	Are the propagules likely to be dispersed unintentionally?	Y	1	Heller 1996, Romijn 2011
	7.02	Are the propagules dispersed intentionally by people?	Y	1	Heller 1996, Romijn 2011
	7.03	Are the propagules likely to disperse as a produce contaminant?	?	?	
	7.04	Are the propagules adapted to wind dispersal?	?	?	
	7.05	Are species propagules water dispersed?	Y	1	Parsons and Cuthbertson 2001
	7.06	Are species propagules bird dispersed?	?	?	
	7.07	Are the propagules dispersed by other animals?	Y	1	Negussie et al. 2013 and Negussie et al. 2015a
	7.08	Does the propagule of the species survive passage through the gut?	?	?	
Persistance attributes	8.01	Does the species have a prolific seed production nature ($>1000/m^2$)?	N	-1	Trabucco et al. 2010
	8.02	Is there evidence that a persistent propagule bank is formed (>1 yr)?	?	?	
	8.03	Is the species well controlled by herbicides?	Y	-1	Parsons and Cuthbertson 2001
	8.04	Does the species tolerate or benefit from mutilation or cultivation?	Y	1	BAZ 2007
	8.05	Are effective natural enemies present locally?	Y	-1	Hannan-Jones and Csurhes 2008, Shanker and Dhyani 2010
Total score:				18	Outcome of the score = 18 that is > 6 (Reject)

Note: detailed scoring procedure at Pheloung et al (1999); Outcome: < 1 ‘accept’, 1-6 ‘further evaluation’ and > 6 ‘reject’
“?” indicates no information or evidence.

Table 22.2 Summary of primary and secondary jatropha seed dispersal (mean ± S.E) in Zambia and Burkina Faso.

Field experiment	Zambia	Burkina Faso
Spontaneous regeneration (land uses adjacent to jatropha plantation)	0 out of 46 ha assessed	1 seedling out of 17 ha assessed
Fruit rain distance from the mother plant (m)	1.32±0.44 (range: 0-2.18)	-
Fruit removal by mammals (%)	83±5	-
Seed removal by mammals (%)	95±4	66±3
Natural seed germination (%)	4±3	11±2
Artificial seed germination (%)	64±3	64±2
Mean new seedling distance from jatropha fence (m)	-	2.27±0.1 (range: 0-11.9)

mainly occurred via humans and gravity (Hannan-Jones and Csurhes 2008, Negussie et al. 2013). Many human activities have a significant role in seed dispersal, intentionally or accidentally (Kolar and Lodge 2001, Lake and Leishman 2004). Additionally, studies conducted in Zambia indicated that the germination rates of naturally dropped fruits under the canopy were low (about 12%), with a high probability of mortality in the subsequent dry season. The fruit rain simulation experiment of Negussie et al. (2013) further showed that fruit dispersal by gravity and post-fruit rain physical surface displacement, possibly by a combination of wind and overland water or sediment flow, is limited. Most of the fruits were found within a distance of 10 cm from their original position. Seed dispersal is also size and weight dependent (Teketay 2005). Jatropha seeds are rather large, and are in a range of 1.69 × 1.4 × 0.84 mm to 1.84 × 1.31 × 0.85 mm in length, width, and breadth, respectively (Misra and Misra 2010), and have an average weight range of 0.5–0.8 g (Abugre and Oti-Boateng 2011, Negussie et al. 2014). It is known that plant seeds that are dispersed easily by wind are usually very light and have a feather-like structure that acts like a parachute when it is caught in the wind (Lake and Leishman 2004). Jatropha seeds clearly do not have such characteristics (Negussie et al. 2013, Negussie et al. 2014). All results (Negussie et al. 2013, Negussie et al. 2015a) showed that the probability of Jatropha seeding through natural processes is minimal, unless anthropogenic factors (such as through seed and cutting transportation to a good environment) are involved.

22.3.3.2 Secondary fruit and seed dispersal

The role of interactions between exotic plants and animals as a determinant factor in success or failure of plant introduction and further spread was explained by Nuñez et al. (2008). Jatropha seeds are very toxic due to the presence of curcin and phorbol esters (Makkar et al. 1997, Li et al. 2010); however, higher seed removal and predation by rodents (up to 100% and 98%, respectively) were observed in Zambia and Burkina Faso (Negussie et al. 2013, Negussie et al. 2015a).

22.3.3.3 Post-dispersal fate of jatropha seeds

The seed searching experiment of Negussie et al. (2013) used a metal detector and soil excavation after dispersal to estimate the seed dispersal distance. Rodents were observed transporting the seeds up to 23 m from the seed source and repositioning them in their burrows up to 0.7 m deep, but none of these seeds managed to establish. About 90% of the seeds detected were predated (Negussie et al. 2013). The predation and depth of the buried seed indicated that the probability of germination and seedling emergence was very low (Negussie et al. 2013), since the seeds were either damaged or buried deep, making it difficult for them to emerge. In addition, in both countries, it was observed that ants were carrying Jatropha seeds, piercing the seed coats, and sucking out the oily part of the nut, which eventually resulted in seed destruction.

Seed survival, germination success, and seedling survival influenced the potential of a plant to be invasive (Greenberg et al. 2001). Our germination experiments in different land-use systems in Zambia and Burkina Faso revealed an average germination success of 4% and 11% at the soil surface and 64% and 65% if buried manually at 1-2 cm depth, respectively, yet the latter is unlikely to occur under natural conditions. *In situ* seed germination success was very low for Jatropha seeds under the existing natural conditions. After germination, the overall seedling mortality rate was high, i.e., up to 83% in the Miombo woodlands in Zambia (Negussie et al. 2013). The primary cause of seedling mortality in Zambia was the consumption of the entire soft shoot and leaves by insects such as grasshoppers, stem feeding weevils, and flea beetles of the genus *Aphtona* (Negussie et al. 2013).

In summary, the experimental findings in Zambia and Burkina Faso did not confirm any risk of invasiveness of *J. curcas* in the observed ecosystems.

22.4 Discussion

22.4.1 Limitations of semi-quantitative risk assessments and experimental tests

In the case of semi-quantitative risk assessment methods, the tools are limited in complex ecosystems such as forests; they are most effective in evaluating invasion risks for open areas (Dawson et al. 2009). The other limitations of these invasiveness risk-evaluation tools are that they rely heavily on expert judgement, climate matching, and the high weight of the invasion history of the plant or its congeneric species (Negussie et al. 2013, 2015a, 2015c). If information is limited, prediction can still be possible, with few questions, but that may lead to unreliable conclusions. In the case of Jatropha, WRAs were largely based on non-scientific reports, unverified observations, and invasion characteristics of its highly invasive congeneric, *J. gossipifolia*.

In the experimental test scenario, the methods require large investments of money, labor, and space. The other important limitation is that the introduction of new biofuel crops for testing might lead to the escape of the plants into natural areas, causing invasion, particularly for plants that produce wind- and bird-dispersed seeds. Therefore, the risk of escape should be reduced by placement of the experiments in a controlled manner and by keeping the trials distant from conservation areas.

22.4.2 Lessons for local adaptive management

Biofuel has some potential to support the livelihoods of rural communities as well as sustainable rural development in Africa, if risks and uncertainties are minimized and cultivation knowledge and skills are conveyed to rural communities (Folke et al. 2003). This would increase the resilience of the social-ecological system of rural communities in Africa. Here, we mention some important issues on how to increase societal resilience through new, potentially invasive biofuel crops with considerable economic and social value (Folke et al. 2003).

Learning to live with change and uncertainty: Risks can never be completely excluded. So it is a matter of managing acceptable risks. Agricultural species, including new plants for biofuels that are below a dangerous risk level, can be assimilated into local cropping systems in order to increase income generation and income spreading.

Nurturing diversity for reorganization and renewal: Assimilate new biofuel crops as part of a mixed-cropping system, e.g., an agroforestry system, hedges, or conservation of connectivity of natural lands. This increases insurance in terms of income spreading, pest and disease control, and, because of a stable vegetated landscape, invasiveness risk.

Combining different types of knowledge for learning: Document basic information of the target species and use the best available resources to evaluate it. Use a combination of different risk assessment models (qualitative, semi-quantitative, and experimental) to screen potentially risky biofuel crops. Empower the rural community to participate in the risk assessment process and equip them to evaluate and monitor introduced alien crops by themselves.

Creating opportunity for self-organization: Learn from past mistakes; develop locally adapted agriculture and governance systems that avoid invasiveness (e.g., through rules that deny the introduction of highly invasive species), or develop rules and regulations that monitor large-scale cultivation and have plans in the case of plantation abandonment by companies (such as inspection and monitoring to prevent spread and naturalization, regular revision of management plans, adoption of new cultivation knowledge and practices, and willingness to pay compensations to the affected rural community in case environmental damage occurs).

22.5 Conclusion

To develop a better future for the biofuel sector, the negative impacts of biofuels need to be understood and minimized in order to ensure their sustainable production and use. To achieve this, we need to design strategies and methodologies to determine actual and potential invasiveness risk prospects of biofuel crops so as to minimize the involved environmental impacts, while managing the associated social and economic perturbations. Cultivating biofuel crops with reduced invasiveness risk implies that we develop the best available management interventions to maintain the capacity of the ecosystem and society to cope with and adapt to changes resulting from new biofuel crop introduction. This must be supported by a better understanding of the plant biological attributes and *in situ* reproduction behavior of the introduced biofuel crops.

From the results of the semi-quantitative risk assessment approach (H-WRA), jatropha is predicted to be a highly invasive plant; however, the first available field experiments in Zambia and Burkina Faso suggest that its invasive potential is low, at least in the studied ecosystems. Therefore, *J. curcas* is not deemed to be an aggressive plant.

This indicates to us that the current semi-quantitative weed risk assessment approaches are valuable as pre-screening tools and are suitable for making precautionary decisions on newly introduced crops. But, to reduce uncertainties in their prediction of invasion risk and avoid the possibility that they would unduly impede the development of promising biofuel crops, they should be combined with *in situ* field experimental trials and survey data. The authors recommend further, similar comparative studies in other tropical countries where jatropha and other exotic biofuel crops are being promoted.

22.6 References

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Climate change, due to both natural and anthropogenic causes, is now widely recognized as the major environmental problem facing our planet. Agriculture is one of the principal drivers of deforestation in developing countries, and it is the second largest source of global greenhouse gas emissions; however, it is also the sector that is most severely responsive to climate change. Currently, agriculture and forestry are under threat from climate change, which increases incidences of floods and droughts; temperature; occurrence of weeds, pests, and diseases; and vulnerability of organic carbon pools. Climate change also affects whole ecosystem balances, functions, and services.

Sub-Saharan Africa (SSA), as a whole, is heavily dependent on rainfed agriculture. The complex topography and low moisture availability, in combination with low adaptive capacity, makes SSA highly vulnerable to adverse impacts of climate change. It is obvious that farming is essential for securing food and generating income for the growing population in the region. However, feeding the growing population with this uncertain traditional agriculture in the face of the changing climate will leave the livelihoods of the farming community at risk. Hence, this calls for integrated and context fit options/actions, such as locally adaptive and smallholder based forests and farming systems, often interwoven in a complex landscape, for addressing challenges and tapping opportunities associated with climate variability and changes. To sustainably tackle climate change associated problems such as food insecurity, it is imperative to generate improved scientific innovations while also building on existing local knowledge and practices. To enhance the crafting of strategies for accelerating scaling, it is important to support policymakers and increase their access to improved management and practice options such as climate-smart agriculture (CSA).

Climate-smart agriculture is a strategy that fits to local contexts and demands, and it is important to achieve a triple win for smallholder farmers: food security, and climate change adaption and mitigation. To that end, this book brings together climate-smart evidence and information that helps to sustainably address climate change related challenges and opportunities in SSA, with a particular focus in the context of Ethiopian farming systems and landscapes. The book, thus, presents evidence-based and adaptive CSA technologies, practices, and policies fit to different levels and scales. These include sustainable agricultural intensification to improve productivity and resilience of smallholder agriculture at plot/farm scales and landscape and forest restoration and conservation to improve ecosystem resilience at watershed/landscape scales, while also enhancing livestock production and energy availability at the household level.

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World Agroforestry (ICRAF)
United Nations Avenue
PO Box 30677, GPO 00100
Nairobi, Kenya
http://worldagroforestry.org/