Advances in Agroforestry 12

Florencia Montagnini *Editor*

# Integrating Landscapes: Agroforestry for Biodiversity Conservation and Food Sovereignty

Springer

# Advances in Agroforestry

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**Aims and Scope**

Agroforestry, the purposeful growing of trees and crops in interacting combinations, began to attain prominence in the late 1970s, when the international scientific community embraced its potentials in the tropics and recognized it as a practice in search of science. During the 1990s, the relevance of agroforestry for solving problems related to deterioration of family farms, increased soil erosion, surface and ground water pollution, and decreased biodiversity was recognized in the industrialized nations too. Thus, agroforestry is now receiving increasing attention as a sustainable land-management option the world over because of its ecological, economic, and social attributes. Consequently, the knowledge-base of agroforestry is being expanded at a rapid rate as illustrated by the increasing number and quality of scientific publications of various forms on different aspects of agroforestry.

Making full and efficient use of this upsurge in scientific agroforestry is both a challenge and an opportunity to the agroforestry scientific community. In order to help prepare themselves better for facing the challenge and seizing the opportunity, agroforestry scientists need access to synthesized information on multi-dimensional aspects of scientific agroforesty.

The aim of this new book-series, Advances in Agroforestry, is to offer state-of-the art synthesis of research results and evaluations relating to different aspects of agroforestry. Its scope is broad enough to encompass any and all aspects of agroforestry research and development. Contributions are welcome as well as solicited from competent authors on any aspect of agroforestry. Volumes in the series will consist of reference books, subject-specific monographs, peer-reviewed publications out of conferences, comprehensive evaluations of specific projects, and other book-length compilations of scientific and professional merit and relevance to the science and practice of agroforestry worldwide.

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*Editor*
Florencia Montagnini
School of Forestry
and Environmental Studies
Yale University
New Haven, CT, USA

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*This book is dedicated to Adriana who would be so proud.*

# Preface

Agroforestry systems (AFS) are becoming increasingly relevant worldwide as society has come to recognize their multiple roles and services: biodiversity conservation, carbon sequestration, adaptation and mitigation of climate change, restoration of degraded ecosystems, and tools for rural development. This book summarizes advances in agroforestry research and practice and raises questions as to the effectiveness of AFS to solve the development and environmental challenges the world presents us today.

Currently AFS are considered to be a land use that can achieve a compromise among productive and environmental functions. Apparently, AFS can play a significant role in rural development even in the most challenging socioeconomic and ecological conditions, but still there is a lot of work to do to reach these goals. Considerable funding is spent in projects directed to enhancing productivity and sustainability of smallholders' forestry and agroforestry practices. These projects and programs face many questions and challenges related to the integration of traditional knowledge to promote the most suitable systems for each situation, access to markets for AFS products, and scaling up of successful AFS. These complex questions need innovative approaches from varying perspectives and knowledge bases.

This book gathers fresh and novel contributions from a set of Yale University researchers and associates who intend to provide alternative and sometimes departing insights into these pressing questions. The book focuses on the functions that AFS can provide when well designed and implemented: their role in rural development as they can improve food security and sovereignty and contribute to provision of energy needs to the smallholders; and their environmental functions: contribution to biodiversity conservation, to increased connectivity of fragmented landscapes, and adaptation and mitigation of climate change. The chapters present conceptual aspects and case studies ranging from traditional to more modern approaches, from tropical as well as from temperate regions of the world, with examples of the AFS functions mentioned above.

The chapters discuss current challenges faced today by agroforestry researchers and practitioners and proposes innovative approaches to tackle them. There is an emphasis on Latin America and North America with case studies from other parts of the world. Contributors are an assemblage of researchers, academicians, and practitioners from agroforestry, environmental management, and related fields who approach the issues from unique perspectives.

This book comprises three parts: **Part I, Agroforestry Challenges and Alternatives**, sets the stage by presenting the major challenges for agroforestry in the new millennium; describing how agroforestry can contribute to the achievement of Sustainable Development Goal 2 (End hunger, achieve food security and improved nutrition, and promote sustainable agriculture), with regional (tropical dry forests, temperate) perspectives; as well as showing the social-ecological framework needed when approaching these issues at the landscape level. **Part II, From Subsistence to Market Oriented Systems**, discusses the concept of sustainability in the context of AFS, including descriptions of indigenous and more modern AFS from several locations of the world, along with case studies demonstrating how AFS products can earn economic value while still maintaining their sustainability and provision of environmental services and energy needs, from small and medium to larger scales, offering recommendations for success. **Part III, Environmental Services in Multifunctional Landscapes,** focuses on the role of AFS on provision of carbon storage, climate change mitigation, and conservation of biodiversity, with examples from both tropical and temperate systems of the Americas. The **Conclusions** chapter summarizes the lessons learned while compiling this volume and lays out the pending challenges and potential solutions ahead.

A holistic, multidisciplinary perspective was taken in approaching each theme, encompassing factors and variables from multiple disciplines. This book is directed to professionals and students in a variety of fields related to agriculture, forestry, agroforestry, rural development, restoration, environmental management, ecology, and agroecology.

The main ideas originating the structure and contents of this book were born during meetings and conversations with students and colleagues whose enthusiasm, energy, and joyful attitude supporting this book made it possible from start to end. The contributors' dynamism, dedication, and persistence drove the rest. Numerous colleagues and friends also helped with their intellectual input and moral support. The contributors acted as independent reviewers of other colleagues' chapters. In addition, other external reviewers generously gave their time to read and offer useful suggestions to improve the chapters.

The following is a list of chapter reviewers: Miguel Altieri, Mark Ashton, Kjell E. Berg, Graeme Berlyn, Asha Berstch, Gillian Bloomfield, Louise Buck, Zoraida Calle D., Frank Sullyvan Cardoza Ruiz, Julián Chará, Ian Cummins, Emily Dolhansky, Beatriz I. Eibl, Carl F. Jordan, Thomas Launer, Eliot Logan-Hines, Lucas Nahuel López, Irene Montes-Londoño, Christopher Martin, Enrique Murgueitio R., Gregory Ormsby Mori, Leonora Pepper, Charles M. Peters, Daniel

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New Haven, CT, USA Florencia Montagnini
July 27, 2017

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# Contributors

**Adriana María Giraldo S.** Fundación CIPAV (Center for Research on Sustainable Agricultural Production Systems), Cali, Colombia

**Ada Albanesi** FAYA-UNSE, Santiago del Estero, Argentina

**Freddy Amores** Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), Turrialba, Costa Rica

**Jorge Araujo** Facultad de Ciencias Forestales, Universidad Nacional de Misiones, Eldorado, Misiones, Argentina

**Héctor Bahamonde** EEA INTA Santa Cruz-Universidad Nacional de la Patagonia Austral (UNPA), Río Gallegos, Santa Cruz, Argentina

**Natalia Banegas** Ciclos Biogeoquímicos, IIACS-CIAP-INTA Leales, Tucumán, Argentina

Facultad de Agronomía y Zootecnia de la Universidad Nacional de Tucumán, San Miguel de Tucumán, Tucumán, Argentina

**Rolando Barahona** Universidad Nacional de Colombia, Medellín, Colombia

**Juan Barquinero** Facultad de Ciencias Forestales, Universidad Nacional de Misiones, Eldorado, Misiones, Argentina

**Kjell E. Berg** Formcell AB/BiorenSystems, Hampden, MA, USA

**Asha Bertsch** School of Forestry and Environmental Studies, Yale University, New Haven, CT, USA

**Willan Caicedo** Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), Turrialba, Costa Rica

World Agroforestry Centre – ICRAF, Turrialba, Costa Rica

**Adolfo Cardozo** Nueva Cendigranja, Guanare, Portuguesa, Venezuela

**Carlos H. Carranza** Instituto Nacional de Tecnología Agropecuaria (INTA)-Estación Forestal INTA-Villa Dolores, Córdoba, Argentina

**Geovana Carreño-Rocabado** Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), Turrialba, Costa Rica

World Agroforestry Centre – ICRAF, Turrialba, Costa Rica

**Laura Cavallero** Instituto Nacional de Tecnología Agropecuaria (INTA)- Estación Forestal INTA-Villa Dolores, Córdoba, Argentina

CONICET (Consejo Nacional de Investigaciones Científicas y Técnicas) - CCT Córdoba, Córdoba, Argentina

**Rolando Cerda** Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), Turrialba, Costa Rica

**Julián Chará** Centro para la Investigación en Sistemas Sostenibles de Producción Agropecuaria, CIPAV, Cali, Colombia

Mainstreaming Sustainable Cattle Ranching Project, Bogotá, Colombia

**Ian Cummins** Runa Foundation, Archidona, Napo, Ecuador

**Lívia De Freitas Navegantes Alves** Núcleo de Ciências Agrárias e Desenvolvimento Rural, Universidade Federal do Pará, Belém, Brazil

**Claus Deblitz** Agri Benchmark Network-Thünen Institute of Farm Economics, Braunschweig, Germany

**Marcos H. Easdale** INTA- Estación Experimental Agropecuaria (EEA) Bariloche / CONICET, Bariloche, Argentina

**Roxana Paola Eclesia** EEA INTA Paraná, Paraná, Argentina

**Beatriz I. Eibl** Facultad de Ciencias Forestales, Universidad Nacional de Misiones, Eldorado, Misiones, Argentina

**Eduardo Esterche** Escuela Agrotécnica Eldorado, Universidad Nacional de Misiones, Eldorado, Misiones, Argentina

**Pedro Fernández** Ciclos Biogeoquímicos, IIACS-CIAP-INTA Leales, Tucumán, Argentina

**Martha Flores** Fundación Produce Michoacán, Morelia, México

**Adolfo Galindo** Fundación CIPAV (Center for Research on Sustainable Agricultural Production Systems), Cali, Colombia

**Ignacio Gasparri** IER-Universidad Nacional de Tucumán, San Miguel de Tucumán, Tucumán, Argentina

**Michael Gold** University of Missouri Center for Agroforestry, Columbia, MO, USA

**Christopher Jarrett** Department of Anthropology, One UTSA Circle, The University of Texas at San Antonio, San Antonio, TX, USA

**Carl F. Jordan** Odum School of Ecology, University of Georgia, Athens, GA, USA

**Shibu Jose** University of Missouri Center for Agroforestry, Columbia, MO, USA

**Héctor Keller** Facultad de Ciencias Forestales, Universidad Nacional de Misiones, Eldorado, Misiones, Argentina

**Julieta Kornel** Facultad de Ciencias Forestales, Universidad Nacional de Misiones, Eldorado, Misiones, Argentina

**Marcela Ledesma** CONICET/INTA-EEA Santa Cruz/UNPA, Río Gallegos, Argentina

**Eliot Logan-Hines** Runa Foundation, Quito, Ecuador

**Irene Montes-Londoño** School of Forestry and Environmental Studies, Yale University, New Haven, CT, USA

**Dardo R. López** Instituto Nacional de Tecnología Agropecuaria (INTA)-Estación Forestal INTA-Villa Dolores, Córdoba, Argentina

CCT-CONICET Córdoba del Consejo Nacional de Ciencia y Técnica, Córdoba, Argentina

**Lucas N. López** Facultad de Ciencias Forestales, Universidad Nacional de Misiones, Eldorado, Misiones, Argentina

**Miguel A. López** Facultad de Ciencias Forestales, Universidad Nacional de Misiones, Eldorado, Misiones, Argentina

**Dante Loto** UNSE-CONICET, Santiago del Estero, Argentina

**Rogerio Martins Mauricio** Universidade Federal de São João del Rei, São João del Rei, Brazil

**Ruth Metzel** School of Forestry and Environmental Studies, Yale University, New Haven, CT, USA

Azuero Earth Project, Pedasi, Panama

**Juan José Molina** Centro para la Investigación en Sistemas Sostenibles de Producción Agropecuaria, CIPAV, Cali, Colombia

Reserva Natural El Hatico, Cali, Colombia

**Florencia Montagnini** School of Forestry and Environmental Studies, Yale University, New Haven, CT, USA

**Roberto Montechiesi** Cámara de Molineros de Yerba Mate de la Zona Productora, Posadas, Misiones, Argentina

**Gregory Ormsby Mori** University of Missouri Center for Agroforestry, Columbia, MO, USA

**Enrique Murgueitio R.** Centro para la Investigación en Sistemas Sostenibles de Producción Agropecuaria, CIPAV, Cali, Colombia

Mainstreaming Sustainable Cattle Ranching Project, Bogotá, Colombia

**Fernando Niella** Facultad de Ciencias Forestales, Universidad Nacional de Misiones, Eldorado, Misiones, Argentina

**Samuel Oblitas Gillés de Pélichy** Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), Turrialba, Costa Rica

**Jenny C. Ordóñez** Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), Turrialba, Costa Rica

World Agroforestry Centre – ICRAF, Turrialba, Costa Rica

**Guillermo Martínez Pastur** CONICET, Río Gallegos, Santa Cruz, Argentina

**Raúl Pedraza** Facultad de Agronomía y Zootecnia de la Universidad Nacional de Tucumán, San Miguel de Tucumán, Tucumán, Argentina

**Leonora Genya Pepper** Fulbright Commission, Brazil 2015

Yale University School of Forestry and Environmental Studies, New Haven, CT, USA

**Pablo L. Peri** EEA INTA Santa Cruz-Universidad Nacional de la Patagonia Austral (UNPA), Río Gallegos, Santa Cruz, Argentina

CONICET, Buenos Aires, Argentina

**Gervasio Piñeiro** IFEVA-Universidad de Buenos Aires, Buenos Aires, Argentina

**Priscila Powel** IER-Universidad Nacional de Tucumán, San Miguel de Tucumán, Tucumán, Argentina

**Ernesto Reyes** Agri benchmark Network-Thünen Institute of Farm Economics, Braunschweig, Germany

**Julián Rivera** Centro para la Investigación en Sistemas Sostenibles de Producción Agropecuaria, CIPAV, Cali, Colombia

Mainstreaming Sustainable Cattle Ranching Project, Bogotá, Colombia

**Eli Roberts** Yale School of Forestry and Environmental Studies, New Haven, CT, USA

**Patricia Rocha** Facultad de Ciencias Forestales, Universidad Nacional de Misiones, Eldorado, Misiones, Argentina

**Fabián Romero** Facultad de Ciencias Forestales, Universidad Nacional de Misiones, Eldorado, Misiones, Argentina

**Belen Rossner** EEA INTA Montecarlo, Montecarlo, Misiones, Argentina

**Eduardo Somarriba** Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), Turrialba, Costa Rica

**Eric Toensmeier** School of Forestry and Environmental Studies, Yale University, New Haven, CT, USA

Project Drawdown, Sausalito, CA, USA

**Katherine J. Young** School of Forestry and Environmental Studies, Yale University, New Haven, CT, USA

**Zoraida Calle D.** Fundación CIPAV (Center for Research on Sustainable Agricultural Production Systems), Cali, Colombia

ELTI (Environmental Leadership & Training Initiative), Yale University, New Haven, CT, USA

**Andrés Zuluaga** Mainstreaming Sustainable Cattle Ranching Project, Bogotá, Colombia

FEDEGAN, Bogotá, Colombia

# Part I
# Agroforestry Challenges and Alternatives

# Chapter 1
# Introduction: Challenges for Agroforestry in the New Millennium

**Florencia Montagnini**

## 1 Past and Current Emphasis in Agroforestry Research and Practice

Worldwide, terrestrial landscapes are being impacted by unsustainable management practices in agriculture, forestry and other human activities, as well as by climate change and subsequent chains of events. Sustainable techniques geared to harmonizing ecosystem productivity and conservation can contribute to mitigating or reversing detrimental effects on landscapes. However, degraded landscapes usually exist in a complex mosaic that is constantly changing, therefore dynamic land use designs and management strategies are needed to overturn these trends. Among these strategies, agroforestry systems (AFS) are becoming increasingly relevant worldwide as society has come to recognize their multiple roles and services: biodiversity conservation, carbon sequestration, adaptation and mitigation of climate change, restoration of degraded ecosystems, and tools for rural development.

Many publications have dealt with different scientific, technical, and educational aspects of AFS. Although AFS have been traditionally practiced in many forms by humans, they only called the attention of the academic world in the 1970s–1980s, when the need to find alternatives to increase agricultural productivity, improve degraded soils and favor small landholders, especially in the more impoverished rural regions of the tropics worldwide, became more pressing.

The initial emphasis of the research in AFS was on showing how AFS could be a viable productive alternative. Most of the books published in this period dealt with different aspects of AFS design, and spatial and temporal arrangement of their components, focusing on multipurpose tree species and their functions and products

F. Montagnini (✉)
School of Forestry and Environmental Studies, Yale University, New Haven, CT, USA
e-mail: florencia.montagnini@yale.edu



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(Steppler and Nair 1987; Nair 1989; Reifsnyder and Darnhofer 1989; MacDicken and Vergara 1990; Jordan et al. 1992; Montagnini et al. 1992; Ong and Huxley 1996; Buck et al. 1999; Huxley 1999; Ashton and Montagnini 2000, among others). Also, numerous "Working Papers" and other documents were published by ICRAF (International Center for Research in Agroforestry, currently World Agroforestry Center), and CATIE (Tropical Agriculture Research and Higher Education Center) (OTS/CATIE 1986; CATIE 1999, 2001), each with their own regional emphasis (Africa, Latin America).

In the same period, nitrogen fixing trees and shrubs received special attention focusing on species of *Acacia*, *Alnus*, *Albizia*, *Erythrina*, *Gliricidia*, *Leucaena* and *Prosopis* (NAS 1979; MacDicken 1994; CATIE 1999; Gómez et al. 1995; Escobar et al. 1996; Shelton 1996; Giller 2001; Cordero and Dossier 2004; Evans and Turnbull 2004). In addition, models were developed for economic and financial evaluations of AFS, as well as for estimations of impacts on soils and for designs directed to specific situations (for example, Ramakrishnan 1992; Sullivan et al. 1992; Young 1997).

Later, responding to increasing environmental and rural development issues worldwide, research subjects on agroforestry turned into aspects related to the challenges to contribute to alleviate poverty and improve food security (Garrity 2004; Nair et al. 2004; CGIAR 2012; Nair and Garrity 2012; Montagnini et al. 2015a). Likewise, in the last decade emphasis has been placed on the role that AFS can play to contribute to the adaptation to climate change, and mitigation of greenhouse gas emissions through fixation of atmospheric carbon (Montagnini and Nair 2004; Montagnini 2005; Palm et al. 2005; Nair et al. 2010; FAO 2012; Nair and Garrity 2012; Montagnini 2015; Montagnini et al. 2015a, among many others).

## 2 Agroforestry Systems: Compromise Among Productive and Environmental Functions?

It has been estimated that AFS cover about 1000 million hectares worldwide (Zomer et al. 2009, 2014; Nair et al. 2010; Somarriba et al. 2012). This is a very rough estimate based on percent tree cover in agricultural land; AFS are assumed to comprise agricultural land which contains 10–30% tree cover (See chapter 2). The most frequent AFS are shaded annual and perennial crops, silvopastoral systems, live fences, and windbreaks. Traditional as well as more modern multistrata AFS such as homegardens and successional agroforestry designs provide households with food sources and fuelwood, as well as high value products to generate cash (Lok 1998; Kumar and Nair 2006; Montagnini 2006; Toensmeier 2007, 2013; Montagnini et al. 2015a, b; Montagnini and Metzel 2015). Perennial crops such as cacao, coffee, and yerba mate gain considerable advantage in terms of quality of products and system sustainability when grown in AFS. In addition, when designed and managed as organic, AFS yield products which can obtain more favorable market prices (Eibl et al. 2015; Rapidel et al. 2015; Virginio Filho et al. 2015). More than 80% of rural people in the developing world still depend on fuelwood for cooking as well as warmth (Angelsen et al. 2014; FAO 2015). AFS can play a role in supplying fuelwood energy and facilitating the provision of other sources of energy, thus avoiding forest cutting for fuelwood (Marlay 2015).

Silvopastoral systems, when properly designed and managed, can provide short term income from cattle products as well as long term returns from the trees helping diversify investments, while providing a full set of environmental benefits and services at the same time (Murgueitio et al. 2009, 2011; Chará et al. 2015; Colcombet et al. 2015; Murgueitio et al. 2015). Live fences, windbreaks and riparian buffer strips are complementary AFS which apart from their uses as such they contribute to connectivity in fragmented agricultural landscapes (Gordon and Newman 1997; Schroth et al. 2004; Batish et al. 2007; Francesconi and Montagnini 2015, among others).

Currently AFS are considered to be a land use that can achieve a compromise among productive and environmental functions. Among the latter, the potential AFS contributions to the recovery of ecosystem and landscape attributes, such as the restoration and conservation of biodiversity, watershed hydrological services, and connectivity of fragmented landscapes have recently received special attention (Mc Neely and Scherr 2003; Schroth et al. 2004; Chará and Murgueitio 2005; Jose and Gordon 2008; Redondo Brenes and Montagnini 2010; Nair and Garrity 2012; Montagnini et al. 2011; Calle et al. 2013; Montagnini et al. 2015a, b, among others). AFS are also playing an important role as part of the so called "climate-smart" landscape approaches that simultaneously embrace mitigation and adaptation policies and programs. Such landscape approaches are proposed as strong alternatives to REDD+ (Reducing Emissions from Deforestation and Degradation) programs (Van Noordwijk et al. 2015).

Several indigenous communities manage AFS using techniques that include residue management and ash deposition, enhancing nutrient recycling and conservation, and maintaining high species diversity which all promote agroecosystem sustainability (Montagnini and Jordan 2005; Montagnini 2006; Montagnini and Metzel 2015). However, several of these communities remain marginalized, and poverty and resource degradation prevail. Likewise, other types of AFS have been shown to effectively increase productivity and maintain sustainability under a varied set of site conditions. Apparently, AFS can play a significant role in rural development even in the most challenging socioeconomic and ecological conditions, but still there is a lot of work to do to reach these goals. AFS can help smallholder farmers attain higher productivity and sustainability, however these achievements do not always translate into significantly larger financial returns to farmers due to difficulties in the value chain of the AFS products and access to the right markets.

## 3 Agroforestry Research for Development: Challenges

Many international institutions and programs, government agencies, foundations, Non-Government Organizations (NGOs) and others are conducting research for development geared to decreasing rural poverty and hunger while maintaining landscape integrity and ecosystem services (CGIAR 2012). Considerable funding is spent in projects directed to enhancing productivity and sustainability of smallholder forestry and agroforestry practices, including food security and nutritional benefits, through better management of production systems.

These projects and programs face many questions and challenges, for example: How can they integrate the traditional knowledge of smallholders with scientific knowledge on environmental and agricultural strategies to promote the most suitable systems for each situation? How can barriers be removed to smallholders to access markets for tree and other AFS products, allowing them to capture more of their value, especially for people who are socially or economically marginalized (including women)? What types of products and markets are most suitable, and what interventions are most cost effective to realize these outcomes? Can successful cases of AFS be scaled-up and scaled-out to reach the target population outside the areas or regions affected by individual projects and programs?

These complex questions need innovative approaches from varying perspectives and knowledge bases. This book gathers fresh and novel contributions from a set of Yale University researchers and associates who intend to provide alternative and sometimes departing insights into these pressing questions. The book focuses on the functions that AFS can provide when well designed and implemented: their role in rural development as they can improve food security and sovereignty and contribute to provision of energy needs to the smallholders; and their environmental functions: contribution to biodiversity conservation, to increased connectivity of fragmented landscapes, and to adaptation and mitigation of climate change.

The chapters present conceptual aspects and case studies ranging from traditional to more modern approaches, from tropical as well as from temperate regions of the world, with examples of the AFS functions mentioned above. The first section is dedicated to describing the main agroforestry challenges and alternatives with case studies from tropical dry, humid and temperate ecosystems worldwide. The second section is dedicated to explaining how agroforestry systems were practiced by indigenous communities in a variety of settings and how they can transition from subsistence to market oriented systems. This transition, to be successful requires an integration of ecological, indigenous and scientific knowledge as tools for sustainable development, as well as adapting indigenous agroforestry systems for integrative landscape management and sustainable value chain development. Section 3 is dedicated to the multiple environmental services that agroforestry can provide in multifunctional landscapes. From the lessons learned, in the Conclusions chapter pending questions and challenges are summarized with suggestions for alternative approaches to fulfill the expectations on the roles that agroforestry can play to satisfy the increasing rural development and landscape conservation needs faced in the current millennium. The Conclusions chapter also deals with larger scale economic problems and barriers that limit the large scale adoption of agroforestry systems and gives suggestions to overcome these barriers.

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# Chapter 2
# The Contribution of Agroforestry to Sustainable Development Goal 2: End Hunger, Achieve Food Security and Improved Nutrition, and Promote Sustainable Agriculture

**Florencia Montagnini and Ruth Metzel**

## 1 Introduction

Agroforestry systems (AFS) that combine trees and crops on the same land, including silvopastoral systems (SPS), the combination of trees and pastures/cattle in the same production unit, can increase productivity in the short and long term. They are also biodiversity friendly and bring social and economic advantages to the farmer. In addition, AFS can serve an important role in climate change mitigation, due to carbon sequestration in woody components of the systems, as well as in soils. AFS can assist farmers as they seek to adapt to climate change due to the ameliorating effects of trees on local air temperatures (Montagnini and Nair 2004; Roshetko et al. 2007; Verchot et al. 2007; Murgueitio et al. 2011).

The most frequent AFS are annual and perennial crops under shade, multistrata systems such as homegardens and successional AFS, silvopastoral systems, live fences, and windbreaks (Nair 1989; Montagnini et al. 1992, 2011; Nair and Garrity 2012; Somarriba et al. 2012). The specific characteristics of each of the systems vary strongly according to system design, objectives and species involved. There are strong differences in AFS design and practices within ecological regions. Countries and locations can influence these practices, along with their productivity, sustainability, and environmental services provided, all depending on the interaction of economic, social, and political factors predominant in each.

F. Montagnini (✉)
School of Forestry and Environmental Studies, Yale University, New Haven, CT, USA
e-mail: florencia.montagnini@yale.edu

R. Metzel
School of Forestry and Environmental Studies, Yale University, New Haven, CT, USA

Azuero Earth Project, Pedasi, Panama
e-mail: ruth@proecoazuero.org



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About 1.6 billion people depend on forests and tree resources for their livelihoods. More than 800 million (30% of the global rural population) live on 9.5 million $km^2$ of agricultural lands (45% of the total area) with >10% tree cover; and 180 million on 3.5 million $km^2$ agricultural lands with >30% tree cover (CGIAR 2011; FTA 2011; Zomer et al. 2014; FTA 2015). Agroforestry systems comprise agricultural land use systems with a minimum of 10–30% tree cover. Estimates of the area under AFS worldwide have yielded over 1000 million ha, with additional large areas that are currently sustaining unproductive crops, pastures, as well as degraded lands that could be brought under AFS in the future (Nair et al. 2009, 2010).

Many indigenous communities manage AFS using techniques that include residue management and ash deposition, enhancing nutrient recycling and conservation, and maintaining high species diversity, all of which promote agroecosystem sustainability. They know appropriate tree species and their management. They also have the knowledge necessary for the application of best nutrient management practices: irrigation timing, pruning, addition of ash to soil, composting, vermiculture, and others (Montagnini and Jordan 2005; Montagnini 2006). However, many of these communities remain marginalized, and poverty and resource degradation prevail. Despite having ancestral knowledge on the management of autochthonous crops, soil, and water, many of them face serious land tenure issues, as they may not own or may have been deprived of their original lands by intrusions, development of infrastructure, roads or other projects. For example, in El Salvador (Central America), as in many other regions of the world, the native peoples who were stripped of their land have no space for their crops and are currently at risk of food insecurity (Frank Sullyvan Cardoza Ruiz, personal communication, Nov. 2016).

Several international programs and projects such as the Forests, Trees, and Agroforestry (FTA) program of the CGIAR,[1] several NGOs, and many academic and government entities are conducting research for development aimed at decreasing rural poverty and hunger while maintaining landscape integrity and ecosystem services (CGIAR 2011; FTA 2011, 2015). These research programs work on similar topics such as: what are the most suitable systems and management techniques that can contribute to achieving sustainable development goals in the target regions; how to integrate the traditional knowledge of smallholders with scientific knowledge on environmental and agricultural strategies to promote the most suitable systems for each situation; what types of AFS products and markets are most suitable; how can smallholders access markets for tree and other AFS products, allowing them to capture more of their value, especially for people who are socially or economically marginalized; and how AFS can scale out of particular situations and be disseminated at larger scales regionally and internationally. This chapter focuses on the role that AFS can play in providing alternative solutions to these issues, presenting examples of projects and case studies and pointing out the remaining challenges.

[1]CGIAR: Consultative Group of International Agricultural Research, http://www.cgiar.org/our-strategy/

## 2 The Sustainable Development Goals (SDGs)

On September 25, 2015, a total of 17 Sustainable Development Goals, also known as the Global Goals, were adopted as part of a new sustainable development agenda to be achieved over the next 15 years. The Sustainable Development Goals (SDGs) build on progress made toward the eight Millennium Development Goals from 1990 to 2015, and incorporate other emergent themes such as climate change, economic inequality, innovation, sustainable consumption, and peace/justice. The Sustainable Development Goals are unique because of the global nature of the goals. Because they are inclusive, their targets embrace ambitious objectives for nations often called "developed" in addition to "developing" countries, uniting countries in a global agenda. The 17 SDGs are:

1. End poverty in all its forms everywhere
2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture
3. Ensure healthy lives and promote well-being for all at all ages
4. Ensure inclusive and quality education for all and promote lifelong learning
5. Achieve gender equality and empower all women and girls
6. Ensure access to water and sanitation for all
7. Ensure access to affordable, reliable, sustainable, and modern energy for all
8. Promote inclusive and sustainable economic growth, employment, and decent work for all
9. Build resilient infrastructure, promote sustainable industrialization and foster innovation
10. Reduce inequality within and among countries
11. Make cities inclusive, safe, resilient, and sustainable
12. Ensure sustainable consumption and production patterns
13. Take urgent action to combat climate change and its impacts
14. Conserve and sustainably use the oceans, seas, and marine resources
15. Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss
16. Promote just, peaceful, and inclusive societies
17. Revitalize the global partnership for sustainable development (United Nations 2015).

A glance at these goals can identify several SDGs where agroforestry can make a significant contribution: SDG 2 on hunger, as shown in this article, SDG 5 on gender equality, SDG 6 on clean water, SDG 7 on affordable, clean energy, SDG 10 on reducing inequalities within and among countries, SDG 13 on climate action, and SDG 15 on sustainable forestry and restoration. However, because of the interconnected nature of the SDGs, agroforestry systems make contributions to achieving an even wider range of goals than immediately apparent, including SDG 1 on poverty, and SDG 3 on good health and wellbeing. In this chapter, we show how agroforestry systems can promote diverse SDGs simultaneously for an enhanced combined contribution to the post-2015 sustainable development agenda.

SDG 2 to "End hunger, achieve food security and improved nutrition, and promote sustainable agriculture" has 5 time-sensitive targets:

- **2.1:** By 2030, end hunger and ensure access by all people, particularly the poor and people in vulnerable situations, including infants, to safe, nutritious, and sufficient food all year round
- **2.2:** By 2030, end all forms of malnutrition, including achieving, by 2025, the internationally agreed targets on stunting and wasting in children under 5 years of age, and address the nutritional needs of adolescent girls, pregnant and lactating women, and older persons
- **2.3:** By 2030, double the agricultural productivity and incomes of small-scale food producers, particularly women, indigenous peoples, family farmers, pastoralists, and fishers, through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment
- **2.4:** By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding, and other disasters, and that progressively improve land and soil quality
- **2.5:** By 2020, maintain the genetic diversity of seeds, cultivated plants, and farmed and domesticated animals and their related wild species, including through soundly managed and diversified seed and plant banks at the national, regional, and international levels, and promote access to, and fair and equitable sharing of benefits arising from the utilization of genetic resources and associated traditional knowledge, as internationally agreed (United Nations 2015).

Agroforestry systems can contribute to achieving all five of these targets by applying practices that have been used traditionally for generations and promoting new innovations that continuously improve upon current best practices.

## 3 How Can AFS Contribute to Achieving the SDGs?

### *3.1 AFS Can Contribute to Alleviate Pressing Needs*

How can AFS contribute to achieving the SDGs? With current human population growth, in order for the SDGs to improve wellbeing for large numbers of people in developing countries, land productivity in agriculture and forestry will have to increase. The sum of areas needed to achieve the SDGs at current production levels exceeds what is available on the globe, if calculations are based on monocultures (van Noordwijk et al. 2015a). As a system that integrates land uses (forest and open-field agriculture), agroforestry can – with the appropriate combinations of trees, crops, and livestock – offer a range of goods, benefits, and services simultaneously, providing nutritious food, renewable energy, and clean water, while conserving biodiversity. By allowing efficient, multifunctional land use (with a Land Equivalent Ratio > 1) agroforestry supports "sustainable intensification" (Roshetko et al. 2008; Leakey et al. 2012; Colfer et al. 2015; van Noordwijk et al. 2015a).

In addition, the historical and current way of segregating forest land from agrarian communities leads to conflicts that reduce land productivity and increase inequity. Development challenges are in part the result of the sectoral (compartmentalized) approach that dominates government systems that tends to attribute the SDGs to separate conventions and Ministries (van Noordwijk et al. 2015a). Again, agroforestry can help as an institutional response to contested resource access, and can allow for gender and social equity enhancement as well as be a source of empowerment. Finally, agroforestry, as an integrative mindset and culture, can help create synergies between the SDGs in multifunctional landscapes, developing innovative partnerships in pursuit of the goals as encouraged by SDG 17 (Roshetko et al. 2008; Leakey et al. 2012; Colfer et al. 2015; van Noordwijk et al. 2015a).

## *3.2 How Can AFS Help in Achieving SDG 2?*

In order to contribute to the SDG 2 targets above, agroforestry projects and programs should:

1. **Meet immediate economic needs by enabling farmers to produce commodities with attractive financial returns** (increased NPV, Net Present Value, IRR, Internal Rate of Return, or other indexes used to evaluate financial profitability of land use alternatives). For example, in Colombia Intensive Silvopastoral Systems (ISPS) have higher NPV and IRR compared with other land use alternatives such as conventional cattle management (Murgueitio et al. 2015; Montes-Londoño 2017). New market development for novel AFS products with added value contributes to increase farmers' income (Fig. 2.1) (see in this volume: Eibl et al. 2017; Jarrett et al. 2017; Pepper and De Freitas Navegantes Alves 2017; see also Sect. 4 in this chapter). These actions contribute to Targets 2.3 and 2.4 through sustainably enhancing productivity.
2. **Integrate into the agricultural or livestock production systems already prevalent in a given region**. For example, organic coffee (*Coffea arabica*) agroforestry systems can be promoted in the region of Turrialba, Costa Rica, where AFS of coffee with native and some exotic trees are already prevalent (Virginio Filho et al. 2015; Rapidel et al. 2015). By decreasing the vulnerability of producers in existing agricultural systems, this integration can support progress toward Target 2.1.
3. **Improve, or at least sustain, current environmental conditions in the region of application**. For example, in Misiones, NE Argentina, yerba mate (*Ilex paraguariensis*) AFS improve the conditions relative to other prevalent systems of monoculture yerba mate or AFS of yerba mate with exotic trees (pines, *Paulownia* spp.) (Montagnini et al. 2013; Eibl et al. 2015, 2018). By increasing food security, agroforestry systems that sustain environmental services while diversifying production would contribute to all SDG 2 Targets.

**Fig. 2.1** *Moringa oleifera* (moringa), Moringaceae family, growing as part of a community project in the outskirts of Port Au Prince, Haiti. The moringa is a fast growing, drought resistant tree native to NW India. Its young seed pods and leaves are consumed as vegetables, and is increasingly being used in herbal medicine. It can be incorporated in AFS as a multipurpose tree that can reward the farmer with its benefits as well as with income in its expanding local and international market (Photo: F. Montagnini)

4. **Consider issues of land tenure and land security**. In addition to land tenure and security, tree tenure rules can affect the desire to plant trees as part of agroforestry projects (Bruce and Fortmann 1999). In Haiti, lack of secure land tenure is a major obstacle to expansion of successful AFS models to the areas where they are most needed to satisfy pressing food, energy, and environmental needs. Through clarifying land tenure and promoting secure and equal access to land and genetic agrobiodiversity, agroforestry projects can contribute to Targets 2.3 and 2.5.
5. **Use effective participatory approaches**. Methods used in participatory research and promotion of agroforestry vary among institutions and organizations, and if not truly collaborative, farmers may fail to adopt the agroforestry practices recommended by the projects (Rocheleau 1999). In restoration projects using AFS alternatives in Hidalgo, Mexico, participatory approaches using workshops with local farmers in some cases changed the projects' main actions to satisfy local people's needs, resulting in long term adoption of the land use alternatives promoted by the projects (Meister and Montagnini 2006; Montagnini et al. 2008). Enhancing collaboration between local farmers and institutions will enhance progress toward all SDG 2 Targets.

6. **Integrate traditional with modern scientific technical knowledge** (see Sect. 4 in this chapter). In Haiti, where reforestation and tree planting to provide basic needs are urgent, the use of bottom up approaches where farmers adapt technical recommendations to their traditional designs and practices has been a major contributor to project success. The traditional agroforestry systems and local famers' knowledge must be incorporated in project design from the start (Marlay 2015). Agroforestry projects that integrate traditional and scientific knowledge would promote progress toward all targets, but are particularly important to fulfill Target 2.5.

AFS alternatives are based on the use of appropriate tree and shrub species (Multipurpose Trees and Shrubs, MPTs) in design and practice (Steppler and Nair 1987; Nair 1989; Montagnini et al. 1992; Buck et al. 1999; Huxley 1999; Ashton and Montagnini 2000; Batish et al. 2007; Jose and Gordon 2008; Nair and Garrity 2012). MPTs should (A) be easy to establish, manage, and maintain; (B) withstand coppicing and pruning; (C) have high survival capacity and resilience to external sources of stress such as disease, drought, and other environmental or human disturbances, including resistance to grazing; and (D) yield a useful product that fulfills farmers' needs and provide extra income (Fig. 2.1).

The most productive MPTs growth shape will vary depending on the products and services it produces. For example, MPTs used for timber/fuelwood purposes should have high wood density, high caloric wood. Some MPTs may provide important non-timber products (bark, leaves, fruits, etc.). MPT management can enhance intercropping potential through pruning to provide light shade under the canopy to allow growth of associated crops or grasses. MPTs needed for nutrient recycling and soil fertilization should have high biomass productivity. The ability to fix nitrogen is an advantage as nitrogen is the main limiting nutrient to ecosystem productivity and often deficient. MPTs should contribute to ecosystem integrity and be unlikely to become invasive. Local acceptance and availability of local seed sources are critical to the integration of MPTs in projects and to their dissemination and promotion. In the face of carbon markets and current concerns about climate change mitigation, carbon capture in MPTs is advantageous (Montagnini and Nair 2004).

Designing and implementing AFS to diversify income can benefit large landholders who can make use of highly technological advances in agriculture, livestock, and forest science (Garrity 2004; Montagnini et al. 2013). However, as many AFS involve intensive management and high labor inputs to compensate for the reduced use or absence of external inputs, AFS are most suited to enhance and preserve the livelihoods of smallholders (Garrity 2004).

Small-scale AFS are often perceived as systems that increase sustainability in the absence of external inputs and ensure subsistence of local or indigenous populations (Scherr 2004; Soto Pinto et al. 2010). One of the major criticisms to AFS is that they do not change socioeconomic status (Rocheleau 1999; Alavapati et al. 2004; Franzel et al. 2004). However, many experiences around the world show that value-added AFS products along with proper market development can improve smallholder livelihoods (Dawson et al. 2014; Scherr 2004; Bennett and Franzel 2009; Montagnini et al. 2011).

### 3.3 Some Major Challenges Faced by AFS

Some of the challenges that agroforestry systems currently face include the following:

1. **Lack of proper infrastructure**: In many rural areas in countries such as Haiti, El Salvador, Ethiopia, poor-quality or non-existent roads make project areas accessible only by powerful 4-wheel drive vehicles or motor bikes (Fig. 2.2) (F. Montagnini personal observations).
2. **Environmental degradation**: Semi-arid regions of Ethiopia and Haiti show how soil compaction and loss, and decreases in water quantity and quality due to the effects of deforestation are often a major bottleneck to the establishment of reforestation and AFS projects (Fig. 2.3) (F. Montagnini personal observations). In such conditions, environmental remediation projects to improve initial conditions are necessary prior to the installation of AFS.
3. **Free-range livestock and improper fencing**: In regions of Ethiopia, AFS projects have tried to solve the problem of free-roaming cattle by encouraging communal fence-building, whereas in Haiti goats often roam free, grazing on planted trees. Selection of species based on the grazing preferences and type of local livestock can avoid some defoliation of agroforestry crops.

**Fig. 2.2** Lack of proper infrastructure can be an obstacle for AFS dissemination. In many rural areas in countries such as Haiti poor-quality or non-existent roads make project areas accessible only by 4-wheel drive vehicles or motor bikes (Photo: F. Montagnini)

**Fig. 2.3** In semi-arid regions soil compaction and loss, and decreases in water quantity and quality due to the effects of deforestation are often a major bottleneck to the establishment of reforestation and AFS projects. Farmer associated with FTA Projects in the Rift Valley of Ethiopia (Photo: F. Montagnini)

4. **Pressing energy needs**: When people need fuelwood for cooking in jurisdictions with lax harvest restrictions, trees and shrubs are harvested early for that purpose, impeding the development of tree planting projects and programs. However, AFS can also provide a way of fulfilling energy needs through coppicing tree and shrub species, and through this harvest, reduce the deforestation pressure on local forests (Olsson 2010).
5. **Low community organizational capacity**: AFS are greatly facilitated by the engagement of existing community groups such as "ejidos" in some regions of Mexico; the Rural Resource Centers in Cameroon and other countries in Africa; local cooperatives in Misiones, Argentina; and other farmers' groups. AFS programs can enhance the capacity of these groups through training to improve organizational and accounting skills. Smallholders and local organizations often feel disempowered in contributing to the design and implementation of internationally funded projects. For example, interviews with farmers in Ghana, Malawi, and Kenya showed a disconnect between the current public-private partnership investment priorities and the smallholders' own development priorities (Fairtrade Foundation 2014).

6. **Lack of or insufficient funding for AFS activities**: Agroforestry is often an "orphan" among land use systems because it is sometimes considered agriculture and at other times considered forestry, resulting in ambiguity and confusion when deciding which government office is responsible for its study, promotion, and funding. Managing the limited funds available so that the funds get to the right hands is also a challenge. Generally only 1.6% of humanitarian funding goes directly to local or national non-profit organizations, despite the fact that they frequently bear a heavy portion of the implementation risk (World Disasters Report 2015). These data suggest that a similarly small percentage of international funding for agriculture reaches local people and grassroots projects, with substantial amounts spent on personnel, infrastructure, and other indirect expenses.

## 4 Integration of the Traditional Knowledge of Smallholders with Scientific Knowledge as Tools for Sustainable Development

Most development projects, and "research for development" strategies are based on the premise that the traditional AFS and local famers' knowledge must be incorporated into project design from the start. Adoption is more likely when existing systems are improved through bottom-up approaches where farmers incorporate technical recommendations into their traditional practices and/or develop new designs rather than imposing new systems in a top-down manner.

What types of AFS products and markets are most suitable; how can smallholders access markets for tree and other AFS products, allowing them to capture more of their value, especially for people who are socially or economically marginalized? The project "Integration of Autochthonous Ecological Knowledge with Scientific Ecological Knowledge as Tools for Sustainable Development of Original Communities" (Rocha et al. 2017), investigated and summarized cases where indigenous non-timber AF products have been incorporated into the local economy, with the assistance of technical and scientific personnel, thus integrating indigenous and scientific knowledge in a purposeful and useful fashion.

For example, organic yerba mate from Argentina, Paraguay, and Brazil obtains higher prices than the conventionally grown product, also resulting in numerous ecological, landscape-level advantages (Eibl et al. 2015, 2017). Runa, an enterprise that buys the guayusa leaves (*Ilex guayusa* Loes.) from indigenous people in Ecuador, promotes growing guayusa in AFS that mimic the traditional systems in indigenous "chakras". This allows innovation upon traditional indigenous knowledge to create a value chain for elaborated high-value drink products sold locally and internationally (Logan-Hines et al. 2015; Jarrett et al. 2017). Pepper and De Freitas Navegantes Alves (2017) discuss the role of açaí fruit juice in the global market, questioning if adding value to the product can ensure sustained income for forest farmers in the Amazon estuary. Coffee, cacao, and *Allamblackia* are other examples of AFS goods for which value chains have been developed for selling high value products in selected national and international markets.

### *4.1 Cacao (Theobroma cacao), a Traditional Agroforestry Product with Increasing Market Expansion*

Cacao, a permanent crop grown traditionally in AFS, can yield high quality products sold nationally and internationally in several Latin American and African countries. An example of indigenous peoples accessing international markets for wild and cultivated cacao products in Bolivia is shown in Rocha et al. (2017). Gourmet markets are currently expanding for cacao grown organically by indigenous people from Ecuador and other countries in Latin America. In many cases NGOs and other organizations are promoting organic, environmentally friendly agroforestry alternatives along with providing advice to add value to products and access markets for more attractive retribution to farmers, as part of development projects and programs (see also Sect. 5).

For example, in El Salvador, the Cacao Alliance seeks to position the country as an exclusive origin for high quality fine aromatic cacao in the profitable specialty of gourmet segments on the international markets. The Cacao Alliance works with over 6500 producers in 10 departments with a total of 6500 ha of cacao in AFS (Fig. 2.4). AFS with cacao allow for association between fruit trees and other crops, generating social and environmental benefits such as: (a) Restoring productive landscapes through increased vegetative cover; (b) Increasing water infiltration capacity in critical areas for aquifers recharge; (c) Implementing technologies and practices of soil and water conservation management; (d) Increasing areas with restored

**Fig. 2.4** Agroforestry system of cacao with fruit and timber trees in farm associated with the Cacao Alliance in the Department of Usulután, El Salvador (Photo: Frank Sullyvan Cardoza Ruiz)

biological significance and quality (reduction of ecological niches due to habitat fragmentation); (e) Improving the connections between already established biological corridors to protect native flora and fauna. These actions, in addition to promoting the restoration of the landscape, also guarantee a reduction in the vulnerability of the productive systems, making them more resilient to climate change.

Moreover, the Cacao Alliance promotes agricultural activities that focus on the economic development of more than 6500 families in rural areas, generating greater food sovereignty and employment opportunities in the field (production) and in the city (industry). To date (2016), 154 nurseries have been established with an average production capacity of 10,000 and 25,000 plants, distributing 2,522,542 plants, generating more than 2300 jobs in 2666 hectares planted with an agroecological approach to agroforestry systems with cacao[2] (Frank Sullyvan Cardoza Ruiz, Environmental Compliance Officer, El Salvador, Cacao Alliance, Catholic Relief Services, personal communication, September 2016).

## *4.2 The Case of Allanblackia (AB) (Allanblackia stuhlmannii) in East Usambara, Tanzania*

The case of Allanblackia (AB) (*Allanblackia stuhlmannii*) in East Usambara, Tanzania exemplifies successful cultivation of commercial-scale food products in AFS (Mpanda et al. 2012). *Allanblackia stuhlmannii* is a tree native to Tanzania whose seeds were originally collected from natural forests for oil production, but has now been converted to a basic AFS product. For centuries local communities used AB seeds for food and soap production. The species has been classified as "vulnerable" by IUCN due to its limited natural distribution and the threatened status of the forests that harbor this species.

NGOs and community organizations strongly promoted AB oil production from 1972 to 1984. After a market collapse in the 1990s and 2000s the AB business again increased substantially in great part due to the efforts of its main manufacturer, Unilever, and research by the World Agroforestry Center (ICRAF[3]). The Novella[4] Project was started in 2002 to develop a sustainable supply chain for Unilever that would decrease rural poverty. In the Tanzanian AB supply chain, a farmer first brings the product to a collection center. It is then sent to a processing plant (GAPEX), then to cooperatives, and finally exported to Unilever sites in the Netherlands. In addition to payments made to farmers that supply the product, municipal funds are given to the 27 participating towns. This supply chain depends on the indigenous knowledge to find the best AB trees to collect seeds from local

[2] For more information: http://alianzacacao.org

[3] Worldagroforestry.org

[4] http://www.inter-cep.com/case-studies/project-novella/

forests, open the fruits, extract, dry, and transport the seeds to the collection center.

Technical assistance and support from international development agencies and NGOs has been instrumental to strengthening the value chain for quality products to reach international markets. Currently, the 11,000+ farmers in the CGIAR-Unilever Allanblackia project are producing about 650 tons of AB oil per year, and from 2002 to 2006, the project almost doubled the farmers' average income, a clear example of how expansion of AFS production systems and value chains can contribute to SDG 2 Targets 2.3 and 2.4.[5] However, for those products that achieve attractive price premiums in gourmet markets, the question remains as to how profit is shared fairly between the famers, intermediaries, and other essential actors in the marketing process.

## 5 Projects of the CGIAR Research Program on Forests, Trees and Agroforestry (FTA) that Contribute to the SDGs

The Sustainable Development Goals (SDG) framework accepted by world leaders in September 2015 offers new impetus for integrated, cross-sectoral, and landscape-wide approaches that integrate forestry, tree, and agroforestry science. The CGIAR Research Program (or CRP) on Forests, Trees and Agroforestry (FTA)[6] intends to contribute to solving some of the evolving global, regional, and national forestry and agroforestry-related challenges (CGIAR 2011, FTA 2011). The CGIAR Strategy and Results Framework 2016–2030 (SRF) is ambitious: By 2030, the action of CGIAR and its partners will result in 150 million fewer hungry people, 100 million fewer poor people – at least 50% of whom are women, and 190 million fewer hectares of degraded land. CGIAR's first results-oriented SRF was developed in 2010, providing for the first time an overarching structure for the combined work of the 16 CGIAR Research Programs (CRPs), steering the CGIAR system toward greater overall impact. The CGIAR has three goals, or System Level Outcomes (SLOs), through which they aim to reduce poverty, improve food and nutrition security, and improve natural resources and ecosystem services. The CGIAR goals contribute strongly to the SDGs targeted at zero poverty, zero hunger, good health and well-being, gender equality, clean water and sanitation, climate action and life on land. They also moderately contribute toward quality education, good jobs and economic growth, reduced inequalities, responsible consumption, good use of water, peace and justice, and partnerships for the goals.

[5] http://www.unilever.com/sustainable-living-2014/enhancing-livelihoods/inclusive-business/livelihoods-for-smallholder-farmers/

[6] http://foreststreesagroforestry.org/about-us/

FTA is led by CIFOR[7] and includes additional CGIAR Centers (ICRAF, and CIAT[8]) as well as other CGIAR (Bioversity International[9]) and non-CGIAR Participant Institutions (CIRAD[10] and CATIE[11]). It is a 10-year multi-partner program which started in 2011 to be implemented within the CGIAR Consortium's Strategic Results Framework (SRF) and along the rules and regulations of the recently reformed CGIAR (2011, FTA 2011, http://foreststreesagroforestry.org/about-us/). FTA is now gearing up for its second phase (2017–2022).[12] The CGIAR System Council has approved the next 6 years of FTA within a CGIAR portfolio of programs critical to food security, natural resource management, and sustainable development. Its budget is about USD 80 million per year, to ensure that FTA can continue to deliver scaled-up impact for livelihoods and landscapes worldwide.

FTA aims at enhancing the management and use of forests, agroforestry, and tree genetic resources across the landscape – from forests to farms and plantations – and strives to become the leading global comparative research initiative focused on forestry, agroforestry, and tree diversity across the developing world. FTA's objectives and research agenda are aligned with the previous Millennium Development Goals (MDGs) and the current Sustainable Development Goals (SDGs). FTA emphasizes sustainable growth pathways through addressing economic factors such as employment and income at a scale beyond livelihood improvements.

The FTA program comprises five flagship projects

1. **Tree genetic resources** to bridge production gaps and promote resilience;
2. Enhancing how trees and forests contribute to **smallholder livelihoods;**
3. Sustainable global **value chains and investments** for supporting forest conservation and equitable development;
4. **Landscape dynamics**, productivity and resilience; and
5. **Climate change** mitigation and adaptation opportunities in forests, trees and agroforestry.

The program is guided by three overall hypotheses:

**Governance Hypothesis** Public and private governance arrangements and institutions must be transformed and aligned to create the necessary enabling environment where forests, trees and agroforestry systems can fully contribute to achieving the Sustainable Development Goals (SDGs).

[7] Center for International Forestry Research, CIFOR.org

[8] Centro Internacional de Agricultura Tropical, International Center for Tropical Agriculture, ciat.cgiar.org

[9] Bioversityinternational.org

[10] French Center for International Research in Agricultural Development, cirad.fr

[11] Centro Agronómico Tropical de Investigación y Enseñanza, Tropical Agriculture Research and Higher Education Center, www.catie.ac.cr

[12] http://blog.cifor.org/44770/forest-trees-agroforestry-research-into-the-next-phase?fnl=en

**Livelihood Hypothesis** There is scope for investments to achieve major increases in income, food and nutrition security, and resilience for at least 100 million people in the face of climate change. This includes more inclusive and gender-equitable access, improved management and better utilization of forests, trees and agroforestry systems.

**Trade-Offs Hypothesis** Maximizing benefits among diverse stakeholders at scales from the farm to the globe requires understanding and actively managing trade-offs between the production of food, fiber, energy, water and other ecosystem services, climate regulation, and the maintenance of biodiversity from forests and trees in landscapes.

## *5.1 Examples of AFS Projects from FTA Related to SDG 2*

FTA's Flagship 2 program on "Enhancing how trees and forests contribute to smallholder livelihoods"[13] intends to call the attention of practitioners, academics, and policy makers to key issues and approaches in agroforestry and related land use systems that address the complex environmental and productivity problems of degraded agricultural lands. The flagship's initiatives use innovative extension approaches to foster entrepreneurship and innovation through integrating existing successful agroforestry knowledge and technology with new, situation-based, developing technologies to contribute to solving rural agricultural production problems (Fig. 2.5). A few of Flagship 2's projects are summarized here to illustrate how FTA is geared to contribute to SDGs, and more specifically to SDG 2.

### 5.1.1 The Trees for Food Security Project

The 2012–2016 'Trees for Food Security' project,[14] with a six million USD budget, started in Rwanda and Ethiopia and scaled out[15] successes from those countries to Burundi and Uganda. Now active in all four countries, this project has begun to scale up[16] technologies to a larger number of farmers, focusing on smallholders in a variety of geographical locations across these four African countries. Agroforestry technologies are promoted and used to sustainably increase agricultural production and maintain environmental services. The approach uses multi-purpose tree/shrub species known for their positive effects on soils and crop productivity, such as

[13] Initially named "Component 1: Smallholder Production Systems and Markets"

[14] Full name: "Improving sustainable productivity of farming systems and enhanced livelihoods through adoption of evergreen agriculture in eastern Africa"

[15] Scaled up: extended work of project out of the countries where it was started to reach farmers in other countries

[16] Scaled out: extended work of the project to reach a larger number of farmers

**Fig. 2.5** The FTA projects use innovative extension approaches to foster entrepreneurship among farmers, identifying and empowering leaders who are involved in adding value to their agroforestry products and increasing marketing opportunities to farmers. ICRAF and visiting researchers with farmers associated with the "Tree Crops Development in Africa and Asia to Benefit the Poor" project run by FTA, in Nkenlikok, Cameroon (Photo: F. Montagnini)

*Calliandra, Leucaena, Gliricidia*, and others (Garrity et al. 2010). "Trees for Food Security" promotes the use of diverse tree species that can be combined with crops on a variety of soils and farm sizes and by farming families working under different financial, cultural, and policy constraints. The project tries these options out across a range of conditions from drylands such as in Melkassa, Ethiopia and Bugezera, Rwanda, to the humid areas of Gishwati, Rwanda and Bako, Ethiopia. The main interventions used by the project focus on participatory approaches that try out best-fit agroforestry options through involving a range of stakeholders and partners. Other interventions include providing quality planting materials, linking farmers to markets, building technical, entrepreneurial and financial management capacity of farmers and extension workers and strengthening of local institutions and policy enforcement mechanisms. Capacity building of professional staff in partner institutions through training in modeling, technical approaches, and methodologies is also a key focus of the project. These techniques and approaches are described in several publications: Coe et al. (2014), van Ginkel et al. (2013), World Agroforestry Center (2013).

The key issue for the "Trees for Food Security" project is scaling-up to address a broader range of the location-specific socioeconomic and ecological conditions that are the most important determinants of project success. In conditions of extreme poverty and environmental degradation, such as the Ethiopian rift valley, the chances of success are lower in comparison with more favorable climatic and soil conditions in Rwanda or Kenya. Although localized success is possible on individual farms, achieving success across a larger population is challenging.

The "Trees for Food Security" webpage[17] provides country-level achievements and farmer testimonials. Key project impacts and outcomes mentioned include the establishment of five rural resource centers and nurseries to enhance training, supply improved tree germplasm, and provide business opportunities; the development of vegetation/species selection maps and tools; the establishment of four long-term tree diversity trials and 20+ controlled on-farm and on-station experiments with over 5000 farmers; the enhancement of tree crop modelling capability through partnership between CSIRO[18] and ICRAF; the training of farmers, MSc/PhDs, and national staff and an associated database/repository of project resources and tools; the improvement of extension systems; and the provision of 2 million tree seedlings with close monitoring. In addition, country by country reports and other publications are available listing country and regional project achievements (Mbugua 2016; Muthuri et al. 2016; Derero 2016, among others). At the time of writing, a second phase proposal is under revision (Catherine Muthuri, Project Leader, ICRAF, personal communication, August 2016).

### 5.1.2 Tree Crops Development in Africa and Asia to Benefit the Poor

FTA is conducting research and promoting development projects where local farmers have nurseries as part of their homegardens for the production of seedlings to sell in local markets. The "Tree Crops Development in Africa and Asia to Benefit the Poor" project (2012–2014, $2,240,000 USD), active in Cameroon, Ghana, Kenya, Mali, and India, focuses on transitioning smallholder farming systems from subsistence to semi-commercial farming of fruit, nuts and oil seed trees; and transitioning small-scale private or community tree nurseries and micro-processors to large-scale commercial enterprises.

The "Tree Crops Development" project has three components: Allanblackia domestication; "Fruit Africa"; and Biofuels. In Eastern Africa (EA) and in West and Central Africa (WCA), the project works with Rural Resource Centers (RRCs) for dissemination of agroforestry innovations including fruit and nut trees (Takoutsing et al. 2014). Most species used are recently domesticated and previously uncultivated. Project researchers study the species' genetic diversity, soil conservation, and cultivation strategies for the target tree products (fruits, nuts, oils, etc.) (Kehlenbeck

[17] http://www.worldagroforestry.org/project/trees-food-security-improving-sustainable-productivity-farming-systems-and-enhanced

[18] Commonwealth Scientific and Industrial Research Organization, csiro.au


**Fig. 2.6** In Cameroon and other countries of Africa, ICRAF collaborates with local NGOs supporting the Rural Resource Centers (RRCs) which promote organic farming practices and homegardens among member farmers, providing technical assistance on selection and design of AFS as well as on product marketing (Photo: F. Montagnini)

et al. 2013), or base recommendations on previous research and existing literature (Franzel et al. 2007). The project focuses on a set of target tree species, establishes gene banks for conservation, and develops propagation techniques using high quality plant material. Fruits are seasonal, so the project develops a location-specific portfolio and production schedule with each farmer/family that combines products to provide a plentiful, year-round supply of fresh fruit. Fruit/nut nutritional components are checked, either from existing literature (Teklehaimanot 2004) or through project-based research (Stadlmayr et al. 2013). This information is used to prioritize the species most useful for alleviating food insecurity in each target region.

The "Tree for Crops Development" project designed Rural Advisory Services (RAS) to disseminate their results as there was low adoption of agroforestry practices because of ineffective conventional dissemination methods. RAS are innovative and low-cost dissemination techniques for agricultural innovation that are a key impact pathway linking research to improved livelihoods. With RAS, extension is decentralized, and empowers the farmers through participatory approaches used by community based organizations (farmers' groups, such as the Rural Resource Centers) (Fig. 2.6).

The World Agroforestry Center has collaborated with partners in Cameroon since 2007–2010 developing programs that relied on farmers' participation to drive nearer to its projects' objectives (Takoutsing et al. 2014). The programs aimed to support smallholder farmers in their efforts to reduce poverty and enhance environmental sustainability. This aim was achieved through the demonstration and dissemination of sustainable land management options that built on existing knowledge and indigenous practices through an innovative extension approach: the concept of Rural Resource Centres (RRC). These are community-based centers used as venues for training and demonstration of new practices and function as a hub for stakeholders' interactions.

This new extension approach focuses on technology development and innovations geared to the specific physical, climatic, economic, and social circumstances of smallholders. It creates a more comfortable environment for farmers to contribute and participate actively in any initiative aimed at improving their livelihood (Takoutsing et al. 2014). In Cameroon, the RRCs have increased awareness of agroforestry options (71% in villages with RRCs versus 52% in those without), and more than doubled the proportion of people planting high value trees (37% with RRCs, versus 17% without) (Degrande et al. 2013).

"Trees for Crops Development" contributes to all SDG 2 Targets by reducing rural poverty and improves nutrition and health by promoting land uses that are compatible with the sustainable management of natural resources, while aiding in conservation of indigenous genetic resources (Kehlenbeck et al. 2011). The project works towards reducing rural poverty by promoting the planting and use of trees that improve nutrition and health (Kehlenbeck et al. 2011) through establishment of tree nurseries and fruit gardens, adding value to tree products and promoting innovative adoption mechanisms through the RRCs in Cameroon (Fig. 2.7).

Ann Degrande, an ICRAF socio-economic researcher with the Project in Cameroon, states that participatory tree domestication is still conducted in Cameroon and West/Central Africa region, although field presence is minimal due to funding constraints. Local grassroots partners (nurseries and RRCs) continue to operate with minimal input from the project (Ann Degrande, ICRAF, pers. comm., August 18 2016).

### 5.1.3 ASB (Alternatives to Slash and Burn)

Projects from other FTA Flagships (or components) also use agroforestry as a means to achieve food sovereignty and improve local livelihoods beyond contributing to other objectives like climate change mitigation/adaptation and biodiversity conservation. For example, ASB (Alternatives to Slash and Burn) is a "legacy" project started before FTA but currently integrated into the FTA program. The ASB "Partnership for the Tropical Forest Margins" project is working to raise productivity and incomes of rural households in the humid tropics without increasing deforestation or undermining essential environmental services.[19] ASB can be placed in Flagship 2 as it works by "enhancing how trees and forests contribute to smallholder

[19] http://www.asb.cgiar.org/

**Fig. 2.7** In Cameroon and other locations in Africa, the "Tree Crops Development in Africa and Asia to Benefit the Poor" project run by FTA promotes establishment of nurseries as part of farmers' homegardens for the production of seedlings to sell in local markets. Farmer nursery in Bangangte, Cameroon (Photo: F. Montagnini)

livelihoods" but it also lies within Flagship 4, "Landscape dynamics, productivity and resilience"; and Flagship 5, "Climate change mitigation and adaptation opportunities in forests, trees and agroforestry".

ASB is a consortium of over 90 international and national partners with an eco-regional focus on the forest–agriculture margins in the humid tropics, with benchmark sites in the western Amazon Basin of Brazil and Peru, the Congo Basin forest in Cameroon and the Democratic Republic of the Congo, southern Philippines, northern Thailand, and the island of Sumatra in Indonesia (ASB 2016). ASB has a multi-layer structure. Coordination and facilitation are provided by the ASB global coordination office, ASB regional facilitators, and ASB national facilitators. The World Agroforestry Centre (ICRAF) has hosted the global coordination office since inception, in Nairobi, Kenya.

ASB initiatives and projects promote AFS as part of land use strategies in multi-functional landscapes. For example, Reducing Emissions from all Land Uses (REALU) is a research project whose goal is to develop a set of approaches, methodologies, and national capacity to implement effective landscape based strategies for Reducing Emissions from Deforestation and forest Degradation (REDD+).[20] The project has been implemented in three phases. Phase I focused on research activities at benchmark sites in Indonesia, Cameroon, Peru, Vietnam, and Nepal. Phase II was a buildup on research in Indonesia, Cameroon, Peru, and Vietnam. The ASB Partnership started work in Peru in 1994 at two different sites: Ucayali and Yurimaguas in the Peruvian Amazon. Researchers have quantified the environmental and socio-economic impacts of land use change at these 2 sites. The Ucayali benchmark site covers approximately 1.6 million hectares of tropical forest biome. Fifty years of deforestation and a steadily growing population have led to a wide range of land uses in the area making it ideal for assessing the impacts of land use change. The main town in the Ucayali region, Pucallpa, experienced a sevenfold population increase from the 1960s to the mid-1990s. REALU Phase III: **S**ecuring **E**cosystems and **C**arbon benefits by **U**nlocking **R**eversal of **E**missions **D**rivers (SECURED) in Landscapes, advances REALU objectives with the following specific areas of research:

- Developing methodological, policy, and investment guidance (Including approaches for private sector involvement and public-private partnerships)
- Designing frameworks for nesting plans and policies at multiple levels and negotiations
- Piloting incentives in 4–5 demonstration landscapes
- Capacity building and promotion of science-policy interactions at global, national and sub-national levels

Central to the research is an analysis of the tradeoffs that arise among the different environmental, economic, and social objectives. The following REALU project serves to illustrate this point:

In the Peruvian Amazon, REALU is using a landscape approach to REDD+ schemes by examining the reductions of emissions by different land use changes with cacao producers (Silva Aguad et al. 2015). The project works with small and medium size agricultural producers associated with a cacao cooperative, the Padre Abad Association for Technified Cacao Producers (ACATPA, Asociación de Cacaoteros Tecnificados del Padre Abad), in the Padre Abad province of the Department of Ucayali. The farmers associated to this cooperative have multiple land uses in their farms, including several permanent and annual crops, fallow fields, and areas with forests in different stages of degradation.

The project investigated the carbon content of the different components in the prevalent land uses, comparing with previous land uses, and conducted group meetings with farmers to present alternatives to increase carbon capture within the systems and to conserve remnant forest in their farms. The project also determined the baseline for carbon emissions and used a software called ABACUS to simulate different scenarios according to farmers' preferences for the alternative lands uses.

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[20] http://www.asb.cgiar.org/project/architecture-realu-reducing-emissions-all-land-uses

The results showed that cacao is the principal family income and farmers expressed interest in enriching their cacao plantings with timber trees. Avoiding deforestation of the remnant forests showed to be the activity with greater potential for reducing C emissions. The simulation of different scenarios revealed that the greater potential for emission reductions is obtained using an integrated approach taking into consideration all the land uses in the farm (Silva Aguad et al. 2015).

However, these integrated land use approaches are complex due to the variability of farmers' socioeconomic conditions and their dynamic livelihoods which influence their decision-making processes. Currently no certification systems are available to encourage an integration of land use systems by the farmers, which results in higher transaction costs for REDD+ projects or leads farmers to focus on selected activities thus decreasing the emissions reduction potential (Silva Aguad et al. 2015).

### 5.1.4 AgFor Sulawesi: Agroforestry and Forestry in Sulawesi: Linking Knowledge with Action

The 2011–2017 'AgFor Sulawesi Project',[21] with a total project budget of $9.34 million USD, is active in three of the seven provinces on Sulawesi island in Indonesia: South Sulawesi, Southeast Sulawesi, and Gorontalo.[22] Sulawesi contains 8 national parks, unique ecosystems like the island's lowland forests, and one of the largest outcrops of serpentine soil in the world that hosts diverse flora and fauna, making the island an important conservation target. The AgFor project assists underprivileged farmers in enhancing their livelihoods through the establishment of agroforestry systems and engagement in social forestry mechanisms to protect local forest resources. Its overall objective is to enhance the agroforestry and forestry livelihood systems of rural Sulawesi communities. The Indonesian government assists and supports migrants ("transmigrants"), to accelerate rural development, often emphasizing the production of commodities. AgFor responds to the needs of local and migrant communities who are struggling to improve their livelihoods amongst environmental and production constraints posed by former lack of sustainable planning and ecosystem management.

For example, recent yields from cacao monocultures have decreased due to an increase in pests and diseases and a loss of soil fertility. The AgFor Sulawesi project promotes cultivation of cacao and other tree crops in mixed AFS to reduce the risks associated with monocultures through diversification of both crops and income sources. To support project activities, AgFor facilitates the establishment of *nurseries of excellence* to empower farmers to produce high quality seedlings and provide them with the skills to operate tree nurseries and manage diverse AFS (Roshetko et al. 2013a) (Figs. 2.8, 2.9).

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[21] Full name: AgFor Sulawesi: Agroforestry and Forestry in Sulawesi: Linking Knowledge with Action

[22] Districts participating in the project include: Bantaeng, Bulukumba, Jeneponto, and Gowa (South Sulawesi province); Konawe, East Kolaka, South Konawe, and Kendari municipality (Southeast Sulawesi province); Gorontalo and Boalemo (Gorontalo province)


**Fig. 2.8** In Sulawesi, monocultures of cacao have decreased yields in recent years due to an increase in pests and diseases and loss of soil fertility, thus the AgFor Sulawesi project promotes cultivation of cacao and other tree crops in AFS to reduce the risks associated with monocultures and diversify crop production and income (Photo: F. Montagnini)

The AgFor Sulawesi project is a development-oriented project that conducts research on strategies to promote sustainable agroforestry and forestry-based livelihoods for rural communities in Sulawesi. Government agencies, local NGOs, and communities are all project partners. The project confronts challenges such as a high dependence of local livelihoods on exotic commodity crops, which expose communities to biological and market risks; suboptimal watershed management leading to erosion, sedimentation, landslides and floods; lack of land title and other land tenure issues; marginalization of women's rights; forest encroachment and deforestation; community-government conflict; and lack of community participation in government land-use planning (Khususiyah et al. 2012; Roshetko et al. 2012, 2013b).

AgFor Sulawesi aims to overcome these challenges through its three project components: livelihoods, environment, and governance:

1. **Livelihoods** works to improve existing AFS by emphasizing multispecies designs and increasing production. AgFor's principal objective in the livelihoods component is to generate more income for the target beneficiaries. This includes finding and developing new markets for farmers' products and improving rural advisory services.

**Fig. 2.9** AgFor facilitates the establishment of "nurseries of excellence" by groups and individuals to empower farmers to produce the high quality seedlings they require for their projects (Photo: F. Montagnini)

2. **Governance** uses participatory community governance, helping farmers understand local land-use issues, enhancing their capacities, and providing access to government social forestry programs (access to land classified as forestland).
3. **Environment** focuses on expanding environmental services (ES) to protect and conserve water quality and quantity, biodiversity, and carbon stocks, and finding mechanisms to reward communities for being good stewards of ES (Fig. 2.10).

AgFor promotes sustainable agriculture and food security through integrated mixed AFS to diversify farmers' livelihood streams, reduce financial and environmental risk, and improve agro-biodiversity by incorporating multiple species and varieties on the same piece of land. These systems use fewer agrochemicals and reduce contamination. The project and its partners provide planting material of improved genetic quality to increase production quantity and quality. Through awareness and capacity building with local communities, the project increases resilience of agricultural systems and food security, including promoting indigenous knowledge (Roshetko et al. 2013c; Dewi et al. 2013). AgFor emphasizes a gender equity approach emphasizing women's participation. Women have gained a stronger role in public discourse, strengthening their confidence and recognition by men for their contribution and knowledge regarding resource management (Colfer et al. 2015; Mulyoutami et al. 2015). The project also promotes farmer-to-farmer

**Fig. 2.10** The Environment component of AgFor Sulawesi focuses on environmental services (ES) to protect and conserve water quality and quantity, biodiversity, and carbon stocks, finding ways and mechanisms to reward communities for being good stewards of ES. The community forest of Bulukumba district in Sulawesi is protected as it harbors the water that is used to irrigate the rice cultivated by the farmers of the community (Photo: F. Montagnini)

communications to enhance the delivery of the agroforestry information that farmers need to improve their livelihoods (Martini et al. 2016).

The project has attained several important achievements in its 5 years: 25,480 individuals have gained greater knowledge of sustainable agriculture and natural resource management through formal workshops, trainings, and meetings; 155 group nurseries and 131 individual nurseries operated by partners during the reporting period produced 1,338,976 seedlings; 95 group and individual agroforestry enterprises have been developed or strengthened; 5 models of participatory governance are operating at 9 sites; 5 environmental service schemes have been initiated at 5 sites; 6 district livelihood-conservation strategies have been finalized, and 2 more district strategies and 3 provincial environmental service schemes are in development. Based on an impact survey, 631,787 people (52% women) have improved incomes as a result of adopting AgFor promoted technologies and 738,459 ha are under improved sustainable management – including agroforestry, agriculture, and forest systems (Rahmanulloh et al. 2012; Roshetko et al. 2016).

### 5.2 Achieving the SDGs through Support for Climate change Adaptation-Mitigation

AFS can serve an important role in climate change mitigation, due to carbon (C) sequestration in woody components and soil, ameliorating effects of trees on air temperatures, and diversification of production that decreases vulnerability (Montagnini and Nair 2004; Montagnini 2005; Verchot et al. 2007; Murgueitio et al. 2011). Estimates of C sequestration potential in AFS are highly variable, ranging from 0.29 to 15.21 Mg $ha^{-1}$ $year^{-1}$ aboveground (Nair et al. 2010). This large range in values is due to the range in production potentials of the diverse AFS, which depend on site characteristics as well as on the type of AFS, species involved, age, and management (Montagnini and Nair 2004; Roshetko et al. 2007; Verchot et al. 2007; Montagnini 2015; Nair et al. 2009, 2010; Nair 2012) (see also chapters by Toensmeier 2017 and by Peri et al. 2017, this volume).

Results of several studies on biomass and C capture in AFS around the world show that generally AFS with perennial crops accumulate greater amounts of C than AFS with annual crops (Montagnini and Nair 2004; Nair 2012; Montagnini 2015). For different locations throughout Latin America, values of C accumulation for AFS of coffee with planted trees range from 47 to 237 Mg C $ha^{-1}$, and values for coffee with forest trees range from 20 to 50 Mg C $ha^{-1}$ (Montagnini 2015). For AFS of cacao with planted trees values range from 24 to 52 Mg C $ha^{-1}$. In Rio Grande do Sul, Brazil it was estimated that yerba mate plants can capture 5.45 Mg C $ha^{-1}$ $year^{-1}$ on average in aerial biomass, with soil C reserves of >56 Mg C $ha^{-1}$ (Alegre et al. 2007).

Comparisons of C sequestration estimations across landscapes in Costa Rica showed that teak plantations and secondary forests had larger amounts of C in aerial biomass (90 Mg C $ha^{-1}$) than degraded pastures, and that C capture in the agricultural landscapes can increase with the use of improved pastures and adding trees to the landscape through silvopastoral systems (SPS), tree plantations, and riparian buffers (Ibrahim et al. 2007). SPS, which currently occupy 450 million hectares worldwide, can help mitigate an estimated 8–18% of global greenhouse gas emissions that come from the livestock sector (O'Mara 2011, Cubbage et al. 2012, Nair 2012). Recent reports of vegetation (above and belowground) carbon sequestration potential of SPS worldwide ranged from 1.1 to 6.55 Mg $ha^{-1}$ $year^{-1}$ depending on geographic location and on the SPS age, design, and management (Nair et al. 2009). Results of studies of several locations in tropical and sub-tropical regions of Latin America showed that SPS of pastures with planted trees had C stocks of 0.31–91.8 Mg/ha, while SPS of pastures with natural trees had tree C stocks of 2.43–74 Mg/ha (Montagnini et al. 2013). This reflects the heterogeneity of the SPS, which differ in their design, species, and site conditions.

Many AFS techniques facilitate soil organic carbon recovery or protection and thus enhance soil C sequestration. AFS have larger soil C sequestration potential than conventional rangelands and grasslands (Lal 2004; Montagnini and Nair 2004; Nair et al. 2010). Overall, AFS can have an intermediate rate of soil C sequestration ranking between conventional tree planting and no-till agriculture (Lal 2005). The impact of AFS on soil C sequestration depends on the amount and quality of input provided by the tree and non-tree components of the system, and on soil properties such as structure and aggregation. Belowground biomass studies in AFS, especially fine roots, are challenging and often lack the required scientific rigor. Thus it is difficult to ascertain the role of fine root production as an input to the soil organic matter pool (Nair et al. 2009).

AFS are considered a cornerstone in the current trend to promote the transformation of agriculture to "Climate-smart agriculture", an agricultural system that sustainably increases productivity, resilience (adaptation), reduces/removes greenhouse gases (mitigation) while enhancing the achievement of national food security and development goals (FAO 2012). AFS can contribute to achieving SDG 13: "Take urgent action to combat climate change and its impacts", by buffering from climate extremes, and by serving as basis for adaptation and net emission reduction (van Noordwijk et al. 2015a, b).

Van Noordwijk et al. (2011) present arguments and evidence on how trees and people can co-adapt to climate change by reducing vulnerability through multifunctional agroforestry landscapes. However, in a recent assessment of the possibilities of land use changes to achieve climate change mitigation goals, the lead author and other colleagues state that current actions are unlikely to achieve globally appropriate mitigation goals (van Noordwijk et al. 2015b). According to these authors, current REDD+ finance is inadequate. They propose climate-smart landscape approaches that simultaneously embrace mitigation and adaptation policies and programs, as well as other environmental services. Given the need for locally adapted options, work needs to continue on a portfolio of practices that promote synergy (van Noordwijk et al. 2015b).

Most smallholder AFS such as homegardens and other AFS in tropical regions of the world are tree- and species-rich systems producing non-wood and wood products for both home use and market sale which display high biomass, and thus contain large carbon (C) stocks (Montagnini 2006; Roshetko et al. 2007). While on an individual basis they are small, on a per-area basis smallholder systems in SE Asia accumulate significant amounts of C, equaling the amount of C stored in some secondary forests of similar age (Roshetko et al. 2007). This makes smallholder systems viable under the Clean Development Mechanism (CDM) of the Kyoto Protocol, with its dual objective of emissions reduction and sustainable development. To assure system productivity and profitability, projects should provide farmers with technical and marketing assistance. Smallholder-focused CDM projects would have high transaction costs, therefore the challenge is to develop mechanisms that reduce the costs of (a) making information (e.g., technology, markets) more accessible to multiple clients; (b) facilitating and enforcing smallholder agreements and (c) designing feasible monitoring systems (Roshetko et al. 2007).

As seen, AFS can play a role in climate change mitigation and adaptation, with strategies and mechanisms designed to compensate farmers for the associated land use changes and management in the form of C credits or as part of REDD+ projects (Silva et al. 2015). The bottleneck lies in the empowering of the local farmers through proper technical assistance when required, so that they can legitimately be inserted in the system of choice and receive proper compensation for their efforts.

## 6 Conclusions

AFS can – with appropriate combinations of trees, crops, and livestock – offer a range of goods and services simultaneously providing nutritious food, renewable energy, and clean water, while conserving biodiversity. Many AFS products have several ecological and economic advantages and can contribute to farm financial stability and viability. Other tree, herb or shrub species with fruit, medicinal or ornamental value increase farm diversification. The case studies in this article on cacao, Allanblackia, FTA's projects Trees for Food Security, Tree Crops Development, AgFor and REALU provide examples of how existing initiatives are contributing to meeting SDG 2 and its targets.

Indigenous AFS can be brought into alignment with integrative landscape management strategies to incorporate supply chains based on the sustainable management of AFS that generate income from a variety of species. There are several examples where indigenous communities have been able to reach local and/or international markets with their AF products. Technical and scientific knowledge can be instrumental in ascertaining the medicinal, nutritional, or other use value of specific products. Research institutions, private companies, foundations or NGOs can inform local communities on the different steps in the value chain to reach key markets for their products. This can involve mechanisms to add value to products before they reach the markets so that the producers obtain better financial returns. Other sectors can inform communities about best practices for processing, packaging, branding, and advertising their products.

The key issue for the projects is scaling-up to reach a broader range of environmental conditions as well as socioeconomic situations. Success can happen in localized situations, however the real challenge is to reach a larger population. The socioeconomic and ecological conditions are most important determinants of success. In situations of extreme poverty and environmental degradation chances of success are lower than in more favorable conditions.

As we consider the role agroforestry systems will play in furthering future sustainable development, many questions remain to be answered: How much are target farmers improving their livelihoods? Are they getting a fair price for their products? Are farmers adding enough value to their products locally so they are obtaining a fairer share of the financial benefits? Sometimes the farmer is paid an apparently "fair" price for a product, for example when the price paid to farmers for organic products is 2–3 times the price paid for conventional products, while in the international market the price is several times more than that paid to the farmers.

Finally, one should critically ask if funds directed to empower farmers to improve their production/working conditions are truly reaching the intended target populations. Do impact assessments reflect the true conditions on the ground? The Sustainable Development Goals provide an exciting new framework through which to view agroforestry and its integration with global development goals. However, the challenges of accessing the global funding environment associated with sustainable development and the differences in jargon between the farming, scientific, and policy communities are issues that must be overcome in order for agroforestry to play a key role in fulfilling Sustainable Development Goal 2 and others.

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# Chapter 3
# Tropical Dry Forests in Multi-functional Landscapes: Agroforestry Systems for Conservation and Livelihoods

**Irene Montes-Londoño**

## 1 Introduction

Over the last several decades, tropical forest landscapes have experienced drastic changes. Forest conversion, fragmentation, and exploitation have created new types of landscapes in many tropical forest areas throughout the world. Today, much of the world's remaining forests exist in a landscape mosaic together with other land uses, particularly agriculture (Lamb et al. 2012). These mosaic landscapes are often labeled as "human-dominated", "human-modified", "multifunctional", or "working" landscapes (Kremen et al. 2012).

Tropical dry forests (TDF) account for 42% of tropical forest areas worldwide. TDF represent one of the most desired habitats in the tropics for human settlements and exploitation (Murphy and Lugo 1986; Quesada and Stoner 2004; Sánchez-Azofeifa et al. 2005a, b). As a consequence, these forests are the most fragmented and endangered forest ecosystem in the world, estimated today to be at only 44% of their original extent (Portillo and Sánchez-Azofeifa 2010) (Fig. 3.1). Conversion of the TDF has resulted in mosaic landscapes in which urban, agricultural, agroforestry, and forestry land uses are mixed. Even though dry tropical forests are less diverse than moist or wet tropical forests (Kalacska et al. 2004), TDF contain many endemic and economically valuable species (Kalacska et al. 2004; Sánchez-Azofeifa et al. 2005a, b). Since TDF are becoming increasingly rare and have the highest forest cover loss in South America (Hansen et al. 2013), conservation of their biodiversity and environmental services depends on the conservation of forest remnants and their restoration in human-dominated landscapes (Zuidema and Sayer 2003).

I. Montes-Londoño (✉)
School of Forestry and Environmental Studies, Yale University, New Haven, CT, USA
e-mail: Irene.montes@yale.edu



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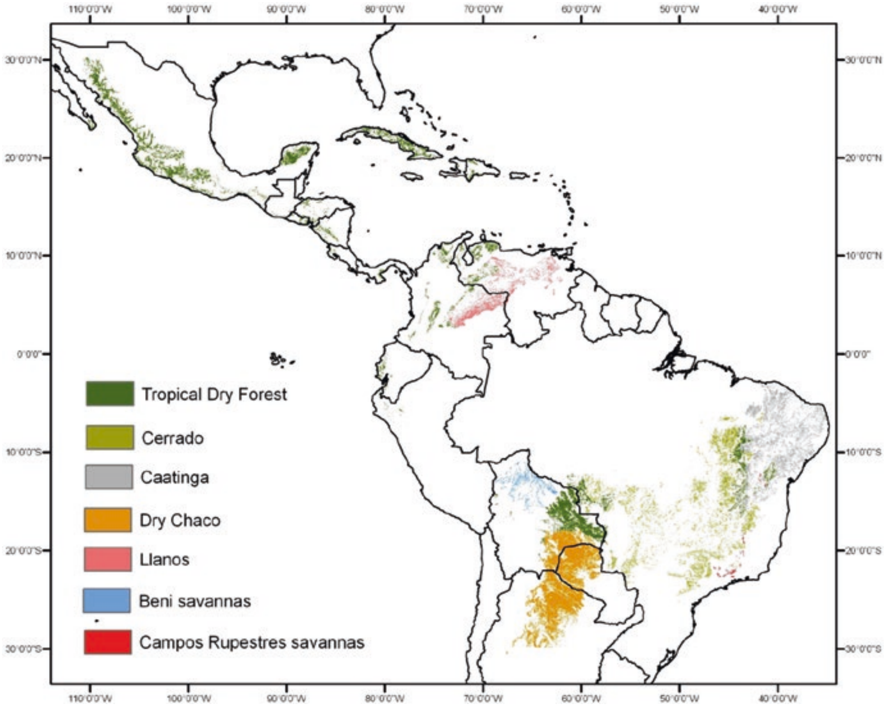


**Fig. 3.1** Extent of arid and semi-arid ecosystems in the Americas. According to the tropi-dry collaborative research network, tropical dry forests are dominated by drought-tolerant deciduous trees (at least 50%), growing in a climate where the mean annual temperature is ≥25°c, annual total precipitation ranges between 700 and 2000 mm, and there are three or more dry months of little to no rain (Sánchez-Azofeifa et al. 2005a, b). The percentage of deciduous trees varies from 50% to 100%, depending on the type of forest and their location along a precipitation gradient (Medina 2005)

Conservation efforts over the past few decades have focused mainly on the protection of fragments of natural ecosystems with little human intervention, while the potential contribution of the prevalent agricultural landscapes to biodiversity conservation has been grossly overlooked (Chazdon et al. 2009). Recently however, a growing body of scientific work is showing that certain types of agricultural land uses and traditional practices can not only support important numbers of native plant and animal species (McNeely 1995; Daily et al. 2003; Mayfield et al. 2005; Philpott et al. 2008), but may also contribute to enhancing the conservation value of nearby tropical forest remnants (Gascon et al. 1999; Daily et al. 2003; Faria and Baumgarten 2007; Harvey et al. 2008). Thus, a new paradigm is emerging whereby the design and management of the agricultural matrix is becoming an instrumental tool for sustainable landscape level conservation (Fischer et al. 2008; Harvey et al. 2008; Perfecto and Vandermeer 2008; Chazdon et al. 2009).

Tropical America holds more than 60% of the remaining global stands of TDF's (Miles et al. 2006). The objective of this chapter is to present case studies in which agroforestry systems (AFS) are being successfully utilized in Latin America to harmonize food production, conservation, and restoration of the TDF. The case studies presented here range from traditional homegardens and pastures of smallholder farmers to intensive silvopastoral and taungya systems of large landholders in dry regions of Latin America. This chapter ends by discussing the opportunities and challenges of adopting AFS in Latin America at a larger scale.

## 2 The Role of Agroforestry in Food Production, Biodiversity Conservation, and Climate Change

With increasing areas of degraded lands in the tropics and little new land for the expansion of agriculture without the loss of now scarce forest, agroforestry becomes a powerful tool to enhance ecological functioning and also to improve the livelihoods of rural people living within the working landscapes of tropical dry regions (Montagnini et al. 2011). Several books and literature reviews (see for example Montagnini et al. 1992, 2011, 2015; Leakey 2014) have emphasized the contributions that agroforestry can make to the rehabilitation of ecosystem and landscape attributes, such as restoration and conservation of biodiversity, connectivity in fragmented landscapes, and hydrological services that regulate water flow and prevent sediment pollution in watersheds.

Most landscapes in the tropics are represented by a heterogeneity of landholders that are likely to have differing perceptions of how to best manage their land. Their decisions will always depend on the resources and technical knowledge available, regional and global markets, and patterns of land tenure. They will also depend on the aspirations and goals of individual landholders (Lamb et al. 2012). While some landowners may wish to maximize short term gains and the production of goods such as timber, non-timber forest products (NTFP), and cash crops, others may seek long term benefits and revenues by maximizing the provision of ecosystem services. Others still may want to achieve both. The most interesting attribute of AFS is their plasticity, which allows to accommodate not only a heterogeneity of objectives but also to diversify socioeconomic and biophysical contexts.

Furthermore, over the last decade, the role of agroforestry systems (AFS) has become prominent in the goal of achieving mitigation and adaptation to climate change in rural landscapes. Almost 50% of the greenhouse gas (GHG) emissions in Latin America come from land use, land-use change, and forestry (LULUCF).[1] This is a particularity of the region in comparison with the rest of the world. AFS, if well

[1]As defined by the United Nations Climate Change Secretariat, Land use, land-use change, and forestry (LULUCF) is "A greenhouse gas inventory sector that covers emissions and removals of greenhouse gases resulting from direct human-induced land use, land-use change and forestry activities."

designed and managed, could enable agricultural soils to absorb and hold more carbon, and thus mitigate climate change. On the other hand, the conservation of agricultural biodiversity is key to climate change adaptation. For instance, the conservation of wild relatives of food crops is considered an insurance policy for the future, as these wild relatives can be used to breed new varieties that can cope with the changing conditions. Thus, species rich agroforestry systems could also bring cross-cutting benefits in terms of both climate change mitigation and adaptation.

## 3 Agroforestry Systems

Agroforestry is a term that has been in use for about 40 years, but the practices that it describes are much older (Ashton and Kelty 2017). For centuries, small farmers throughout the world have refined a range of traditional practices that combine the production of agricultural crops with growing trees to provide firewood, fruit, construction materials, and other products (e.g., Nair 1991; Altieri 2004; Miller and Nair 2006; Michon et al. 2007).

Hundreds of millions of farmers have shifted to a new, sedentary lifestyle that is the result of population growth, the effects of land distribution policies, and the lack of new forest to clear for the practice of shifting cultivation.[2] The majority of these farmers are trying to support their families on a small area of land (approximately two to five hectares) without access to fertilizers and other technologies. Fallow periods in traditional swidden agricultural systems must be shortened to the point where they no longer serve their purpose and agricultural yields decline (Ashton and Montagnini 2000; Leakey 2014).

Agroforestry can make agriculture permanently sustainable on a site. By integrating trees with herbaceous crops, agroforestry lengthens the time that crops can be grown on a given piece of land and increases crop productivity. Agroforestry systems offer additional benefits, increasing protection value (soil conservation, fertility improvement) and utility value (timber, fuelwood, fodder). Examples of agroforestry systems in dry regions of Latin America for food sovereignty and

[2] According to Ashton and Kelty (2017), the traditional system of agriculture used originally across both temperate and tropical forest climates is called swidden agriculture, or shifting cultivation. It has been derogatorily termed “slash and burn”. The natural forest vegetation is cut and burned, a crop such as maize or beans is grown for two or three cycles, and then the area is left fallow. Forest vegetation is allowed to develop, and soil nutrient stocks build up from atmospheric inputs, or in the case of nitrogen, from biological fixation. The native populations of soil organisms recover, and insects, fungi, and other pest species decline with the absence of their crop hosts. The developing tree canopy also shades out agricultural weeds. Food is grown on alternate plots until the fallow site has been restored to a condition suitable for clearing and cropping again. The ratio of fallow period to cropping period that is needed on a site varies with climate and soil conditions, but is frequently on the order of 10:1 (Ramakrishnan et al. 1992; Cairns and Garrity 1999). Thus, this system requires a good deal of land.

environmental services, like carbon capture and biodiversity, are silvopastoral systems, taungya, homegardens, and other combinations of trees and food crops.

## *3.1 Silvopastoral Systems (SPS)*

Cattle grazing is the main economic activity within the agricultural sector in Latin America, occupying more than 550 million hectares (ha) or about 27% of the total land area (Calle et al. 2012). Livestock production has been a major driver of deforestation in Latin America (Janzen 1988; Jarvis et al. 2010) and most of the remaining TDF fragments are separated by pasturelands.

Cattle ranching is not likely to decline any time soon in Latin America (Murgueitio et al. 2011; Calle et al. 2012). Not only is this activity deeply rooted in the Spanish and Portuguese ancestry of the region, but it also has become instrumental as a means to consolidate land ownership (Murgueitio and Ibrahim 2008). Moreover, a high and growing demand exists globally for all cattle products. Thus, the environmental transformation of livestock production is a priority for the Latin American region (Murgueitio 2000; Murgueitio et al. 2011). In 2014, eleven Latin American countries[3] committed, under the "Initiative 20×20", to bring 20 million ha of degraded land (that resulted from unsustainable practices of agriculture, infrastructure, and mining) into restoration by 2020 through sustainable land use schemes (WRI 2014).

The main SPS include dispersed trees in pastures, managed plant succession, live fences, windbreaks, fodder tree banks, cut-and-carry systems, tree plantations with livestock grazing, pastures between tree alleys, and intensive silvopastoral systems (ISS) (Murgueitio and Ibrahim 2001; Calle 2007). This chapter will focus mainly on ISS, trees dispersed in pastures and living fences, since these are the most commonly reported in dry tropical regions of Latin America.

### 3.1.1 Intensive Silvopastoral Systems (ISS)

Intensive silvopastoral systems (ISS) are a form of natural intensification for animal production that integrates multiple vegetation layers that maximize biomass production, combined with improved animal management techniques for optimal grazing (Calle and Chará 2013b; Murgueitio et al. 2011, 2015).

Experiences with ISS at a large scale started in Australia in the 1970s, when cattle ranchers integrated stands of leucaena (*Leucaena leucocephala*) with grasses to form highly productive grass-legume grazing systems for cattle (Dalzell et al.

[3] Currently, there are eleven countries, three states, and four NGO's participating in Initiative 20x20, committing a total of about 27.7 million hectares to place into restoration by 2020. The countries include Chile, Argentina, Brazil, Ecuador, Peru, Colombia, Costa Rica, Nicaragua, Honduras, El Salvador, Guatemala, and Mexico.

**Table 3.1** Beef and milk productivity in different SPS of dry regions in Colombia and Mexico

| Location (Source) | Type of System | Cattle density (animals/ha) | Cattle weight gain (g/day) | Beef Productivity (Kg/ha/year) | Milk Productivity (liters/ha/year) |
|---|---|---|---|---|---|
| Cesar Valley, Colombia (Cordoba et al. 2011) | Traditional extensive | 1.2 | 296.0 | 130 | 1150 |
| | ISS with timber trees | 4.7 | 790.2 | 1341 | 5552 |
| Cauca Valley, Colombia (Murgueitio et al. 2011) | Traditional extensive | 0.7 | N/A | N/A | 400 |
| | ISS with *L. leucocephala* and timber trees | 4.3 | N/A | N/A | 2350 |
| Tepalcatepec, Michoacán, Mexico (Solorio-Sánchez et al. 2011) | Traditional, extensive | 0.9 | N/A | N/A | 1150 |
| | ISS with | 3.9 | N/A | N/A | 11,388 |

2006; Shelton 2009). In Latin America, the development of an equivalent system to the Australian began 20 years ago and is already showing particular promise due to its many benefits. ISS are being successfully adopted in TDF regions for dairy and/or beef production.

For example, Murgueitio et al. (2011) and Calle et al. (2013a) report an ISS established in Valle del Cauca department, a dry region in Colombia, which has been proven to increase cattle stocking rates to 4.3 dairy cows per hectare (four times the mean stocking rate in conventional pastures without trees) and milk production to 2,350 liters of milk daily (compared to 400 liters a day in conventional systems) (Table 3.1).

This ISS is comprised of fodder shrubs planted at high densities (more than 10,000 plants $ha^{-1}$), intercropped with improved, highly-productive pastures, timber and/or fruit trees, all combined in a system that can be directly grazed by livestock. The species that comprise the system are as follows:

1. A mix of native and exotic grasses in the first strata including *Cynodon plectostachyus*, *Panicum maximum*, *Cynodon dactylon*, and native *Paspalum notatum*;
2. *Leucaena leucocephala* that is kept as a fodder shrub for cattle in the second strata and at high density (10,000–15,000 shrubs $ha^{-1}$);
3. Medium sized trees in the third strata and at medium density (30–50 $ha^{-1}$) such as *Prosopis juliflora, Senna spectabilis, Guazuma ulmifolia, Guarea guidonia*;
4. A canopy of large trees in the fourth strata and at low density *Ceiba pentandra, Samanea saman, Enterolobium cyclocarpum*;
5. A top layer of native and non-native palms in the fifth strata (*Syagrus zancona, Attalea butyracea,* and *Roystonea regia*) and timber trees like mahogany (*Swietenia macrophylla*), cedar *(Cedrela odorata)*, and others *(Zanthoxylum rhoifolium*).

This ISS completely eliminated the use of chemical fertilizers, effectively lowering production costs of meat and dairy. This ISS has been in use for two decades and still shows no evidence of declining grazing potential.

Calle et al. (2013) showed the promising results of another farm with an ISS located in the Magdalena valley in Colombia, a tropical dry forest region. The farm combines rice cultivation, silvopastoral systems, and small forest remnants. The ISS supports 2.5 large animals per ha and produces 1,036 kg of beef per ha per year,[4] as well as 3.5 milking cows per ha, with a daily production of 9.5 L per cow. Two decades ago, its extensive cattle grazing system supported an animal load of only 0.55 large animals per ha. Such improvements were achieved by implementing a 3.7 ha fodder bank of *Gliricidia sepium* in a cut-and-carry system that supplements the diets of milking cows and calves (Table 3.1). Additional fodder is produced on the farm's live fences of *Gliricidia, Ceiba pentandra*, and *Erythrina fusca*. The ISS on this farm includes timber trees such as *Tectona grandis, Azadirachta indica*, and *Albizia guachapele*. Additionally, in the deforested landscape of the Magdalena valley, this farm's silvopastoral system serves to connect riparian buffers and secondary forest fragments (Calle et al. 2013a).

In the dry tropics of Mexico (Michoacan), milk production was increased in several ranches by 45% in the first 2 years of establishment of an ISS. These systems have improved animal diet by increasing forage supply, which has made it possible to produce up to four times more milk and improve its quality compared to traditional systems of pure grasses (Rivera et al. 2010; Ku Vera et al. 2011). Producers have managed not only to increase the stocking rate and the milk production per unit area, but also to improve the rate of conversion of raw milk to mature cheese due to the milk's higher concentration of protein and solids[5] (Solorio-Sánchez et al. 2011) (Table 3.1).

### Costs of Implementation and Management of ISS

In tropical America, conventional pasture monocultures are often started by cutting down the forest. The first years the rancher is exploiting the residual soil organic matter from the forest and cattle ranching is profitable for the landowner. However, after a few years, the treeless pastures lose vigor by compaction, overgrazing, and frequent burning which favors the invasion of non-fodder plants and leads to declines in forage production, and consequently in animal production. Depending on the type of soil and the landowner resources, the soils can be decompressed and the prairies renewed every 3–5 years (Murgueitio et al. 2015).

Murgueitio et al. (2015) presented a detailed structure of establishment and management costs for: (i) renewing grasses in a conventional system with rotational

[4] Local average productivity of meat is 74 kg $ha^{-1}$ $year^{-1}$ and the Latin American average is 19.9 kg $ha^{-1}$ $year^{-1}$ (Mahecha et al. 2002).

[5] In this region mature cheeses have geographical designation of origin (Cotija cheese type) greatly appreciated in local markets.

**Table 3.2** Investment and management costs of a conventional pasture and an ISS in Valle del Cauca, Colombia

| Costs | Conventional pasture monoculture | Intensive Silvopastoral System (ISS) |
|---|---|---|
| Investment cost ($/ha) | 1,855 | 2,531 |
| Management cost ($/ha) | 1,270 | 220 |

grazing, electric fencing, livestock water supply, irrigation and fertilization, and (ii) an ISS with no use of agrochemicals that starts from a degraded treeless pasture[6] (Table 3.2). Although the ISS has higher investment costs than a conventional pasture (about 45% more) it has much lower management costs (about 85% less). In the end, ISS are more profitable and generate higher rates of return, which can greatly increase when a forestry business is included in the same area of production.

The amortization of the investment depends on the period of time that the system remains fully productive. In the case of conventional pasture monocultures, it has been estimated a mean lifespan of 4–12 years, depending on soil fertility and management practices, whereas in Colombia there are 24 year-old ISS where renewal or land use change hasn't been necessary. Thus, the investment cost in a conventional pasture monoculture depreciates in half the time of an ISS.

Finally, although the investment cost structure for an ISS can vary widely due to the diversity of situations present in agricultural regions of Latin America, evaluations of several projects in Brazil, Colombia, Mexico, Nicaragua, and Panama indicate that costs can range between $1,800–$2,700 USD per hectare (Murgueitio et al. 2015).

### 3.1.2 Trees Dispersed in Pastures

It is not necessary to have an ISS to observe the positive effects of tree cover in livestock productivity. In dry regions of Central America and northern South America, dispersed trees are a common feature and an integral part of the agricultural landscapes; particularly in dry regions, dispersed trees in pastures have an important value as shade, fodder, timber, fruit, and firewood (Harvey and Haber 1999; Cajas-Girón and Sinclair 2001; Barrance et al. 2003; Scheelje et al. 2011).

In the southern dry regions of Honduras, farmers actively protect naturally regenerated trees to ensure a continued supply of tree products, in response to increasing scarcity of forest and fallow resources. The most significant tree husbandry practice, both in terms of the area which it covers, and its potential as a

[6] The establishment and maintenance of pastures with electric fencing, rotational grazing, livestock water supply, irrigation, and fertilization is the most appropriate comparison because it's the closer option to the stocking density and productivity in meat or milk of the ISS.

vehicle for sustainable ecosystem management, is the management of natural regeneration in paddocks[7] (Barrance et al. 2003; Esquivel et al. 2009).

In general, farmers of dry regions are aware of the potentially negative effects of trees on grass production (through shading and competition). In a study comprising four agricultural landscapes and more than 50,000 ha in Costa Rica and Nicaragua's dry regions, Harvey et al. (2011) reported that Costa Rican and Nicaraguan farmers try to balance their demand for tree products and services against the negative impacts of too much shade on grass production; choosing to maintain low tree densities (8–33 trees per ha) to avoid over-shading the grass. Similarly, in the dry zone of southern Honduras, shade is regulated either by felling trees, or by pruning or pollarding them to 3–4 m height (Barrance et al. 2003).

Farmers in dry tropical regions actively retain and protect useful tree species (*Samanea saman, Cecropia spp., Gliricidia sepium*), and eliminate those that are not beneficial (Garen et al. 2009; Harvey et al. 2011; Metzel and Montagnini 2014). Thus, in active pastures most trees belong to a reduced number of species (Villanueva et al. 2007). Additionally, due to the presence of cattle and the frequent use of fire and herbicides, tree species that tend to dominate these landscapes are of sprout origin, dispersed by cattle or wind, and fire tolerant (Esquivel et al. 2009; Griscom and Ashton 2011). For instance, in Panama, *Guazuma ulmifolia* dominates in pasturelands because farmers favor it for fodder, it readily sprouts, and its seeds are dispersed by cattle (Griscom et al. 2009). Likewise, Esquivel et al. (2009) reported that some of the most dominant species in dry pastures of Nicaragua were pioneer species dispersed by cattle (e.g., *G. ulmifolia, Cassia grandis, Enterolobium cyclocarpum, Leucaena shannonii*). Finally, Harvey et al. (2011) reported that dispersed trees include a wide range of sizes and species (72–101 species per landscape[8]; 255 species total), and are dominated by a subset of common species important for timber, fodder, or fruit (Table 3.3).

Recent studies evaluating farmers' preferences when planting trees in pastures have shown that farmers in TDF regions understand the value of trees in their pastures. For instance, the landscape of the Azuero peninsula in Panama is a mosaic of grassy savannahs and small fragments of dry tropical forest that has between 5 and 7 dry months a year. When Garen et al. (2009) evaluated the experiences of farmers participating in PRORENA,[9] a native species reforestation project in the country, it was found that the primary motivations of farmers to plant trees in their farms were both environmental and economic. Farmers' motivations for tree planting varied between the studied sites, but overall they were interested in trees that ameliorate the climate, improve water quality, reduce soil erosion, provide shade and fruits for

[7] A common practice of smallholder farmers in the dry regions of Honduras and Nicaragua is to manage their land on a cyclical basis: alternating between periods of food crop production, cattle grazing, and fallow to recuperate degraded land.

[8] Each landscape comprising an area of approximately 12,000 ha.

[9] PRORENA (Proyecto de Reforestación con Especias Nativas), a research initiative of Yale University and the Smithsonian Tropical Research Institute (STRI) to examine ways to more effectively approach Panama's reforestation process.

**Table 3.3** Summary of the most abundant tree species occurring as dispersed trees in pastures and living fences in dry regions of Panama, Costa Rica, Nicaragua, and Colombia and their respective uses

| Type | Panama | Costa Rica | Nicaragua | Colombia | Honduras |
|---|---|---|---|---|---|
| Timber species | *Anacardium excelsium, Andira inermis, Calycophyllum candidissimum, Cedrela odorata, Cordia alliodora, Inga vera, Ficus spp., Enterolobium cyclocarpum, Ormosia macrocalyx, Pachira quinata, Samanea saman, Spondias mombin, Sterculia apetala, Swietenia macrophylla, Tabaebuia rosea, Tectona grandis, Zygia longifolia* | *Acosmium panamensis, Albizia guachepele, Andira inermis, Bombacopsis quinata, C. odorata, C. alliodora, E. cyclocarpum, Guazuma ulmifolia, Myrospermun frutescens, P.quinata, T. rosea, T. ochracea.* | *Cordia alliodora, Cordia bicolor, Enterolobium cyclocarpum, Lonchocarpus minimiflorus, Samanea saman, Swietenia humilis, T. rosea, T. ochracea* | *Albizia caribaea, A. excelsium; Bulnesia arborea; Ceiba pentandra, C. alliodora; C. dentata, Maclura, tinctoria, Pachira quinata; Platymiscium pinnatum; Sterculia apelata; T. rosea; Tabebuia billbergii;* | *Bombacopsis quinata* |
| Firewood species | *Anacardium occidentale, Andira inermis, Bursera simaruba, Calycophyllum candidissimum, Gliricidia sepium, Inga vera.* | *Guazuma ulmifolia* | *Cordia bicolor, Gliricidia sepium, Guazuma ulmifolia, Myrospermun frutescens* | | *Albizia adinocephala, A. saman, Cedrela odorata, C. alliodora, E. cyclocarpum, G. ulmifolia., S. glauca,* and *S. humilis.* |
| Foliage and fruits for cattle | *Enterolobium cyclocarpum, Gliricidia sepium, Guazuma ulmifolia, Samanea saman, Spondias purpurea.* | *Guazuma ulmifolia, Acrocomia aculeate, Guazuma ulmifolia* | *Acrocomia vinifera, Albizia saman, Enterolobium cyclocarpum, Gliricidia sepium, Gliricidia sepium, Guazuma ulmifolia, Samanea saman.* | *Acacia farnesiana, Albizia lebbeck, Albizia saman, Cassia grandis; Caesalpinea coriaria; Calliandra spp., Crescentia cujete, Enterolobium cyclocarpum, Gliricidia sepium, Guazuma ulmifolia, Prosopis juliflora, Senna spectabilis, Spondias mombin.* | *A. saman, Caesalpinia coriaria, Crescentia alata, E. cyclocarpum, Guazuma ulmifolia.* |

| | | | | | |
|---|---|---|---|---|---|
| Fruits for human consumption | *Anacardium excelsum, Anacardium occidentale, Byrsonima crassifolia, Citrus latifolia, Cocos nucifera, Enterolobium cyclocarpum, Mangifera indica, Persea americana, Spondias mombin, Spondias purpurea, Sterculia apetala, Zygia longifolia* | *Acrocomia aculeate, Byrsonima crassifolia* | *Byrsonima crassifolia, Cordia dentata* | *Maclura tinctoria* | |
| Publications with additional details | Wishnie et al. (2007), Garen et al. (2009), Hall et al. (2011), Griscom and Ashton (2011), Metzel and Montagnini (2014). | Harvey et al. (2011), Scheelje et al. (2011) | Harvey et al. (2011) | Cajas-Girón and Sinclair (2001),<br>Author's personal communications with farmers of the Colombian Caribbean coast, 2016. | Barrance et al. (2003). |

their cattle, and/or produce high quality timber. From a set of seven native timber species provided by PRORENA to participating farmers, the trees that ranked highest were those that performed best, and improved soil and pasture quality while providing fodder and timber. Listed in order of preference, the species were: *Pachira quinata, Cedrela odorata, Tabebuia rosea, Samanea saman, Swietenia macrophylla, Cordia alliodora,* and *Anacardium excelsum.*

Interestingly, when comparing land managers with and without existing forest on their land in a larger study area in the same region, Metzel and Montagnini (2014) found that, when it came to planting, farmers planted trees primarily for two tangible economic reasons: timber and fruit.

In terms of productivity, Yamamoto et al. (2007) found that farms with moderate tree density (approximately 20% of tree cover) have significant positive impacts on annual milk production in dual-purpose cattle production systems in the lowlands of central Nicaragua. In the studied area, milk price is maintained rather low, which does not allow farms to invest on supplementary fodder to increase milk yield during the dry season. However, farmers have conserved and dispersed tree species such as *G. ulmifolia*, *E. cyclocarpum*, and *Albizia saman* which produce fruits and fodder, as well as provide shade and increase grass yield to support milk production in the dry season.

Regarding biodiversity and value for conservation, dispersed trees also play important roles providing habitat, resources, and nesting sites for animals, facilitating tree regeneration within pastures (Griscom and Ashton 2011), increasing overall tree cover within the landscape; therefore conserving biodiversity, enhancing landscape connectivity (Guevara et al. 1998; Fischer and Lindenmayer 2002; Harvey et al. 2006; Medina et al. 2007), and ameliorating microclimatic conditions within the pasture matrix for forest-dependent species (Sekercioglu et al. 2007). Thus, dispersed trees play both productive and environmentally protective roles within the agricultural landscape, and can contribute to both sustainable development and conservation initiatives (Barrance et al. 2009; Harvey et al. 2011).

### 3.1.3 Living Fences

Living fences are commonly used throughout Central American pasturelands. They are another type of SPS where the trees are purposefully chosen to serve their function as a fence and at the same time improve soils, control erosion, and serve as fodder (often in a cut-and-carry system). *Gliricidia sepium* is a N-fixing tree often planted as a living fence. It is an important firewood species and a good soil improver, and has been found to have excellent qualities for fodder production (Montagnini 2008).

Francesconi et al. (2011a, b) studied the potential of living fences and windbreaks to restore connectivity in fragmented landscapes and found that living fences provide bird habitat, therefore promoting bird abundance and diversity in the landscape in a similar way that forest patches do. Living fences are used by all forest, generalist, and savanna specialist bird species. However, all living fences are not equally effective at attracting birds. Structure and composition of the fence are important factors influencing usage by bird species. Therefore, the presence of birds in living fences could be improved by altering living fence management practices such as (1) increasing tree diversity, (2) allowing some trees to develop to mature stages (large diameter), and (3) allowing trees to develop large crowns.

### 3.1.4 Timber Products in SPS

The development of silvopastoral systems with timber trees represents an opportunity to diversify production and to increase income of livestock farmers (Somarriba 1997; Pezo and Ibrahim 1998; Beer et al. 2000; Pomareda 2000; Ibrahim and Camargo 2001) (Fig. 3.2). SPS can combine the short-term profit from milk and/or meat production with a long-term investment in timber (Calle et al. 2012). Moreover, timber trees in farms have the direct consequence of reducing pressure on TDF remnants (Barrance et al. 2003).

In Costa Rica and Nicaragua, farmers often harvest trees for fence posts, construction material, farm implements, and sporadically sell timber to earn money (Harvey et al. 2011). For example, small farmers in the dry region of Honduras listed 41 different species of trees which, when fallow areas are cleared for cultivation, are left unfelled and protected from fire because of their potential future value.

**Fig. 3.2** *Paquira quinata*, one of the timber tree species commonly found in silvopastoral systems of dry tropical regions in Latin America. Silvopastoral systems with timber trees have the potential to diversify farm incomes and to improve their profitability (Photo by: Irene Montes. Azuero peninsula, Panama. March, 2016)

The most frequently used species in this region are *Cordia alliodora*, small-leafed mahogany or caoba (*Swietenia humilis*), quebracho (*Lysiloma spp*.), guanacaste negro (*Enterolobium cyclocarpum*), and carreto negro (*Albizia saman*) (Barrance et al. 2003) (Table 3.3). Similarly, in the Esparza Region of Costa Rica, 42 native timber tree species were found to be present in active pastures and preferred by farmers for their several convenient attributes (e.g., their hardiness in pasture management, high yield, and easy seed dispersal) and their diverse products (e.g., saw timber, poles, shade, and fodder for livestock) (Scheelje et al. 2011). Some of the commonly used species in this region are *Tabebuia rosea, Enterolobium cyclocarpum, Cordia alliodora, Guazuma ulmifolia, Cedrela odorata, Myrospermun frutescens, Bombacopsis quinata* (Fig. 3.2) and *Albizia guachepele* (Table 3.3).

Scheelje et al. (2011) examined the financial viability of commercial timber production of natural regenerated trees dispersed in active paddocks in the Esparza region of Costa Rica. They found considerable variability on the profitability between farms depending on the density of merchantable timber species, the number of logs per hectare, and the quality of the logs.

In the Caribbean region of Colombia, Murgueitio et al. (2015) found that a SPS with planted timber trees[10] (*Eucalyptus tereticornis)* at a density of 500 trees per hectare and a 12-year rotation increased the IRR by 4.3%[11] when compared to a SPS without timber trees.

However, farmers often have insufficient knowledge and experience with silvicultural practices or timber marketing, technology for the introduction of forest species in ranchlands is scarce, and markets and wood-processing techniques for timber produced in silvopastoral systems are insufficient (Piotto et al. 2004; Calle et al. 2012, 2013). For instance, although farmers prune the trees destined for timber to promote straight trunks, the branches are typically cut at a distance of several inches from the stem, leaving protruding pegs and thereby reducing the quality of the timber and its value by contributing to the formation of black knots (Barrance et al. 2003; Author's personal observations in the Azuero Peninsula 2016) (Fig. 3.2).

### 3.1.5 Yield Increase and Diversification in Silvopastoral Systems

Silvopastoral systems, when well designed and managed, can enhance milk and meat production and cattle reproduction (Table 3.1), while production costs decline as external inputs are replaced by agroecological processes (Murgueitio et al. 2011) (Table 3.2). Several studies now prove the efficiency of biological processes such as photosynthesis, nitrogen fixation, solubilization of soil phosphorus, and the

[10] Total volume of wood is estimated to be 30% lower than in conventional plantations, but this reduction is offset by the increased price of timber at final harvest. In SPS, thinning and pruning are designed to maximize diameters above 30 cm, increasing the volume of high-priced timber by 50% (Esquivel et al. 2010).

[11] In regions with a well-developed timber industry and market of value-added wood this increase would be greater (Colcombet et al. 2009).

enhancement of soil biological activity that allow a natural intensification in silvopastoral systems (Guggenberger et al. 2000; Montagnini 2008; Giraldo et al. 2011; Murgueitio et al. 2011). A number of leguminous nitrogen-fixing trees and shrubs initiate agroecological restoration which addresses simultaneously land degradation and soil fertility. In turn, space can be freed up to diversify the farming system with other income-generating crops or indigenous tree species that produce useful and marketable products for local and regional trade (Leakey 2014). Therefore, silvopastoral systems can simultaneously improve agricultural yields and increase the availability of productive land (Table 3.1).

### 3.1.6 Biodiversity Benefits of Silvopastoral Systems

Many unprotected TDF remnants of high conservation value are embedded within a matrix of cattle grazing areas formed by pasture monocultures with few trees (Fig. 3.3). Because of their higher stocking density, SPS allow farmers to concentrate production in the most suitable areas of their farms and release fragile lands for soil recovery and biodiversity protection (Giraldo et al. 2011; Chará et al. 2015).


**Fig. 3.3** Poor pruning of cocobolo (*Dalbergia retusa*) trees in a silvopastoral system of the Azuero peninsula in Panama. The branches that are encased in stem wood are called knots, and they are the most common defects of wood that is grown for timber products. In some situations, pruning these branches can be an important silvicultural practice for producing clear wood (that is, knot-free wood). The use of pruning to confine the knots to a small core in the center of the stem can greatly increase the timber value of a tree. This is the main goal of pruning in commercial forestry (Ashton and Kelty 2017) (Photo by: Irene Montes. Azuero peninsula, Panama. March, 2016)

Reforesting pastures can preserve biodiversity, restore ecosystem services, and create working landscapes with valuable timber and non-timber products (Griscom and Ashton 2011). Moreover, the tree-rich matrix of SPS may act as a buffer for remnant old-forest fragments: ameliorating edge effects, improving landscape connectivity, and extending source habitat for a subset of the regional species pool (Harvey et al. 2006; Sáenz et al. 2007). Additionally, SPS can be easily integrated with other landscape level strategies, such as connectivity corridors, in order to conserve biodiversity and enhance other environmental services, i.e., natural pest control, carbon sequestration (Montagnini et al. 2013), water and soil conservation, nutrient cycling, hydrological protection, and crop pollination (Chazdon et al. 2009; Calle et al. 2010).

## *3.2 Homegardens*

Homegardens are the oldest and probably the most widespread agroforestry system in the world. Homegardens are important because they provide the household with a basic food source as well as high value products to generate cash income (Montagnini 2006); therefore, they are often used as tools in development projects that promote food security (Fig. 3.4). They tend to be dominated by planted trees,

**Fig. 3.4** Agricultural landscape in the Azuero peninsula with living fences, isolated pasture trees and riparian forests. Remnant forest fragments and individual trees left after clearing land for cattle ranching have lasting effects on native forest ability to regenerate (Griscom and Ashton 2011) (Photo by: Irene Montes. March 2016)

**Fig. 3.5** In dry areas, the potential for livestock or agricultural production is limited by water availability. This homegarden recently established in the Azuero peninsula in Panama was only possible after the farmer installed a solar powered hydraulic pump and an irrigation system (Photo by: Irene Montes. Odialca's Farm, Los Asientos, Panama. March, 2016)

usually a diverse range of fruit trees (both native and exotic), which can easily be protected and watered due to their closeness to the house. Homegardens are also used as a trial site for new species, and can serve as a crop gene bank (Montagnini et al. 1992, 2015).

As described by Barrance et al. (2003), homegardens in southern Honduras vary greatly between communities. In some communities, they include an area of secondary forest near the house, which is kept as a reserve of tree products. Sometimes they include a small area of staple grain cultivation, and in communities in which cattle raising is important, many homegardens are used as night corrals for cattle (a practice which can seriously limit opportunities for trees growing in the homegardens, or requires that planted trees are elaborately protected against browsing) (Fig. 3.5).

Several studies (see Méndez et al. 2001; Barrance et al. 2003; Blanckaert et al. 2004; Montagnini 2006; Terrones Rincón et al. 2011) indicate that homegardens in arid and semiarid regions are highly diverse, often holding a similar level of biodiversity to that found in homegardens of humid regions. As noted by Price (1989), the presence of two distinct and marked seasons facilitates the existence of various forms of plant life, which allows the farmer to plant a diverse range of species that provide food year-round. In tropical dry forest regions of Costa Rica where socioeconomic and biophysical conditions are less favorable than in other regions, homegardens become more important for subsistence.

Due to their social, cultural, economic, and food security functions, homegardens should be considered an important tool in providing environmental services, and meeting conservation and livelihood needs in dry regions where land degradation and poverty prevail.

### *3.3 Taungya Systems*

Taungya systems are used throughout the world and refer to the practice of planting annual crops such as beans, cassava, corn, or other species among young tree seedlings in the initial stage of reforestation (Montagnini et al. 1992). Because farmers simultaneously manage for both crop and tree species, Taungya improves survival and growth of both types of species, reduces establishment costs of plantations of valuable timber, and generates early and yearly income (Somarriba and Beer 2011; Silva 2002; Beltrame and Rodrigues 2007).

Escalante and Guerra (2015) describe two successful taungya systems that have been established in tropical dry forest regions of Venezuela. The first one, established by Danac – a foundation that develops technology for improving seeds of corn, rice, and soybeans and does research and promotion of agroforestry systems – consists of a mixed species plantation of valuable timber trees (*Cordia alliodora, Swietenia macrophylla, Tectona grandis, Tabebuia rosea, Gmelina arborea, Pinus caribaea*) intercropped with corn and leguminous annual crops (*Cajanus cajan, Crotalaria juncea)*. In 5 years, 7,322 kg of *Cajanus cajan*[12] beans were harvested by members of neighboring communities. In the sixth year around 8,800 trees were harvested during the first thinning, which were then used to maintain the farm fences, donated to the local communities, and sold to livestock enterprises and construction companies.

The second taungya system described by Escalante and Guerra (2015) was established by the private forestry company DEFORSA in Cojedes state. This taungya system integrated the production of pulpwood (*Eucalyptus urophylla*), intercropped with cash crops (watermelon, cantaloupe, beans, corn, rice, coffee, sugar cane, and sorghum) which were later followed by grass for livestock production. This project allowed for a yearly production of 215 tons of rice and 30 tons of sorghum for 2 years; 600 tons of corn, sorghum and sugar cane used for livestock feed; and 900 tons of hay that were used to feed the herd during the dry season.

[12] *Cajanus cajan* is a shrubby species whose beans are frequently used in Latin America for food while the leaves and branches can be used as green manure. A few studies have shown that when planted with forest tree seedlings, it increases tree survival and growth compared with planting trees alone (Silva 2002; Beltrame and Rodrigues 2007).

## 4 Agroforestry Systems for Restoration of Tropical Dry Forests

Agroforestry systems can promote recovery of dry tropical forests in two ways. 1, by integrating restoration within the same area of production; and 2, by naturally intensifying production in certain areas of the farm, which would allow farmers to release key areas for restoration and conservation of TDF, provided that the right incentives and/or regulations are in place (Phalan et al. 2016).

Agroforestry systems can provide food and income from selling cash crops, timber, and non-timber forest products (NTFPs), while promoting forest recovery. For example, when examining two reforestation projects recently implemented in Haiti, a country well known for its extreme deforestation and poverty,[13] Marlay (2015) concluded that the success of both reforestation projects was due to the great interest of Haitian farmers in planting trees in agroforestry systems in their farms. Trees provided one of the farmers' main sources of annual income in the form of timber, firewood, and fruit. In addition, because trees could be harvested whenever needed, they were used as savings and emergency resources. Moreover, trees increased soil fertility and prevented soil degradation, increased water retention, and provided habitat for wildlife. Thus, restoration approaches need not to be in conflict with providing for human livelihoods (Vieira et al. 2009).

It is reasonable to think that farmers are often much more interested in the production benefits from agroforestry systems than in the wildlife per se (Leakey 2014). Thus, when engaging farmers in restoration projects it is important to consider the local context, and value farmers' knowledge and necessities (González 2006; Manuel-Navarrete et al. 2006; Chambers 2013; Parmentier 2014).

Farmers often have extensive knowledge of propagation methods, species suitability for specific light and soil conditions, and management methods for a range of crop and native tree species (Diemont et al. 2006; Isaac et al. 2007), which can help in designing agroforestry and restoration projects. For instance, in order to increase the acceptance and interest of the local population in woody species, Suárez et al. (2012) studied and documented the local knowledge of the usefulness, scarcity, and importance for wildlife of 76 native tree species in central Veracruz, Mexico – a region with mainly secondary vegetation and remnants of tropical dry forest. Using this information, they later proposed a number of tree species (all useful for humans, mainly for rural construction, food, fence posts, and fuel) for restoration, agroforestry systems, and enrichment plantings on degraded dry tropical regions. Similarly, Cajas-Girón and Sinclair (2001) asked farmers of the Caribbean Region in Colombia about their current knowledge and practice about trees and adapted it to design multi-strata silvopastoral systems that incorporate greater

[13] Haiti remains the poorest country in the Americas and one of the poorest in the world (with a GDP per capita of US$ 846 in 2014) (World Bank 2016).

structural, functional, and species diversity than the more traditional approach of managing dispersed trees on pastures.

As for spared land for habitat restoration and conservation, rehabilitation of dry tropical forests in released areas may be accomplished either by establishing native species plantations or by relying on the natural regenerative capacity of the landscape (Guevara et al. 1986; Holl 1998, 1999; Griscom et al. 2009; Vieira and Scariot 2006; Garen et al. 2009; Hall et al. 2011; van Breugel et al. 2011). There is reason to believe that farmers and large scale restoration projects would prefer the latest. Fortunately, in dry tropical forest regions of Latin America there is now increasing information about the factors that facilitate or inhibit forest succession and on restoration models, both key to effectively capitalize on natural regeneration mechanisms that can complement the more time and cost-intensive plantation strategies (Griscom and Ashton 2011).

# 5 Discussion

## *5.1 Common Obstacles Limiting the Adoption of Agroforestry Systems*

Despite conclusive research findings on the benefits of agroforestry systems in providing habitat for flora and fauna, enhancing soil processes, augmenting nutrient cycling, supplying different timber and NTFP, increasing resiliency to climate change, and providing benefits for livelihoods, there is still a large number of producers that are reluctant to adopt agroforestry systems in their farms. Thus, it has become necessary to understand and address the barriers for their large-scale adoption (Dagang and Nair 2003; Murgueitio et al. 2011; Calle et al. 2012; Calle et al. 2013a). Some of the common obstacles contributing to low rates of adoption of AFS identified in the case studies presented in this chapter and in the literature include:

### 5.1.1 Limited Knowledge of Tree Density, Species Composition, and Spatial Arrangements

In general, the case studies demonstrate that farmers in dry regions understand the importance of trees for shade (reducing animal heat stress and maintaining a favorable microclimate) and as a source of fruits and foliage for cattle during the dry season when grass availability is low. In dry regions water tends to be the limiting resource rather than nutrients (Ashton and Montagnini 2000) and farmers often understand the effect of trees on pasture productivity. However, as noted by Harvey et al. (2011), farmers often do not have detailed information on thresholds of tree cover at which negative impacts outweigh positive effects. Additionally, farmers often lack knowledge about the phenology[14] of some of the most commonly utilized tree species in seasonally dry pastures (Cajas-Girón and Sinclair 2001) or on the shade tolerance of pasture species (Harvey et al. 2011). Moreover, technology for the introduction of forest species in ranchlands is poor (Calle et al. 2012). Thus, scientific advice on tree densities, spatial arrangements and pasture composition (Dagang and Nair 2003) might improve farmers' management of cattle on pastures with dispersed or dense tree cover.

### 5.1.2 Limited Silvicultural Knowledge of Native Trees

Farmers could also benefit from having more knowledge on silvicultural techniques (i.e., pruning regimes, thinning, mixtures with different species, planting density, etc.) to improve timber quality of native species. Several studies discussed in this chapter show that farmers protect and invest on trees that have high timber value, and are interested in planting trees that provide fruit and timber. However, it has become necessary to generate and disseminate appropriate silvicultural practices in order to enhance timber quality (Piotto et al. 2003, 2004; Wishnie et al. 2007; Garen et al. 2009; Hall et al. 2011) and increase earnings from timber harvesting. This, in turn, could augment farmers' interest in keeping more trees in their farms and investing on managing more complex and productive agroforestry systems.

### 5.1.3 Financial Incentives and Access to Finance

As discussed by Montagnini and Finney (2011), planting native tree species in agroforestry systems can be an attractive commercial opportunity for farmers and investors. Non-timber forest products (NTFPs), firewood, and fodder from pruning and thinning provide additional early returns. However, the conversion of degraded, simplified production systems to diverse, agroecological, resilient systems, represents high costs of plantation establishment and/or opportunity costs of setting aside areas for conservation. Land tax exemptions, credit schemes that are synchronized with the biological aspects of the system, and payments for environmental services (PES) can play an important role in alleviating these costs (Goldstein et al. 2006; Montagnini and Finney 2011; Calle et al. 2012).

Although PES are subject to some limitations that may represent an obstacle to their wider adoption, PES programs have been successfully implemented in several countries of Latin America (see for example, Ibrahim et al. 2007, 2011) and demonstrate that agroforestry, forestry, and forest conservation can be attractive to landholders when the economic value of PES and forestry production are combined (Montagnini and Finney 2011).

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[14] Phenology of trees, in terms of when they provide shade as well as fodder from leaves and pods or fruits, is of critical importance in the design of appropriate mixtures of species in silvopastoral systems.

Based on the lessons learned by the pilot project "Regional Integrated Silvopastoral Approaches to Ecosystem Management (RISAEM)[15]", Murgueitio et al. (2011) proposed a combination of short term and long term PES schemes to promote the adoption of SPS in Colombia. Short-term PES would be given to those land uses that establish SPS that foster high levels of biodiversity and are profitable in the medium and long term, and therefore will most likely be kept in place by farmers. Additionally, land uses that foster high levels of biodiversity but are not profitable in the medium and long term (i.e., riparian forests, connectivity corridors, secondary forests, and wetlands) would need to receive both short term payments and additional long-term PES.

Montagnini and Finney (2011) recommended PES systems that incorporate bundling or layering of multiple services (i.e., biodiversity, carbon sequestration, and watershed protection, to name a few) as opposed to PES systems that include only one environmental service in order to reduce perverse incentives.

Basic access to finance in adequate terms and conditions are also required for the conversion of a conventional tree-less system to an agroforestry system. As put by a cattle rancher in the Azuero region of Panama, in general, longer term and grace periods are required, coupled with insurance systems to provide sufficient guarantees to cover the risk of the loan (Author's personal observations in the Azuero Peninsula, 2016).

### 5.1.4 Markets and Timber Harvesting Requirements

Access to markets and wood-processing techniques for timber produced in AFS has been identified as an important obstacle that keeps farmers for planting more trees on their farms (Calle et al. 2012). For example, Barrance et al. (2003) observed that famers living in isolated communities and who have limited access to markets for tree products often keep less trees in their pastures. Similarly, Scheelje et al. (2011) concluded that if all farmers had the opportunity to sell timber in a sawmill the activity would become profitable earlier in the rotation cycle and with less number of logs per hectare.

Prohibitive timber harvesting requirements are another major obstacle impeding farmers to plant trees on their farms (Scheelje 2009). As discussed by Detlefsen and Somarriba (2015), when the process to get a permit to harvest and transport timber trees planted on the farm gets too complicated and bureaucratic, farmers prefer to maintain the minimum number of trees that satisfies their own needs at the farm. This is the case for Honduras, Nicaragua, Panama, and Colombia. By contrast, Belize, El Salvador, and Guatemala have simplified protocols for obtaining these permits.

[15] This project was designed to test whether Payment for Environmental Services (PES) is an appropriate tool to promote the transition from conventional cattle ranching to silvopastoral systems. Funded by The Global Environment Facility and administered by the World Bank, the project took place between 2002 and 2007 in three regions of Colombia, Costa Rica, and Nicaragua.

### 5.1.5 Analysis of Food Production Decoupled from Social and Ecological Variables

The scientific community agrees that reconciling agriculture and conservation is one of this century's greatest challenges (Leakey 2014). In recent years, the daunting challenge of meeting the growing demand for agricultural products while conserving biodiversity and preventing a global climate crisis has been raised in terms of two opposite approaches (Calle and Chará 2013b). On one side are those who propose a strategy of shared land ('land sharing'), where the production and conservation goals are integrated into complex multifunctional landscapes (Fischer et al. 2008; Harvey et al. 2008; Perfecto and Vandermeer 2008; Kremen et al. 2012; Tscharntke et al. 2012). On the other side are the proponents of the strategy of reserved land ('land sparing'), according to which agricultural production should be maximized on high-performance systems in order to keep other lands exclusively for protection and conservation of natural habitats (Green et al. 2005; Phalan et al. 2016). Often the focus of this discussion is polarized, regardless of the many socioeconomic and political factors that end up influencing land use decisions in human-dominated landscapes. Thus, there is increasing emphasis on analyzing coupled socio-ecological systems for the construction of future policy and management alternatives (Fischer et al. 2008).

There is now widespread evidence that a land sparing strategy could benefit a larger proportion of wild species than a land sharing approach, provided that spared land is conserved as natural habitat (Phalan et al. 2016). However, conservation needs not just involve tiny islands of natural vegetation in a barren world of agriculture, as there can be great biodiversity increases in sustainably managed farmed areas (Harvey et al. 2008). The increase of food production per unit area (yield) needs to be achieved in a sustainable manner in order to ensure long-term productivity of designated agricultural lands. Therefore, it is possible to have an alternative to the land sharing vs. land sparing dilemma that involves a combination of sustainable intensification, ecological restoration, and conservation strategies (Rodrigues et al. 2009, Calle et al. 2013a, Kremen and Miles 2012).

### 5.1.6 Policies and Economic Practices That Favor Industrial Agriculture Models Over the Most Cutting-Edge Ecological Farming Methods

Scaling-up agroecological approaches, such as agroforestry systems, implies radical changes in the current dominant agrifood system as a whole. Cattle and food production models that are intensive in the use of agrochemicals are favored by today's dominant socioeconomic model. As discussed by Parmentier (2014), current policies and economic practices support a 'corporate food regime' that is characterized by "unprecedented market power and profits of monopoly agrifood corporations, globalized animal protein chains, growing links between food and fuel economies, liberalized global trade in food, increasingly concentrated land ownership, a shrinking natural resource base, and growing opposition from food movements worldwide".

For instance, just recently in Colombia the government approved a law (colloquially called ZIDRES – Areas of Interest for Rural, Economic and Social Development – for its acronym in Spanish) that deprives farmers and farm workers of the wastelands of the state and grants them to multinational corporations for big agricultural projects. This law violates the right of accessing land of agricultural workers, perpetuates the unequal structure of land ownership in Colombia, and threatens food security and food sovereignty. As put by a congressman that opposes this law, "food security is offended because it allows the accumulation of land and the transference of economic benefits of its exploitation to foreign hands, as investors of such projects come mainly from abroad, as indicated by the global economic trend. Furthermore, the rules of experience and economic logic, imply that the products will go to international markets because higher profits are obtained in exporting than selling them in domestic markets".

Thus, expanding agroecological approaches that improve food production and farmers' incomes, while also protecting the soil, water, and climate requires a paradigm shift in agricultural development. Many scientists, politicians, and advocates of agroecology claim that for that to happen, "peasants, consumers, pastoralists, indigenous communities and other civil society actors will have to regain control over the food system" (Parmentier 2014).

### 5.1.7 Land Speculation

As mentioned in Sect. 3.1, extensive ranching has become instrumental as a means to consolidate land ownership. Extensive ranching gives the landowner control over large areas of marginal lands that later valorize when roads penetrate the area. In this sense, large ranches are seen as profitable long term investments, even when current per hectare production is low.

## 6 Conclusions

Looked through the lens of tropical forest restoration, agroforestry could be used more widely to overcome socioeconomic and ecological obstacles in restoring degraded lands that merit tree planting. Incorporating a range of agroecology and agroforestry techniques (e.g., taungya systems) as a transitional phase early in forest restoration reduces tree maintenance costs relative to planting trees alone and stimulates the development of the woody species. Combining agriculture and restoration offers many benefits including extending the management period of restoration, offsetting some management costs, providing food security for small landholders, and involving small landholders in the restoration process (Vieira et al. 2009).

Rather than seeing land sharing and land sparing as mutually exclusive options for land management, it should be recognized that both offer different, and sometimes complementary advantages to biodiversity conservation. Because each landscape has a different socioeconomic and biophysical context, different approaches will suit different regions (Fischer et al. 2008). The different types of agroforestry systems described in this chapter provide a wide range of alternatives to achieve sustainable intensification and biodiversity conservation in tropical dry regions while accommodating to the necessities and values of both small and large landholders.

Successful approaches of sustainable land management will acknowledge the importance of complex social-ecological processes. In this chapter it has been shown how agroforestry can be a strategy to increase the productivity and profitability of a farming system, enhance the generation of ecosystem goods and services, and facilitate the release of strategic areas for restoration and strict conservation, all at the same time. AFS should be considered an essential component of a broader strategy that incorporates environmental and socioeconomic aspects to overcome the challenges of deforestation, land degradation, mitigation and adaptation to climate change, and poverty. Successful tropical forest restoration will require integrating ecology, agronomy, and traditional knowledge in a way that engages farmers in resource conservation (Vieira et al. 2009).

Case studies presented here show that SPS not only exceed the capacity of extensive tree-less pasture systems but also their productivity is similar to cattle production models that are intensive in the use of agrochemicals, concentrates, and medicines. Silvopastoral systems can restore degraded pasturelands and rapidly increase productivity, allowing the spatial concentration of cattle production in the most appropriate areas while freeing other lands for ecological restoration and conservation.

The scaling-up of AFS will require a combination of policy reforms, financial and market incentives, and basic access to finance in adequate terms and conditions. Incentives like PES should be used to promote the transition toward land uses that involve conservation and restoration, which are not always attractive to farmers in the absence of those incentives. Economic incentives are important but not sufficient to promote AFS. Other forms of incentives, in particular specialized and subsidized technical assistance, are necessary for the successful adoption of AFS by farmers.

AFS can provide benefits to farmers by significantly improving sustainability performances (notably for boosting yields and productivity per unit of land), by diversifying farmers' income, and by increasing resilience to environmental and economic shocks. Additionally, the higher complexity of AFS has important benefits to biodiversity conservation.

Although further development of technological solutions like agroforestry is essential to develop biodiversity friendly, resilient agricultural systems, it is socioeconomic changes and political actions that are urgently needed to scale-up agroecological approaches.

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# Chapter 4
# Agroforestry for the Northeastern United States: Research, Practice, and Possibilities

**Eli Roberts**

## 1 Introduction

Agroforestry is a broad category of land management strategies that combine crops and/or livestock with trees and/or shrubs in useful ways. The United States Department of Agriculture (USDA) says that agroforestry must be "intentional, intensive, integrated, and interactive" (www.usda.gov/agroforestry) and recognizes five agroforestry practices: silvopasture, windbreaks, alley cropping, riparian buffers, and forest farming. This paper addresses multi-layer homegardens in addition to each USDA practice. It summarizes the available literature and considers how each practice might apply to the Northeastern United States.

The patterns and processes of most agroforestry systems are adaptable to many ecological contexts. This paper focuses on the six states of New England (Connecticut, Rhode Island, Massachusetts, Vermont, New Hampshire, and Maine), and New York. Some examples apply only in Connecticut, where the author lives and works. The primary factors common across this geographic area are the cold, humid temperate climate, soils of glacial till origin, relatively small parcel sizes, largely private land ownership, proximity to the markets of large cities along the eastern coast of the USA, high proportion of part-time farmers, high labor costs, a longer-term decline in the number of farms with a more recent increase in smaller farms, an ageing corps of farmers (www.agcensus.usa.gov), consumer interest in local products, and land-use conflicts between agriculture, conservation, and housing/business development.

Of course, there is much diversity even within those realms. Some soils formed through sediment depositions of glacial lakes and rivers, and are therefore better drained than others. Plant communities also vary: the lower Hudson Valley of

E. Roberts (✉)
Yale School of Forestry and Environmental Studies, New Haven, CT, USA
e-mail: eli.a.roberts@gmail.com



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New York hosts different plant communities than Northern Maine. The point of this chapter is not to state universal truths, but to consider how agroforestry practices that are well-researched in the tropics, the Mediterranean, and the Midwestern and Southeastern US might apply to this cold, humid, diverse section of the world.

Five percent of the land in New England is devoted to agriculture (Donahue et al. 2014). Seven percent of Connecticut's land is classified as farmland, while 8% is lawn or turf (CT Department of Energy and Environmental Protection 2014). The average farm size, at 34 hectares (85 acres), is the third smallest in the US. Half of the state's 4000 farms are fewer than 50 acres. Still, direct-to-consumer sales are increasing and agri-tourism is growing 33% annually (CT Department of Energy and Environmental Protection 2014).

This chapter is not a training manual per se (Bentrup 2008; Hamilton 2008; Idassi 2012; Gold et al. 2013a, b; Karki 2013; 2015, Matthews et al. 2013, Stedman 2013 are all excellent manuals). Nor is it a full assessment of the economic or ecological impact of land management in the Northeast (Foster et al. 2010; Donahue et al. 2014). This chapter should inform farmers, foresters, extension personnel, grant makers, students, and policymakers to consider the ways they might make agroforestry more useful to themselves and their constituents.

## 2 Silvopasture

Silvopasture is the intentional combination of tree, livestock, and forage crops on the same piece of land. Benefits to livestock producers can include increased forage quality (Buergler 2004; Garrett et al. 2004; Chedzoy and Smallidge 2011) lower heat stress, extended fall grazing (Comis 2005), and extra income from forest products (Clason 1995; Gold et al. 2013a, b). Silvopastures sequester more carbon and provide better wildlife habitat than open pastures (Riedel et al. 2008); forest conversions to silvopasture can increase the amount of land under active management (Brubaker 2013), and provide cash flows to assist in financing timber stand improvement (Garrett et al. 2004; Sharrow et al. 2009).

Silvopastures can be created by adding trees to pasture or by adding pasture to woods. Some variations include fodder banks, where forages are cut and carried to livestock (Roshetko 1994; Toensmeier 2016); living fences (or fence posts), where trees occupy field border areas (Martin 2010); living barns, which are blocks of evergreens that provide winter shelter (Orefice 2015); and intensive silvopastures, where densely planted medium-sized forage plants are added to the tree and grass layers (Murgueitio et al. 2011).

### 2.1 Converting a Forest to a Silvopasture

Converting an existing forest stand to silvopasture can improve its timber quality and provide benefits to a livestock enterprise. Site selection is important: the soils must be relatively well drained; there must be access to water; and it is best to avoid sites where the soils or vegetation are sensitive to disturbance. General recommendations are thinning to 3.7–6.5 $m^2$ (40–70 $ft^2$) residual basal area (Garrett et al. 2004; Chedzoy and Smallidge 2011; Orefice 2015), and selecting for tree crown position, location, species diversity, health, and future timber value (see principles of thinning in Smith et al. 1997). Residual branches and unmerchantable trunks should be mulched, chipped, piled or burned to leave growing space to grasses (Chedzoy and Smallidge 2011; Fike and Downing 2015; Orefice 2015); brush piles are a particularly easy way to manage the "slash" and provide wildlife habitat (Robinson 2005). Cool-season grasses benefit most from a partly-shady environment; orchardgrass (*Dactylis glomerata*) performed best in trials in New York state (Orefice 2015).

Fencing and water infrastructure should divide the silvopasture into paddocks that provide adequate forage resources and ready access to fresh drinking water (Blanchet et al. 2000). Maintaining mast-producing trees in the canopy and shrubs in the understory can make silvopastures more hospitable to wildlife like wild turkey (Robinson 2005). The author worked on a 2.8 ha (7 acres) forest-to-silvopasture conversion where he and collaborators retained small hemlocks (*Tsuga canadensis*) and sugar maples (*Acer saccharum*) (Fig. 4.1) underneath the canopy trees to maximize vertical structure for songbirds without occupying much growing space (Roberts and Marsters 2015). The project also included retaining a 15 m (50 ft) wide forested buffer around a vernal pool within the silvopasture.

The cost of establishing silvopastures from existing forests depends on the size of the plot, complexity of treatment, and value of the cut timber. Combining silvopasture thinnings with forest management operations (like thinning or regeneration) on nearby stands could take advantage of economies of scale for operators moving expensive equipment. Hiring a forester to manage contracts with operators can be useful to achieve desirable results, especially for avoiding rutting and damage to residual trees.

### 2.2 Converting a Pasture to a Silvopasture

Planting trees into pasture is another option. There are tradeoffs between the degree of control over species and spacing and the time until benefits begin to accrue. The primary consideration is protecting the trees against livestock browsing or rubbing: the area should be harvested for hay until trees are big enough, or temporary electric

**Fig. 4.1** This overstocked pine stand in Connecticut has been marked for conversion to silvopasture. Basal area will be reduced from over 46 $m^2$ $ha^{-1}$ (200 $ft^2$ $ac^{-1}$) to 16 $m^2$ $ha^{-1}$ (70 $ft^2$ $ac^{-1}$) (Photo: E. Roberts)

fence can protect entire rows. Individual cages are more expensive but also work (plastic tree guards may not be strong enough, but may be stabilized against livestock using two stakes). Weed control is another important task; any of the standard methods (mulching, mowing, hand weeding, herbicide application) are appropriate in different contexts. It may be worthwhile to apply fertilizer to accelerate the trees' growth above the browsing of livestock (but that might increase the tree leaves' palatability as well).

Tree species selection and management depend on producers' goals: timber, livestock, or an optimized combination. The best trees will grow quickly, have relatively straight form, display apical dominance, have few pest problems and high value (for wood or other products), grow fine leaves that cast filtered light, leaf out late in the spring, and be aesthetically pleasing (Fig. 4.2). Of course, there is no perfect tree, so silvopastoralists must decide which characteristics they will prioritize. Pruning is necessary for some species (oaks grown with little competition, for example) to keep a single, straight stem. This effort may be weighed against a denser planting where trees provide side shade to each other and encourage stem straightness. This arrangement requires more frequent thinning, but less management of individual trees. A study in Arkansas looked at the effects of various nitro-

**Fig. 4.2.** This silvopasture in Connecticut, USA, has widely spaced oaks and hickories, and a very low stocking density of cattle. The grass is growing well because it has had adequate time to recover from its previous grazing (Photo: E. Roberts)

gen fixing trees as support trees for pecan (Van Sambeek et al. 2008). Black locust provided the most nitrogen to the pecans, but grew so fast it overtopped them and ultimately slowed their growth. Tree species diversity can create management complexity.

Good candidates for planted silvopasture trees in the Northeastern US include larch (*Larix* spp.), red pine (*Pinus resinosa*), white pine (*P. strobus*), black locust (*Robinia pseudoacacia*), honey locust (*Gleditsia triacanthos*), pin oak (*Quercus palustris*), red oak (*Q. rubra*), white oak (*Q. alba*), black walnut (*Juglans nigra*), sycamore (*Platanus acerifolium*), tulip poplar *(Liriodendron tulipifera)*. Fruit trees like persimmon (*Diospyros virginiana*), mulberry (*Morus* spp.), pawpaw (*Asimina triloba*), apple (*Malus* spp.) and pear (*Pyrus* spp.) are also good candidates. If shade is the only goal, fast-growing trees like poplar (*Populus* spp.), willow (*Salix* spp.), and birch (*Betula* spp.) are appropriate. Mixtures are more complicated but still possible.

Producers should plan for their various tree species to grow, mature, and die at different rates, and respond differently to competition, thinning, and shade. Site index curves can provide a rough estimate of how quickly different species will grow. Black walnut can be interplanted with autumn olive (*Elaeagnus umbellata*), alder (*Alnus* spp.), or black locust to benefit from the nitrogen those plants fix (Scott and Sullivan 2007). It is important to keep plantings simple for ease of management, and so that these systems are relatively easy to explain to potential adopters.

### *2.3 Summary of Benefits from Silvopasture Systems*

The shade from silvopasture trees can reduce heat stress in cattle enough to make the investment in trees worthwhile even before harvesting them (L. Godsey, personal communication). Cattle use more energy staying in their thermoneutral zone when the temperature is higher than 25 degrees C (77 degrees F); shade that keeps the temperature below that threshold decreases the energy the cattle have to put into making milk or meat. Silvopasture had a higher net present value than open pasture or pine plantations in Louisiana (Clason 1995). Amphibians like the red-backed salamander benefited from silvopasture as compared to open pasture in Appalachia (Riedel et al. 2008). Silvopastures in Florida prevented some phosphorous from leaching into waterways (Nair and Graetz 2004). Carbon sequestration (Montagnini et al. 2013), aesthetics, animal welfare (Broom et al. 2013) and control of invasive plants (Chedzoy and Smallidge 2011) are other benefits. Silvopastures can also make use of under-used land (Brubaker 2013), encourage forest management, provide an alternative management strategy for "high-graded" forest, and increase economic resilience and farm viability.

Silvopasture is listed as a practice eligible for reimbursement under the Natural Resources Conservation Service's Environmental Quality Incentives Program (EQIP) (Natural Resources Conservation Service 2012). In Connecticut, thinning woods to create silvopasture is only eligible for EQIP cost sharing if the woodlands are already being grazed. One soil conservationist said extension staff are generally supportive of silvopasture done well, but worry that people will not follow through on the complexities of management, and create more resource concerns than they solve (B. Purcell, personal communication). For this reason, regional proponents of the practice always begin presentations by differentiating woodland grazing (no management of forages, no grazing rotations, Fig. 4.3) from true silvopasture (Chedzoy, personal communication, Orefice, personal communication). Early adopters should be careful, and document their progress to share with others. One resource (Chedzoy and Smallidge 2011) gives valuable advice: "…experiment and start small – but above all, start. The cost of doing nothing will likely outweigh the cost of making some mistakes."

**Fig. 4.3** (L) Compaction and bare soil under this apple tree in Germany is the result of poor grazing management. (R) Cattle had access to this riparian forest for several weeks during the winter in Missouri. This stand has a closed canopy, and no intentional management of grasses. These are examples of poor management (Photos: E. Roberts)

## 3 Intensive Silvopastoral Systems

Silvopastoral systems integrate a tree crop, a forage crop, and a livestock crop in ways that optimize ecological or economic interactions. Intensive silvopastoral systems (ISS) rely on a layer of directly grazed, medium-sized fodder shrubs or cut-and-carry "fodder banks"; most current systems also integrate widely spaced overstory trees. Their intensiveness comes from the degree of management, design complexity, and efficiency of biological processes (Murgueitio et al. 2011); one of their primary benefits is a reduction in the off-site inputs required. ISS have undergone research in South and Central America over the past few decades (Dagang and Nair 2003; Montagnini 2008; Giraldo et al. 2011; Murgueitio et al. 2011; Calle et al. 2013; Montagnini et al. 2013; Cuartas Cardona et al. 2014); these studies answer many questions and raise a significant number more, yet the results are promising enough to warrant examining the possibility of adapting ISS to temperate North America (Dumont et al. 2014).

Some researchers (Murgueitio et al. 2011) assume that cattle ranching is integral to the culture and economy in tropical Latin America, and justify converting existing pastures to ISS as a means to achieve "sustainable intensification" that will forestall deforestation. Reforestation or preservation might provide more ecosystem services than silvopastures, but food production is another worthwhile goal of land management. Intensive silvopastures are economically productive enough so that they might be adopted by people who would not otherwise reforest their land. Farming is also central to rural culture in the Northeastern US, both economically (Donahue et al. 2014) and aesthetically (Foster et al. 2010); thus it is worth exploring whether intensive silvopastoral systems are applicable here, as well.

**Fig. 4.4** (L) Intensive silvopasture with *Alnus* and *Tithonia* as sheep enter. (R) Sheep have fully defoliated the *Tithonia* after 3 days. Both pictures from highland tropics in Veracruz, Mexico (Photos: E. Roberts)

## *3.1 Intensive Silvopasture in the Tropics*

The intensive silvopastoral systems developed in Central and South America rely on the use of *Leucaena leucocephala* in the lowland dry forest regions as well as the humid tropics, and on *Tithonia diversifolia* in the highlands (Fig. 4.4). Other species are used as well, depending on climate and availability. Both plants are high in protein, highly palatable, and regrow vigorously after defoliation. They are planted densely (often over 10,000 plants per hectare—4000 per acre), often in combination with improved pasture grasses and timber or fruit trees (~500 trees per hectare) (Montagnini 2008; Murgueitio et al. 2011; Montagnini et al. 2013). *Leucaena* is native to Mexico, but its integration into pasture began to be formalized in Australia in the 1970s (Murgueitio et al. 2011) as "*Leucaena* pastures." These systems feature widely spaced rows of *Leucaena* with grass in the inter-row space, primarily used as a dry season reserve of high-protein feed (Dalzell et al. 2006; Shelton and Dalzell 2007).

## *3.2 Benefits of Intensive Silvopastoral Systems*

### 3.2.1 Yield Improvements

Intensive silvopasture has improved yields by factors of up to ten (for beef) and five (for milk) over continuously grazed, traditional degraded pastures in dry tropical Colombia (Montagnini et al. 2013). Yield improvements are common for both meat and milk (Yamamoto et al. 2007). In a dry region of Colombia, a switch from conventional management to rotational management resulted in a fourfold increase in beef yields per year; switching to intensive silvopastures with timber trees resulted in a tenfold increase (Montagnini et al. 2013). Other studies compare continuously grazed open pasture with rotationally grazed intensive silvopasture, so it is difficult to determine the relative effects of switching to rotational management from the effects of including woody fodder crops.

Forage quality declines as plants reach later stages of maturity. Cool-season grasses in the humid Northeastern US are an important resource; the addition of fodder shrubs should only enhance, not supplant them. Tropical pasture grasses tend to have lower nutritional value than temperate species, and so the yield improvements from adding high-protein shrubs might be less dramatic in the Northeast US. Still, there is good evidence to suggest that integrating woody forages can have benefits for farmers and their livestock.

### 3.2.2 Carbon Sequestration

Silvopastoral systems capture carbon dioxide; the amount varies based on the size, age, number, and density of their woody components (see chapters by Toensmeier 2017 and Peri et al. 2017). Estimates of carbon sequestered for intensive silvopastoral systems in the tropics range from 4.4 to 26.6 Mg of $CO_2$ equivalent per hectare per year (the high end includes timber trees) (Montagnini et al. 2013; Cuartas Cardona et al. 2014). The stems and branches of plants in fodder banks do not hold much carbon because of their high turnover: longer-term timber and tree crop production is better for carbon sequestration. To the extent that ISS displace deforestation, the retained carbon in preserved forests should also be accounted for. The methane emissions from livestock decrease as livestock feed becomes more digestible, and with a certain level of condensed tannins. When accounting for plant and soil carbon and livestock methane emissions, open pastures tend to be net emitters of greenhouse gases; when well designed and well managed, silvopastoral systems tend to be net sequesterers (Montagnini et al. 2013). *Leucaena* pastures in Australia decreased methane emissions and increased yields in beef cattle in Australia. This decrease outweighed the increase in soil nitrous oxide content that resulted from the higher protein feed (Harrison et al. 2015).

### 3.2.3 Other Ecosystem Services

Intensive silvopastoral systems can improve soil fertility, promote good management practices, and reduce chemical inputs. They contribute to climate change adaptation (Murgueitio et al. 2011) by reducing the seasonal variation in production (Cuartas Cardona et al. 2014) and diversifying farmers' income streams (Montagnini 2008). ISS can also preserve fragile ecosystems (by allowing set-asides through intensification), reduce production costs and methane emissions (Cuartas Cardona et al. 2014), and increase biodiversity by providing habitat for wildlife (Montagnini 2008; Giraldo et al. 2011). Of course, intensification does not automatically lead to preservation; incentives and policy changes must also accompany yield increases (Kremen 2015).

### 3.2.4 Benefits to Animal Welfare

Several elements of intensive silvopastoral systems benefit animal welfare. Shade reduces heat stress, and habitat that increases biodiversity improves natural biocontrol of pests such as ticks. In some studies, cattle were calmer and displayed fewer stress responses to the presence of people in silvopastoral systems when compared to open grass monocultures. This difference was associated with improved body condition scores in silvopasture cattle, despite the same forage resource availability (Broom et al. 2013).

### 3.2.5 Cattle and Sheep Parasite Control

Intensive silvopastoral systems offer many direct and indirect benefits to farmers, livestock, and society. In many cases, ISS change the vegetation structure, increase the level of anti-parasitic tannins, or alter ecosystem processes in ways that benefit animals. When livestock browse above ground level instead of grazing near ground level, the life cycle of some parasites is interrupted (Halvorson et al. 2011; Hart 2013). Lambs raised on a pasture planted with high densities of willow in New Zealand had lower fecal egg counts and higher weight gains than lambs on conventional pasture (though they did not perform as well as lambs with antihelmintic treatments) (Barry et al. 2006). Research in Colombia suggests that silvopastoral systems' increased leaf litter and shade, reduction in agrochemicals, and, possibly, connectivity to intact habitat increase the fitness of dung beetles, which interrupts the life cycle of hornflies, a problematic cattle pest (Giraldo et al. 2011).

## *3.3 Plant Species Worth Considering for Intensive Silvopasture for the NE USA*

Adapting intensive silvopasture to cold, humid temperate climates will involve the development of a plant "palette" for various species of livestock and site conditions; design, layout, and management specifics; and financial and technical supports for farmers that are applicable in their situations. The top candidates are black locust, mulberry, and mimosa; other plants like willow and bamboo will likely play supporting roles (Table 4.1).

### 3.3.1 Other Promising Plants

Other plants with promise as alternative forages in the Northeastern United States include Illinois bundleflower (*Desmanthus illinoensis*), wild senna (*Senna hebecarpa*), *Cassia marilandica*, and others (Ristau n.d.). Many other species of trees

**Table 4.1** Protein and Yields from Several Woody Forage Species from Temperate Regions.

| Plant | Crude Protein% | Notes | Source | Yields, kg ha$^{-1}$ |
|---|---|---|---|---|
| **Black locust (*Robinia pseudoacacia*)** | 18–25% | Palatability decreases, protein increases throughout season. "Monophylla" variety may be better adapted: Higher leaf production, fewer thorns | Addlestone et al. (1998), Burner et al. (2005), Burner et al. (2007), Djumaeva et al. (2009), Papachristou and Papanastasis (1994), and Papanastasis et al. (2008) | 804–3200 (up to 7200[a]) |
| **Mimosa (*Albizia julibrissin*)** | 16% | More digestible than black locust; lower yields; possible to start from seed; may be more sensitive to defoliation | Addlestone et al. (1998), Burner et al. (2007), and Pitman (2008) | 945–1600 |
| **Mulberry (*Morus alba, M. rubra*)** | 12–25% | Research in warmer climates; wide variation in leaf nutrition, but very palatable; does best with high soil fertility; tradeoff between protein % and dry matter throughout season | Azim et al. (2011), Kabi and Bareeba (2008), Kitahara et al. (n.d.)., Miller et al. (2005), Papanastasis et al. (1998), and Sanchez (n.d.) | 370–505 |
| **Bamboo (*Phyllostachys spp.; Arundinaria giganteum; Semiarundinaria fastuosa*)** | 12–20% | Potential for winter fodder: Protein peaks late in season; possibly integrate into riparian buffer areas | Anderson and Oakes (2011), Halvorson et al. (2011), and Kashyap et al. (2014) | – |
| **Willow/poplar (*Salix spp., Populus spp.*)** | 10–16% | Evapotranspiration for pasture improvement; easy to propagate | Baertsche et al. (1986), and O'Reilly (2015) | 50–3600, (4000[a]) |
| **Russian Olive (*Elaeagnus angustifolia*)/Autumn Olive (*E. umbellata*)** | 11–25% | Protein decreases over season; tender shoots most palatable to cattle; can outperform black locust in dry conditions | Azim et al. (2011), Djumaeva et al. (2009), and Webb et al. (2011) | 2223 |

(continued)

**Table 4.1** (continued)

| Plant | Crude Protein% | Notes | Source | Yields, kg ha$^{-1}$ |
|---|---|---|---|---|
| ***Amorpha fruticosa*** | 13–30% | Variable reports on preference; protein yield comparable to alfalfa | (DeHaan 2001, DeHaan et al. 2006, Papachristou and Papanastasis 1994) | 7200 + |
| ***Lespedeza cuneata/bicolor*** | 15–21% | Palatability varies with age; some low-tannin varieties | Ball and Mosjidis (2007), Gucker (2010), Pieters et al. (1950), Southern SARE, Tuskeegee University Extension (2013) | — |
| **Seabuckthorn (*Hippophae rhamnoides*)** | 21% | May be slow to establish; used as feed in Central Asia | Hu and Guo (2006), Kashyap et al. (2014), Singh et al. (2012), Stobdan et al. (2013), and Wenhua (2001) | — |

[a]likely total biomass, not leaf

and shrubs are widespread in the Northeastern United States. Red maple (*Acer rubrum*), poplar (*Populus spp*.), alder (*Alnus spp*.), oak (*Quercus spp*.), birch (*Betula spp*.), and beech (*Fagus grandifolia*) have many good properties, but do not have high enough nutritive value or regrowth potential to justify intensive planting. Honey locust grew much more slowly than mimosa or black locust in trials in Arkansas and North Carolina (Addlestone et al. 1998; Burner et al. 2005); it is probably worthwhile using it only as an overstory tree. Some producers prefer to avoid black cherry (*Prunus serotina*), whose wilted leaves can be toxic to most livestock; horse and chicken owners should also avoid black locust. The Goats in the Woods project at Cornell examined goats' ability to consume common forest species; juvenile goats gained weight, or were able to gain weight after leaving a forest grazing situation (Smallidge 2004). Diverse diets made up of woody and herbaceous plants are good for animals (Rinehart 2008). Simplicity is important overall, especially when testing relatively new production systems, but producers should experiment with what works best for their interests, situation, and risk tolerance.

Black locust, mulberry, mimosa, bamboo, false indigo, willow, *Elaeagnus*, *Lespedeza* and seabuckthorn are all vigorous perennial plants that hold potential as livestock feed. Their nutritive value varies with life stage and across seasons; animals' nutritional requirements vary, too. Producers should map their animals' needs throughout the year to see where these woody forages can be included. Goat producers may have the easiest time incorporating these feeds, because of goats' tendency to choose woody plants, and ability to process tannins, but sheep and cattle may be used with some careful management. Chickens and horses cannot eat black locust, but it is worth testing whether other species are valuable to them. Black locust, mimosa, false indigo, seabuckthorn, *Eleagnus*, and *Lespedeza* all fix atmospheric nitrogen, and may be particularly adapted to nutrient-poor sites.

### *3.4 Design Considerations*

Design is an important part of intensive silvopastoral systems. There is much variation in spacing in the research on temperate species, which is likely a reflection of ease of planting and maintenance, moisture availability, and site conditions (Papanastasis et al. 1998). Research in North Carolina (Addlestone et al. 1998) found that the highest per-acre herbage mass growth for black locust and mimosa occurred at 50 cm in-row spacing and 50 cm coppice height, compared to 100 cm spacing or 25 cm coppice height (in single-row plots 3 m apart). In contrast, a study in that same region found that black locust planted at 3 m × 1 m spacing (and coppiced to 50 cm yearly starting at year 1) produced the same herbage biomass as 3 m × 0.5 m spacing. The denser spacing cost an additional $650 per hectare to establish, with no additional production (Snyder et al. 2007). In a system that relied on human harvesting of mulberry branches in temperate India, a coppice height of 2 m out-yielded 0.5 m, 1 m, and 1.5 m (Kashyap et al. 2014).

One project (Ainalis and Tsiouvaras 1998) tested spacing patterns for black locust, honey locust, mulberry, and *Amorpha fruticosa* in Northern Greece. The researchers compared 1.5, 2.5, and 3.5 m–square spacing (4440, 1600, and 810 plants per hectare). The densest treatment significantly increased the per-hectare herbage mass production rate for all species, though the difference was most pronounced in black locust. The researchers coppiced the plants every winter, and noted no competition with the herbaceous vegetation.

Practitioners in arid Australia recommend 7–12 m spacing between *Leucaena* rows to reduce water competition with grass (Boadle 2010). Other Australian researchers (Dalzell et al. 2006) suggest double rows spaced 6–8 m apart. Double rows may reduce the vigor of *Leucaena* so that it stays within browsing reach of livestock. They suggest a minimum distance between rows of 3 m (grass grows poorly at closer spacing), and note that rainfall and equipment widths are the primary determinants of row spacing. Researchers in dry Pakistan (Azim et al. 2011) used 1 × 1.75 m spacing to test black locust, honey locust, and Russian olive. In Japan (Kitahara et al. n.d.), mulberry at 3 × 0.7 m spacing with pasture out-yielded mulberry or pasture alone. One site in humid warm temperate India planted fodder trees in ditches along the contours of sloping land to slow runoff and accumulate soil particles. They included mulberry spaced 1 m apart within the row, with rows (contour ditches) 4 m apart, with satisfactory results (Kashyap et al. 2014).

Producers' choice of spacing will ultimately depend on how their intensive silvopastures fit within other farm enterprises. Farmers wishing to maximize eventual per-acre output would be wise to choose closer spacing (as in Ainalis and Tsiouvaras's 1.5 × 1.5 m (1998)). The highest coppice height is probably best for encouraging regrowth, but plants must also be kept within the reach of livestock. Australian proponents (Dalzell et al. 2006) recommend coppicing *Leucaena* at 1 m high using a rotary blade mower, suggesting that the lacerated and split stems produce better regrowth than cleanly-cut stems. Well-timed browsing may eliminate the need for additional coppice management. Many people will need to use the space between the tree rows in the years before the woody forages are ready to be browsed; in this case, row spacing should accommodate the equipment needed to produce vegetables, cut flowers, or hay, or move pastured poultry ("chicken tractors"). In these cases, the results of Snyder et al. (2007) suggest that spacing plants 1 m apart within rows is appropriate, at least for black locust; on-farm trials are needed to determine the tradeoffs between individual plant productivity, per-acre productivity, and installation cost. In general, drier sites should need wider spacing, whereas wetter or more fertile sites should tolerate closer spacing. Farmers and experiment stations will need to investigate which plants fit their production needs *and* grow best on the various sites on their farms.

## 3.5 Management Practices

Grazing timing, stock density, and rotation times are key areas for investigation. Producers need to balance nutritional quality with the ability of shrubs to regrow, and coordinate that with the growth rate of the pasture grasses. Most current research measures biomass, leaf mass, nutritional characteristics, or animal performance, but recommendations for best practices on working farms must be inferred. In one Greek study, the crude protein content of black locust, honey locust, *A. fruticosa*, and mulberry leaves did not change in regrowth after grazing, but acid digestible fiber (ADF) and lignin decreased, and digestibility increased after grazing in July and August (Ainalis et al. 2006). In North Carolina, increasing levels of black locust in goats' diets led to a greater proportion of nitrogen in their feces, which implies lower digestibility. The author is careful to suggest further research giving goats a diverse diet selection to dilute the tannins in black locust that reduce the animals' ability to digest nutrients (Snyder 2004).

Plant defoliation levels above 50–60% reduce the plant's ability to regrow (Hendrickson and Olson 2006). When researchers in North Carolina (Luginbuhl and Mueller 2000) tested goats' relative preferences for black locust, mulberry, and mimosa, they found that the goats completely defoliated the locust and mulberry before eating the mimosa. Optimizing each species' ability to regrow will be difficult if animals browse them preferentially (although optimizing the combination, rather than the individual plant species would make better sense). One strategy would be planting single-species blocks (though it makes sense to have different species in different paddocks to minimize risk and diversify diets, i.e. Le Houérou 2000). More research is needed to examine how the presence of fodder shrubs affects livestock's use of grass and other herbaceous plants.

Stocking rates and grazing periods are quite variable in the literature. Researchers in New Zealand (Barry et al. 2006) used grazing periods of 7–10 days for 120 lambs on high-density willow fodder banks, and an 8-week rest period, but did not specify the area. Practitioners in Australia (Boadle 2010) recommend 1 animal unit per 0.4 ha, 8–12 week return periods, and grazing until 10% of the leaves remain on *Leucaena*.

Hart (2013) notes the difference between browsing for plant control (early spring/late fall, full defoliation, inadequate rest (<8 weeks)) and browsing for sustainability (the opposite: late spring/summer/early fall, rest >8 weeks, 50% defoliation). The recovery time and degree of defoliation tolerated probably varies by species (Pitman 2008).

Some Greek researchers propose once-per-year grazing in summer for sheep and goats, with an 11-month rest period, using plants with similar Relative Acceptance Indices (a measure of how likely an animal is to eat a particular plant), which seems most applicable in their dry, Mediterranean climate (Papachristou and Papanastasis 1994). Characterizing this system as a seasonal "reserve" for dry season grazing (Papanastasis et al. 2008) speaks to a particular need of livestock producers.

Annual cutting of black locust and *Amorpha fruticosa* does not affect their survival for at least 8 years. To maximize biomass and herbage production, it is best to wait until the plants are 3 years old to begin grazing (Papanastasis et al. 1998). Cutting and grazing have different effects on plants; cutting increases the necessary recovery time. Different species and varieties tolerate different degrees of defoliation (including 100% in mulberry "Kokuso 21") (Papanastasis et al. 1998).

Many of these studies did not test directly browsed systems, and so did not address concerns about fencing and water provision. Rotational management provides optimal forage availability, but also requires more intensive fencing and water infrastructure. This tradeoff applies to grass pasture-based rotational grazing, too (Gillespie et al. 2008). Many extension resources exist on animal water and fencing design for rotational management (eg. Blanchet et al. 2000), and these considerations should be similar for intensive silvopastoral systems. Designers of ISS must consider accessibility for people and vehicles, and clear paths for electric fences. If paddock sizes change throughout the year, designs must incorporate this variability, and will likely mean less-dense plantings.

The benefits of manipulating complex agro-ecological systems depend on harnessing "additive yields," or positive interactions between components (Jose et al. 2009). Research in North Carolina (Montagnini et al. 1986) found that black locust-dominated young forests had higher soil net nitrogen mineralization than adjacent late successional forest. The researchers characterized this as a risk for nutrient leaching, but it also indicates the possibility of harvesting this useful resource in terms of increased tree growth. It is unclear how the nitrogen dynamics of regularly-browsed black locust might differ, or what the effects of locust-mineralized nitrogen are on nearby grass and forbs. Van Sambeek et al. (2008) assessed the relative contributions of various nitrogen-fixing trees to pecan growth, but found that black locust's fast growth rate made management difficult. Even though it increased the pecan's leaf nitrogen, black locust did not increase the pecan's size or diameter. This trial placed two "support" trees per one "crop" tree; maybe higher density legumes with more frequent defoliation or coppicing might have different results. So, it is worth investigating the contributions of legumes like black locust to nitrogen cycling within silvopastures. Future research should measure the relative shade cast by densely planted shrubs, and how those shrubs' nutrient levels respond to conditions of partial shade from overstory trees.

Pasture-based livestock management is complex; adding a woody component only increases its complexity. One key area for investigation is the relative preferences of livestock for woody species versus pasture grasses. More work on the relationship between defoliation rate and recovery time will be useful to producers trying to integrate woody plants into pasture rotations. Woody plants are probably better able to withstand overgrazing because of their extensive root reserves. Small scale and non-commercial livestock owners can play an important role by observing their animals' preferences and grazing habits for various combinations of woody species and pastures across different seasons. The most concrete recommendations seem to be waiting until trees are 3 years old to browse, not browsing more than 50% of leaves, and determining the relative palatability of various plants for a particular herd of livestock. Of course, these must be weighed with the real needs of livestock producers.

### 3.6 Browse Preference and Nutrition

We know some about what affects goats' browsing preference, but some is known "only to the goat." Goats tend to browse hierarchically: they fully defoliate one species, then move to another (Hart 2013). Seasonality affects animals' preference; other factors include "available woody and herbaceous species, forage availability and availability of nutritious alternatives, period of grazing, stocking rate, and whether goats and sheep forage as sole rangeland users or together with other animals" (Papachristou et al. 2005). Livestock tend to eat foods their mothers eat, younger animals are more likely to try new foods, and livestock that have experience eating some kinds of shrubs may be more likely to eat other kinds (Burritt and Frost 2006).

Plants can have chemical or mechanical defenses, but neither completely prevents herbivory. Mechanical defenses (e.g. spines) tend to reduce the size and speed of bites, and chemical defenses change the order in which animals eat particular plants, or the efficiency with which they digest them (Papachristou et al. 2005). Condensed tannins play a role by decreasing the palatability and efficiency of digestion of many nutrients, but the relatively high crude protein of leaves increases the amount that goats eat by offsetting tannins (Papanastasis et al. 2008). Mueller-Harvey (2006) offers a useful review of tannins' relationship to animal nutrition. The fact that animals prefer certain plants to others makes their management more difficult.

Supplemental nutrients may help make plants with secondary compounds more palatable (Smallidge 2004; Papachristou et al. 2005). Polyethylene-glycol (PEG) added to the water deactivates tannins and increases feed intake (Papanastasis et al. 2008). Snyder (2004) describes PEG's effectiveness when added to feed, calling it "relatively inexpensive," but claims it is impractical for most farmers. Mueller-Harvey, citing the expense and variable results of PEG supplementation, notes that feeding high-tannin foods in combination with other foods may dilute the effects of tannins. The energy costs of processing tannins may be offset by energy-rich diets, especially foods high in sugars (Mueller-Harvey 2006). Bhat et al. (2013) suggest that animals are likely to self-regulate their levels of toxic plant intake, but are only able to do this when adequate levels of other forage are available. They say tannins at 1–2% of dry matter intake can be beneficial to livestock, and that digestibility problems arise only when levels surpass 5%. Livestock owners have variable experiences with this.

Researchers in Arkansas (Burner et al. 2007) compared the yield and nutritional quality of black locust and mimosa. While black locust had higher yields, mimosa had higher in vitro dry matter digestibility, likely related to the tannins in black locust (which are roughly equivalent to those in *Leucaena*). Still, they found that concentrations of digestible nitrogen in mimosa were higher than requirements for goats and cattle, and concentrations in black locust were higher than requirements for growing cattle, even when controlling for digestibility. They also tested for mimosine, the secondary compound that causes some concern about *Leucaena* toxicity, but did not find detectable levels in either black locust or mimosa.

Despite having comparable nutritional analyses, black locust was more readily eaten by goats, whereas *Amorpha fruticosa* was much less preferred (Papachristou and Papanastasis 1994). The researchers note the goats had no prior experience with *A. fruticosa*, which may have affected the results. They use a "Relative Acceptance Index," which is the number of bites taken from all browse species divided by the number of bites taken from a particular species.

Defining grazing preferences along a continuum is preferred (to characterizing cattle as grazers, sheep as forb-eaters, and goats as browsers) because most animals graze or browse opportunistically. One assumption is that animals choose forages to maximize nutrient intake, but some evidence suggests they may choose less nutritious forages in order to reduce *variation* in nutrition content, or in tannins, specifically (Papachristou et al. 2005). It would be wise to be careful of research that studies the effects of single-plant diets because intensive silvopastures will always have a combination of grasses and woody plants.

Some practitioners (Voth 2010) have had success teaching cattle to eat weeds that have tannins, spines, or other chemical/mechanical defenses. It is worth testing these procedures before dismissing woody perennial forages as unpalatable.

The evidence in this section suggests that, rather than finding one perfect species for intensive silvopasture, the real work entails managing several good species for optimal results. A safe general recommendation is to interplant high-tannin plants with low-tannin plants (alternating blocks of mulberry and black locust, for instance), but designs will vary among producers with different breeds, production goals, and risk preferences. An interesting study could compare PEG supplementation with diet diversity on the basis of animal performance, ease of management, and cost. Practitioners will have to experiment with easy ways of managing many species of forage, balancing simplicity of management with the diverse diet needs of their animals.

### 3.7 Adoption of Intensive Silvopasture

It is important for intensive silvopastoral systems to compare favorably to other existing livestock raising systems. One study cautions against the common comparison to alfalfa: if alfalfa won't grow competitively or sustainably in a certain place, it is not a good comparison (Burner et al. 2005). In case studies in Colombia, the return on investment (ROI) for ISS was 13–28% for dairy; 12–27% for beef (without timber), and 22% including 500 trees per hectare. This compares favorably with close to 0% ROI for conventional pasture! ROI was higher on 15 ha parcels than on 5 ha parcels because of economies of scale (Cuartas Cardona et al. 2014).

Dagang and Nair (2003), noting the slow adoption of silvopasture throughout the tropics despite striking yield improvements, suggest that it is important to consider farmers' reasons for keeping cattle: as alternative income, emergency reserve, or daily survival. Their degree of mechanization is also important. They propose understanding why farmers are not adopting, considering what their needs are, and designing research with that in mind.

Murgueitio et al. (2011) note that the main barriers to adoption of ISS are initial cost (and perception of ranching as low-capital by technicians, producers, banks), and knowledge barriers because of ISS systems' technical complexity. They discuss payment-for-ecosystem-services schemes that differentiate among life stages of silvopastoral systems and their relative tangible benefits to land owners. Gillespie et al. (2008) confirm that rotational grazing in Louisiana can have higher labor inputs on a per-animal and per-acre basis (though they do not include labor for haymaking). Individual producers' values between time and profitability are important to consider. In the Northeastern United States, demonstration sites using "intensive silvopastures" are scarce (though, of course, pastured livestock producers' animals browse woody plants all the time).

Le Houérou (2000) summarizes the challenges of expanding fodder tree systems: high establishment cost, the need for secure land tenure, the need for skilled matching of plants to different landscapes, lack of research on best management practices, improved plant material, and the requirement of disciplined/skilled grazing management.

Farmers' current relationships with particular plants are important determinants of adoption. A West Virginia study noted that autumn olive's tender regrowth is more palatable; they mention that a similar proposal for grazing cattle on the invasive woody legume gorse (*Ulex europaeus*) in New Zealand "has not met widespread acceptance by producers" (Webb et al. 2011). Many of the plant species mentioned in this chapter are on some states' "invasive" lists (Table 4.2), or, at least, are well adapted to disperse onto continuously grazed, nutrient-poor pastures. In promoting these systems, we must be sympathetic to people's antagonism to particular plants *and* state-mandated barriers to their planting.

The *Leucaena* Network in Australia has adopted a voluntary code of practice that encourages managed *leucaena* for farmers but minimizes its invasiveness. These practices include only planting *leucaena* for livestock use, only using commercial cultivars, maintaining vigorous pasture for competition, not planting within 10 m of boundary fences, maintaining buffers from waterways to prevent dispersal, managing plants to stay within reach of cattle (and therefore unable to produce seed), controlling unwanted seedlings, and determining that escapees are the responsibility of the "source" owner (Dalzell et al. 2006). Farmers who find that black locust, bamboo, *Amorpha fruticosa*, or *Elaeagnus* work for them may need to establish similar codes of practice to improve acceptance of their production systems.

**Table 4.2** Potential ISS Species and their legal status in New England States

| Species | CT | MA | RI | VT | NH | ME |
|---|---|---|---|---|---|---|
| ***Amorpha fruticosa*** | Prohibited | OK | OK | OK | OK | OK |
| **Black locust** | OK | Prohibited | OK | OK | OK | OK |
| **Mulberry** | OK | OK | OK | OK | OK | OK |
| **Bamboo** | *Phyllostachys* genus isrestricted | OK | OK | OK | OK | OK |
| **Autumn olive** | Prohibited | Prohibited | OK | OK | Prohibited | OK |
| **Mimosa** | OK | OK | OK | OK | OK | OK |
| ***Lespedeza cuneata/ bicolor*** | OK | OK | OK | OK | OK | OK |
| **Seabuckthorn** | OK | OK | OK | OK | OK | OK |

## 3.8 Scaling Up Intensive Silvopasture

A variety of incentives are possible for encouraging larger-scale adoption of intensive silvopasture. Projects in Colombia combined on-farm research, capacity building, payment for environmental services schemes, low-cost loans, and market access; these helped support several hundred hectares of ISS (Calle et al. 2013). The Colombian efforts were a collaboration between government, non-profits, and industry organizations. The Northeastern US does not have that level of collaboration yet, but some resources do exist to support adoption. The Natural Resources Conservation Service (NRCS) —a program of the US Department of Agriculture—administers the Environmental Quality Incentives Program (EQIP) to encourage landowners to use conservation practices. Each state's NRCS office reimburses landowners for a variety of practices, typically on a per-acre or per-plant basis. Practices eligible for reimbursement vary from state to state and include silvopasture establishment, forested riparian buffers, windbreaks, and hedgerows. Forest farming, alley cropping, and homegardens are not listed as eligible practices, but there may be some flexibility with Tree Establishment (practice number 612). Table 4.3 shows which practices are eligible for reimbursement in some states in the Northeastern US. Some of these practices require a forest management plan or grazing management plan (also eligible for cost-sharing) to be in place before they can be reimbursed.

## 3.9 Future Research on Intensive Silvopasture Systems in the Northeast USA

Future research will encompass the technical aspects of ISS development and its social and political elements. Animal breeding will have to balance adaptive and production traits (Dumont et al. 2014), specifically, to improve efficiency of feeds with higher fiber and lower digestibility, like tree leaves. There is a need to

**Table 4.3** NRCS listed agroforestry practices

| | State | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Practice | CT | MA | RI | NH | VT | ME | NY | PA |
| Silvopasture | 381 | 381 | 381 | – | – | – | – | – |
| Riparian buffer | 391 | 391 | 391 | 391 | 391 | 391 | 391 | 391 |
| Windbreak | 380 | 380 | 380 | – | 380 | 380 | 380 | 380 |
| Alley cropping | – | – | – | – | – | – | – | – |
| Forest farming | | – | – | – | – | – | – | – |
| Homegardens | – | – | – | – | – | – | – | – |
| Hedgerow planting | 422 | 422 | 422 | – | 422 | 422 | – | 422 |
| Tree establishment | 612 | 612 | 612 | 612 | 612 | 612 | 612 | 612 |

Natural Resources Conservation Service- CT (2015), USDA Natural Resources Conservation Service (2016), USDA Natural Resources Conservation Service- ME (2016), USDA Natural Resources Conservation Service- NH (2016), USDA Natural Resources Conservation Service- RI (n.d.), USDA Natural Resources Conservation Service- VT (2016))

understand animals' physiological, genetic, and epigenetic (across generations) adaptation to heat, and how that might be different under distributed shade conditions. Goat browsing preference is influenced in part by heritability (Hart 2013); goat breeding might focus on strains adapted to woody browsing. Rotational management of grasses, forbs, and legumes relies on grazing to a certain residual height to optimize the regrowth of plants. Future research should examine the relative palatability of woody forages versus herbaceous forages so that producers can optimize the grazing system overall. For instance, what if livestock fully defoliate mulberry before eating the grass, and there is a tradeoff between mulberry regrowth time and grass nutritive value upon reentry? Will a fully-defoliated black locust recover in the same amount of time as a half-defoliated mimosa? Is the effort required for managing livestock towards partial defoliation worth the maximized yield? Or are easier management strategies acceptable?

Plant breeding will need to emphasize palatability, adaptability, and ability to regrow after browse. Researchers will study plants' response to different fertilizer regimes (phosphorus for black locust, how much N fertilizer might legumes displace, or is it economic to have lower overall yields for lower inputs?). To allay concerns about unwanted plant dispersal, it may be worthwhile to breed sterile varieties of certain plants (but weigh this against its cost and limitations for smaller-scale breeding). Many studies have compared plants on similar sites; it is likely that different plant species are optimal for different sites. Future research should examine variability in soil parent material, moisture, and fertility and their effects on different species' forage growth. Most research studies plants' nutritive value under full sun conditions. It is worth researching how nutrition changes under partial shade conditions to inform planning and management of trees in the overstory. It would also be worthwhile to investigate the potential of ISS systems as part of a transition zone between riparian buffers and open pastures as a way to increase their usefulness and leverage their ecosystem services potential (Schultz et al. 2004), while, of course, following good grazing practices (as detailed in (Moechnig 2007)).

Efforts to scale from on-farm research to larger-scale projects in the Northeastern US should follow the process suggested by Calle et al. (2013). It will also be important to separate the influence of switching from set stocking to rotational management from the influence of additional woody species. Practitioners of rotational grazing (farmers, extension workers, researchers, and teachers) are among the necessary collaborators in investigating ISS, and we should complement, not undermine their work. It will be important to build on existing research and practitioner networks, as well as sources of technical assistance and plant material. The many hundreds of livestock owners and tree enthusiasts in the Northeastern United States should begin (or continue!) their trials so that intensive silvopasture knowledge and practice can expand rapidly.

## 4 Forest Farming in the Northeastern USA

Forest farming describes several practices where agricultural products grow under a closed canopy of trees. These products can include gourmet mushrooms and edible, medicinal, or decorative plants. Forest farming is one of the five agroforestry practices recognized by the United States Department of Agriculture.

### *4.1 Gourmet Mushrooms*

There has been renewed interest in log-grown shiitakes in the Northeast USA, thanks largely to efforts at Cornell University, the University of Vermont, and the USDA's Sustainable Agriculture Research and Extension program. A clear and detailed guide came out recently (Matthews et al. 2013), and various shorter extension documents and email lists (http://blogs.cornell.edu/mushrooms/, for instance) provide introductory and advanced information to growers. This section will briefly summarize that body of work, and suggest how mushroom cultivation might fit within forest management more broadly.

Shiitake mushrooms are the most commonly grown gourmet mushroom, other than button mushrooms (*Agaricus bisporus*) (Gold et al. 2008). They grow on many species of wood, but sugar maple and red and white oaks are particularly suitable (Mudge and Gabriel 2014; Field and Forest Products n.d.). There is, of course, a tradeoff between what substrates are ideal and which are available (Matthews et al. 2013). Sugar maple substrate produced more mushrooms by weight than red or white oak in natural-fruiting trials in Missouri (Bruhn et al. 2009). The researchers attribute this difference to the relative amounts of discolored heartwood, which is more difficult for shiitake mycelium to colonize. The proportion of non-discolored sapwood is higher in open-grown saplings and on branches higher in the tree (Bruhn et al. 2009). They found that yields averaged close to 1 kg per log over the lifetime of the log (5 years). Mudge and Gabriel (2014) suggest that force-fruiting (soaking

**Fig. 4.5** The author grew shiitake mushrooms on white oak (*Quercus alba*) and sugar maple (*Acer saccharum*) logs. These fruited after a rain in July, 13 months after a June inoculation (Photo: E. Roberts)

logs to initiate fruiting) can be beneficial because it pushes logs to yield in a shorter window of time—which reduces the time available for competing fungi and pathogens to colonize the log—without affecting lifetime yields. Producers must balance the extra labor requirements of forcing with the benefits of regular harvests and potential for higher lifetime yields.

There are several methods for inoculating mushroom logs ("bolts"): manufactured hardwood dowels, pre-colonized sawdust, and "plugs" with Styrofoam caps (See Matthews et al. 2013 for details). Each method makes sense at different scales. In general, dowels make sense up to about 50 logs, when sawdust becomes more economical. Plugs are appropriate for much larger scales, but, of course, producers should work out their own enterprise budgets (Szymanski et al. 2003 is a good resource). Bruhn et al. (2009) found that sawdust-based spawn had higher yields than dowel or plug-based spawn.

Gourmet mushrooms provide a unique opportunity to transform relatively low-value products (small diameter hardwood logs) into relatively high-value food (Fig. 4.5). Gold et al. (2008) mention the possibility of combining mushroom log production with timber stand improvement, but give no further details. In an analysis of silvicultural rehabilitation in Northern hardwoods in Quebec, Bédard et al. (2014) suggest that markets for low-quality wood (unacceptable growing stock, or UGS) are required for rehabilitation to make financial sense. Developing a market for mushroom bolts may increase forest managers' financial ability to rehabilitate forests. These markets may develop locally as loggers can connect with mushroom growers, and may require a certain "critical mass" of mushroom log buyers.

The profitability of mushroom enterprises varies based on local markets, grower practices, and scale, but the majority of enterprises are profitable by their third year (Gold et al. 2008; Matthews et al. 2013). Growers perceive that the market will keep expanding or remain steady, and it is likely buoyed by sawdust-grown shiitakes and other mass-produced gourmet mushrooms that continue providing customer education. Most growers' mushroom enterprises are side businesses (Gold et al. 2008), but there is still an opportunity for significant income.

Matthews et al. (2013) found that a major part of shiitake growers' time is spent acquiring logs. In some areas, loggers sell pre-cut bolts for between one and two dollars each. This represents an opportunity to expand markets for lower-value wood, even though the price is comparable to firewood. Of course, the existence of markets does not guarantee sound forest management practices, but it does make them more feasible. There may be opportunities for landowners who harvest their own wood to conduct timber stand improvement operations and provide substrate for mushroom enterprises.

Potential mushroom growers should start small and slow, and establish their markets. A cooperative arrangement that allows small producers to pool their products in order to fulfill larger orders would help access markets. Creative loggers could market small diameter mushroom logs to boost their business and the mushroom growers'.

### *4.2 Ramps*

Wild leeks, or ramps (*Allium tricoccum*) grow in the eastern deciduous forests of the United States and Canada. They are a popular and pungent springtime food but some wild populations are declining because of overharvesting (Sen 2011). Managing ramps can take several forms, from sustainable wildcrafting to varying intensities of cultivation.

Wildcrafting means collecting plants from relatively un-managed populations. Ramp populations are sensitive to overharvesting. Ramp seeds do not survive in the seed bank for more than 2 years, which means that populations may not recover if all mature individuals are harvested (Connor et al. 2015). One study in Tennessee suggests that, at least at the edges of their range, individual ramp patches should be harvested at a 10% level once every 10 years (Rock et al. 2004). This provides an 85% chance that the population will reach its un-harvested level in the ensuing 10 years. Administrators at the Great Smoky Mountains National Park in Tennessee and North Carolina used that study to justify a ban on ramp harvesting, which led to citations in 2009 to—among others—members of the Eastern Band of Cherokee Indians (Lewis 2012). These people had been harvesting ramps sustainably for thousands of years and pointed out, in the trial in which they were eventually found guilty, that Rock et al. (2004) only examined full removal of ramps, not cutting leaves above the bulbs in the traditional Cherokee way. This raises an important issue: academic ways of knowing and their influence on policy do not always match with traditional ecological knowledge. Formal academic research on population effects of tops-only harvesting is difficult to find but is worth cautious, small-scale experimentation.

In places without robust wild populations of ramps, propagation through seeds or transplants is possible. Soil nutrient and moisture levels are more important contributors to seedling and transplant survival than light levels (Vasseur and Gagnon 1994). This suggests that site quality is more important than the existing forest vegetation in selecting a site for ramp cultivation. The authors also suggest that ramps may be field grown in more intensive settings and then transplanted to forest sites for naturalizing, as a way to increase seedling survival rate, or as a potential enterprise.

One study in Quebec compared the effects of applying gypsum ($CaSO4$) and organic fertilizer, and planting time on bulb survival and harvest weight (Bernatchez et al. 2013). Ramps responded positively to applications of gypsum and organic fertilizer. In transplanting 2-year-old bulbs in West Virginia, slaked lime ($Ca(OH)2$) and gypsum increased soil calcium levels, slaked lime increased pH (from 4.0 to 4.7), and both treatments increased bulb survival and weight (Ritchey and Schumann 2005).

Transplanting bulbs in spring leads to bigger bulbs at harvest, but fall transplanting is more feasible logistically because there is a wider window of time to transplant leaf-less bulbs (Bernatchez et al. 2013). The concentrations of leaf nitrogen decreased in years following fertilization with N, suggesting that ongoing fertilization would be beneficial for plant growth, but more research is necessary on the economics and effects on the rest of the forest (Bernatchez et al. 2013). These recommendations might be more applicable to growers who are field-growing ramps to transplant into forests.

Some people build raised beds in the forest for ramp cultivation (Forest Farming 2013). These are built from treated lumber, lined with landscaping fabric, and filled with garden soil to reduce weed competition. This represents a more intensive growing strategy, but could help with keeping the ramp patch organized, and make calculations for fertilizer applications and other management easy.

Seeds planted in September in North Carolina produced roots after 11 months, and shoots after 20 months (the second spring) (Connor et al. 2015). Ramps grown from seed can take up to 5 years before they are ready for harvest, so this method of propagation is recommended for relatively extensive management, or as a complement to shorter term, more intensive cultivation. Ramp seeds mature in the late summer; selling them may be an additional enterprise possibility for growers with large populations.

Ramps are an important part of Appalachian identity, and are a traditional spring food. Before their current boom in popularity, they were sometimes viewed as a "survival food," where only those poor enough would eat the pungent bulbs (Rivers et al. 2014). Throughout Appalachia, ramp festivals provide a means of celebration, and marketing and fundraising opportunities for ramp foragers, growers, artisans, and cooks. These festivals have become tourist attractions, which bring people from the cities out to the country. As the restaurant market for ramps is strong in New York, a southern New England Ramp Festival might be a worthwhile endeavor for a town or nonprofit looking to increase agritourism. Land trusts might include sustainable ramp harvests as a perk to encourage new members.

Land managers with relatively moist forests should test ramps to see if they grow well under their conditions. It is wise to start with transplants as well as seeds to avoid a discouragingly long period before harvest. Because ramps will survive in high light conditions if soil moisture and nutrients are adequate, they might also be integrated with other agroforestry practices. The understories of windbreaks or alley cropping rows might be appropriate if the competing understory vegetation does not leaf out in early spring.

Marketing ramps should be relatively easy because they are a well-known crop whose seasonal availability is part of their appeal. Small growers might need to collaborate to meet volume requirements of some buyers, and there is opportunity to add ramp products (pesto, infused butter) to value-added enterprises with infrastructure already in place.

## *4.3 Ginseng*

Ginseng (*Panax quinquefolium*) is a high value medicinal herb that is widely grown throughout Appalachia. Much of the harvest is exported to China where it is valued for its medicinal properties. The most suitable sites are fertile, sloping North- or East facing sites with a mostly-closed canopy (Hankins 2009). A Virginia Tech Extension document says that optimal ginseng sites also support sugar maple, black walnut, and tulip poplar (Vaughan et al. 2009). In southern New England, the relatively mesic sites will have sugar maple, ash, and tulip poplar, though Ginseng might do well on sites with other species, like oaks, in the canopy, as long as the other site criteria are met. Associated herbaceous plants include jack-in-the-pulpit (*Arisaema triphyllum*), trillium (*Trillium* spp.), bloodroot (*Sanguinaria canadensis*), Solomon's seal (*Polygonatum* spp.), lady's slipper (*Cypripedium* spp.), mayapple (*Podophyllum peltatum*), spicebush (*Lindera benzoin*), and jewelweed (*Impatiens capensis*) (Hankins 2009; Vaughan et al. 2009).

Vaughan et al. (2009) describe variations on ginseng planting strategies that balance space, seed cost, germination rate, labor intensity, and final outcomes. In general, the seeds are scattered on bare soil, then covered with leaf litter, or individually planted around one inch deep.

Dried wild-grown ginseng roots can be sold for up to $850 per pound, though prices fluctuate depending on the day and the particular buyer (Hankins 2009). "Wild-simulated," or extensively cultivated ginseng plants, fetch similar prices. Ginseng cultivated in tilled soil under artificial shade commands a much lower price, and—because these practices are underway in China—the export market is virtually nonexistent. The conditions for wild-grown ginseng are not abundant in China, so that export market still exists, and is likely to persist.

Lest ginseng be considered a get-rich-quick scheme, there are serious threats to a successful ginseng enterprise. Poaching, pests like deer and slugs, environmental stresses, and a disorganized market can all take their toll in the 7–10 years it takes for wild-grown ginseng to mature (Hankins 2009). Producers receive more favorable prices if they can sell at least a pound of dried roots at a time: about 275 plants' worth.

Ginseng grows best in soils with low pH and (somewhat counterintuitively) high calcium.[1] Though prior recommendations supported adding lime, the current best practice is the addition of gypsum (calcium sulphate), which increases available Ca but does not change pH (Hankins 2009). The authors are clear that more research on agronomic practices for ginseng is necessary.

Forest owners with appropriate sites would do well to test ginseng as an additional enterprise. As with ramps, starting with transplants as well as seeds might lead to earlier, more encouraging harvests. Markets may be necessarily informal and diffuse, but more easily accessible information would help growers in the Northeastern region.

## 5 Homegardens

Homegardens are generally understood as "intimate, multi-story combinations of various trees and crops, sometimes in association with domestic animals, around homesteads" (Kumar and Nair 2004). The practice is several thousand years old, with roots in Java and India, as well as Mesoamerica (Kumar and Nair 2004; Montagnini 2006). Research has been primarily focused on description and inventory, rather than measuring biophysical or dynamic ecological interactions.

Homegardens in China are variable in their products (fuelwood, food, livestock, medicine, cash crops, nursery stock), climates (subtropical through temperate), and utility (productivity can be high, but sometimes gardens are mismanaged) (Wenhua 2001). In some Chinese homegardens, a family's income can be six times that of farmland output for the same area input because of higher labor inputs, complexity, and smaller scale.

Homegardens can cycle nutrients efficiently, conserve biodiversity, diversify farm products, and provide non-market-valued products. They can be associated with and promote social and cultural values, including the opportunity for women to be primary agents (Kumar and Nair 2004). Homegardens might be threatened by urbanization, but they are still widespread, and worth promoting: homegardens can inform the development of other agroforestry practices. Though many writers focus on tropical homegardens, this last point may be even more relevant in temperate systems, where agroforestry arrangements are even less well-developed and studied than in the tropics.

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[1] From Hankins 2009, citing Beyfuss 1997: "Beyfuss was surprised at the soil test results that came from this study. He said in his report, *"The most interesting and puzzling result of the analysis was the positive correlation of very low pH and very high levels of calcium. This is the exact opposite of what would be expected in mineral soils. The average pH for these samples was 5.0 + or − 0.7. Soils that are strongly acid such as this usually have calcium levels in the range of 1000–2000 pounds per acre or less. The average calcium levels in these samples (where ginseng was growing well) was 4014 + or – 1679. It is my suspicion that this abnormality may, in fact, be the key to the limited range of healthy populations of wild ginseng. Duplicating this soil condition may be the key to successfully cultivating American ginseng in a forested environment."* (Beyfuss 1997)

The permaculture movement (Ferguson and Lovell 2014) has been promoting a resurgence of homegardens (or forest gardens, or food forests) particularly among Australians, Western Europeans, and North Americans. Contemporary records of temperate homegardens refer to the homestead of Robert Hart in England as a model (Jacke and Toensmeier 2005). The Agroforestry Research Trust in England has established forest gardens, and its director has written several books on the topic (Crawford 2010). Eric Toensmeier details his experience over a decade of urban homegardening in Massachusetts (Toensmeier and Bates 2013). There are many other "gray literature" treatments of the subject (i.e. Flores 2006; Hemenway 2009); many more less formal reports exist in the records and communications of the North American Fruit Explorers (http://www.nafex.org/), Northern Nut Growers Association (http://www.northernnutgrowers.org/), and various Facebook groups and websites dedicated to temperate homegardens. Of course, many people have "homegardens" but do not use that term to describe the diverse, multi-strata plantings close to their houses (Zinkhan and Mercer 1996).

The USDA does not recognize homegardens as one of the primary agroforestry practices (United States Department of Agriculture 2011), which may limit their adoption. Gordon and Newman (1997) say that temperate homegardens are not a significant agroforestry practice. To some extent, this may be a self-fulfilling prophecy. Current research is examining the rise of "community food forests," or homegarden-style land management on public land, often in cities (http://communityfoodforests.com/). One prominent example is Beacon Food Forest in Seattle, which began as an idea in a permaculture design course, but has expanded to include partnerships with city and community groups (McLain et al. 2012). Temperate homegardens are also being promoted for their ecosystem services benefits like habitat creation, biodiversity promotion, and carbon sequestration, as suggested by Toensmeier (2016).

Homegardens should be more widely practiced and supported in the Northeastern United States. Homegarden proponents should seek to complement, learn from, and enhance the work of home orchardists, organic gardeners, homesteaders, pollinator enthusiasts, and public park administrators. The current trajectory of informal hobbyist networks could be supplemented by the United States Department of Agriculture recognizing homegardens as a sixth agroforestry practice, land conservation organizations practicing homegarden-inspired management, and making conservation funding available for homegarden practitioners.

## 6 Alley Cropping

Alley cropping refers to rows of trees or shrubs planted in lines in the same land as cultivated crops in the alleys or space between the rows (Fig. 4.6). The woody component may increase soil fertility, soil organic matter, produce timber, fruit/nuts, or

**Fig. 4.6** Gooseberries (*Ribes* spp.) grow between widely spaced rows of white pine in Iowa, USA (Photo: E. Roberts)

to give shade to the crops. Benefits can include wind speed reductions, wildlife habitat, and the potential to run a tree-based enterprise on the same land as a row-crop enterprise.

While some tropical research promotes planting frequently-coppiced legumes in the tree rows (Smith et al. 1997), work in Oregon suggests that the improvements in soil organic matter do not offset the decrease in yields of corn due to the shade provided by red alder (*Alnus rubra*) or black locust (*Robinia pseudoacacia*) in the tree rows (Seiter et al. 1999). Jordan (2004) *did* find that pruned mimosa (*Albizia julibrissin*) in tree rows improved the soil condition in farms in the Southeastern United States. This difference in results is likely related to the fast growth rate of the mimosa in the warmer climate of the Southeast; prospects for a similar system justified on crop yields alone in the Northeast are probably not realistic.

Gordon and Newman (1997) and Wenhua (2001) discuss paulownia (*Paulownia tomentosa*) alley cropping in China, which provides fast-growing quality timber, minimizes light competition with late leaf emergence, and provides some frost protection from late leaf holding. Other Chinese systems also include fruit trees, and have higher yields driven by resource sharing and the humidity and temperature mediating effects of the trees.

A study in Missouri (Gillespie et al. 2000) tested corn's response to black walnut and red oak rows: 10 years after establishment, the corn rows closest to the tree rows showed declining yields. Root pruning treatments mitigated most of the row closeness effect, suggesting that belowground competition was a much stronger factor than light limitation for crops. Interestingly, the walnut had slower diameter growth in response to root pruning, whereas the red oak had a much smaller response. The authors speculate that differences in root physiology might explain the differential responses. Importantly, corn yields in the root-pruned walnut block were comparable to or *higher* than in the adjacent corn monoculture. The authors are also careful to suggest that the pruning depth was particularly extreme: 1.2 m. They speculate that a shorter pruning depth may have benefited the corn without such detriment to the trees in the alley. Using a single shank subsoil plow every year on alternating sides of the tree rows is a cost-effective way to "train" the tree roots to grow below the level where they compete with crops (Garrett et al. 2009).

### *6.1 Black Walnut Allelopathy*

Root pruning may also mitigate the effects of juglone exuded by the roots of black walnut trees. Juglone is a chemical exuded by the roots of black walnuts that inhibits respiration and photosynthesis in some other species of plants (Scott and Sullivan 2007). Trials with polyethylene barriers in black walnut alley cropping systems reduced juglone in the alleys to near nothing (but increased concentrations within tree rows). Root pruning has been suggested as a more cost-effective intervention that might also "train" the roots to spread into deeper soil levels and further partition belowground resources, and act to catch water and nutrients that seep below the root zone of the crops (Jose and Holzmueller 2008).

Different crop species respond differently to juglone. Corn, wheat, and barley are less damaged than soybeans in the presence of juglone. Especially when black walnut plantings are young, there is good opportunity to grow even sensitive crops in the alleys for at least the first 10 years. Four meters away from the row, juglone is reduced by 80% (Jose and Holzmueller 2008). This emphasizes the point that alley cropping systems are dynamic over time, and the nature of interactions can change (Fig. 4.7).

Scott and Sullivan (2007) consider plants that can grow well with black walnut in the beginning, intermediate, and mature phases of plantations. They emphasize that, especially at wide row spacings (i.e. Fig. 4.8), the first 15 years of a black walnut planting produces relatively little juglone, and most crops will grow satisfactorily (Scott and Sullivan 2007). They note that soil moisture can modify juglone's effect on other plants; walnuts share drier sites better. Noting the almost mythical status of juglone toxicity, these authors propose a reorientation, where juglone is considered as a resource to be managed, like low pH or soil dryness, rather than a liability.

**Fig. 4.7** (L) Hybrid chestnuts (*Castanea* spp.) spaced 20′ × 30′, 8 years after establishment, intercropped with winter wheat. Chinese chestnut spaced 30′ × 30′, 23 years after establishment (R). Both in Missouri, USA. Alley cropping can provide income in the early years of a tree plantation before the primary crop matures and the canopy closes (Photos: E. Roberts)

**Fig. 4.8** Black walnut rows spaced 18 meters (60 feet) apart in Missouri, USA have no apparent negative effect on the pasture grasses underneath, 25 years after establishment (Photo: E. Roberts)

### *6.2 Alley Cropping in the Northeast United States*

In the Northeast USA, alley cropping could be more widely used. Trees can take up excess fertilizer (Nair and Graetz 2004), which contributes both to tree growth and to mitigating water quality concerns. Black walnut and red oak would be appropriate in this region, too, as would other trees with some commercial value. Corn has a C4 photosynthetic pathway, and so is not very tolerant of competition for light. C3 crops such as wheat and soybeans might have different responses to shading and belowground competition. The shade of trees from the tree rows might be particularly useful in growing heat-sensitive crops like lettuce for longer into the summer months. Best practices for easy root pruning should be a research priority.

The mitigation of nonpoint source pollution is a priority for conservation and water quality agencies in the Northeast (CT Department of Energy and Environmental Protection 2014). Alley cropping can reduce the nutrient and sediment loads that are entering waterways and becoming a public liability; alley cropping should be financially supported by entities that benefit from clean water. There are also direct conservation benefits to farmers, and trials should be happening to determine species, spacings, management practices, and enterprises that work well. Informal networks and university-based documentation should encourage a diverse group of practitioners to experiment.

## 7 Windbreaks

Windbreaks are rows of trees or shrubs located near agricultural land to slow the wind. They can control erosion and snow deposition, improve animal health, survival, and reproduction, and provide habitat for predatory birds and insects (Brandle et al. 2004), as well as sequester up to 6.4 tons (Mg) of carbon per linear kilometer in aboveground biomass (Toensmeier 2016). Windbreaks can be classified by their primary purpose or location, though the mechanisms and other benefits often remain the same. *Field windbreaks* occur in cultivated crop land, *livestock windbreaks* protect livestock, often on pasture, and *farmstead windbreaks* manipulate the wind patterns around houses or other farm buildings (Williams et al. 1997). There are many factors that influence windbreaks' functions, like structure, width, height, shape, orientation, and leaf and branch arrangement within the windbreak (Brandle et al. 2004). Much windbreak research and writing has taken place in the American West (Jairell and Schmidt 1999), but there are examples from western Europe (Caborn 1957), and the technology is worth adapting to landscapes in the more humid Northeastern USA.

### 7.1 The Physical Effects of Windbreaks Can Influence Temperature and Plant Growth

Windbreaks are typically oriented perpendicularly to the problematic winds which are prevalent in a given region (Brandle et al. 2004), but those might be different from the most frequent winds (Cleugh 1998). Height is the most important factor in determining the protected area: usually 2–5 times the height (2–5H) upwind, and 10–30H downwind (Brandle et al. 2004). Yield benefits are generally found 2–5H upwind, and 10–15H downwind of windbreaks, but it depends a lot on the year, site conditions, design of the windbreak, and crops (Williams et al. 1997). There is some yield reduction because of the space windbreaks occupy, and within 1H of the windbreak, but this is more than offset by larger increases in yield farther downwind (Williams et al. 1997). Puckett et al. (2009) suggest combining windbreaks with grassy strips where tree root competition would otherwise affect crop yields. This would diversify the habitat and not have a large relative impact on yields. Tree root pruning is another way to manage competition between tree rows and crops, which becomes especially important as water becomes more limiting (Brandle et al. 2004).

Windbreaks for different purposes require different densities, which is an approximate measure of the trunk, branch, and leaf area the wind must blow through. For snow distribution along a field, a lower density windbreak is appropriate. Medium density windbreaks benefit crop and soil protection during the growing season (Fig. 4.9). For protection of buildings and livestock, relatively higher densities provide the most benefit (Straight and Brandle 2007). The National Agroforestry Center in Nebraska has a series of resources about windbreak design, maintenance, and integrating income-producing products into windbreaks (http://nac.unl.edu/practices/windbreaks.htm). Denser windbreaks generate relatively short, deep drifting snow (probably better for protecting roads and buildings), but more porous ones spread shallow snow drifts over longer areas (probably better for crops) (Brandle et al. 2004). Research from Scotland suggests that windbreaks with abrupt edges, rather than gradual increases in height along the cross section, better reduce wind speed by creating a series of eddies (Caborn 1957).

Plants tend to grow better with less wind speed, but the effects of windbreaks on yields are quite variable (Brandle et al. 2004). Grains and pasture have mixed yield responses, but specialty crops, vegetables, orchards, and vineyards have more consistent positive yield responses to windbreaks, especially between 3H and 10H (Cleugh 1998). Horticultural crops like fruits and berries are especially sensitive to wind speed (Brandle et al. 2004).

One review from Australia detailed the complexities in determining which mechanisms affected the variety of yield outcomes (Bird 1998). Across temperate Australia, Europe, and Asia, the authors found yields that were influenced by reduced evapotranspiration, some by snow trapping, and some where the pasture

**Fig. 4.9** A farmstead windbreak of black walnut (*Juglans nigra*) in Connecticut, USA. This seems to be designed for summertime wind protection, because it is not very dense when the leaves have fallen (Photo: E. Roberts)

yield did not increase, but animals' performance improved because of temperature or stress reduction. The authors emphasize that it is difficult to give unequivocal advice about why windbreaks often work when studying them is so complex. For instance, if windbreaks have wind speed effects up to 30H downwind, it is hard to assume that site conditions are otherwise similar, especially in variable topographies. Daytime temperatures within 8H tend to be warmer because of reduced turbulence (but between 8 and 24H turbulence is higher, so temperatures are cooler) (Brandle et al. 2004).

Windbreaks may help accumulate heat units, which is useful especially in cold places (Brandle et al. 2004). The reduced turbulence in windbreak-sheltered areas may also increase the risk of frost damage (Cleugh 1998), so sites where frost is a limiting factor might need more judicious planning (sloping topography with no trees, for instance).

### 7.2 Effects on Livestock

All animals have a temperature below which they must use more physical resources to maintain their body condition. This temperature varies with species, age, size, health, coat thickness, and whether the animal is wet or dry, but in general, windbreaks reduce wind chill, which can lead to animals needing less feed to meet their maintenance requirements (Williams et al. 1997). Dairy cattle produce less milk at temperatures below 2 degrees C (35 degrees F) and pigs must eat more when they are faced with cold winter temperatures. Whether these animals are raised outside or in confinement systems, windbreaks will either reduce wind chill or reduce the amount of energy needed to heat/cool their buildings (Quam et al. 1994).

### 7.3 Biological Diversity, Pest Control, and Non-timber Forest Products

The wind moderating effects of windbreaks are the primary purpose for installing them, but auxiliary benefits like pest control, non-timber forest products, and aesthetics are also important factors. Thin windbreaks improve conditions for insect diversity and survival primarily through wind speed reductions, but the more complex they get, the more habitat they provide (Brandle et al. 2004). Vegetative structure provides perching substrate, cover for predator avoidance, and travel corridors for birds (Jones and Sieving 2006). Diverse native vegetation supports specialist herbivore caterpillars that make up the bulk of breeding birds' diets (even if those birds are primarily seed-eaters) (Tallamy 2009). This suggests that trees as in windbreaks can improve bird habitat in agricultural areas.

A study in Quebec found that cutworms and weevils were less abundant in corn plots that birds had access to, especially those near (0–7 m) the field edge. The overall pest pressure was low, so there was no effect on yields, but there was also some evidence for control of aphids and corn rootworms (Tremblay et al. 2001). Downy woodpeckers are significant predators of overwintering corn rootworm; windbreaks likely increase their spread into crop fields (Williams et al. 1997). Bird exclosures had higher levels of aphids and thrips on kale than non-exclosed plots in Kenya, especially in the dry season (Ndang'ang'a et al. 2013). These studies suggest that birds contribute to pest control.

The effects of vegetative structural diversity of windbreaks on bird activity can be significant even if the additional plants are relatively small. Rows of sunflowers increased insectivorous bird foraging activity at a density of only one or two 1 m rows per 0.4 ha (Jones and Sieving 2006). A study in Florida found significant bird foraging within 20 m of woody edge, especially birds they called "functional insectivores" who eat cutworms, corn borers, and weevils, at least during their breeding season. The authors recommended the 20 m zone as a target area for reducing pesticide use and performing other bird-friendly practices (Puckett et al. 2009).

One study in Quebec (Bernier-Leduc et al. 2009) compared bird abundance and diversity in 12 year old larch-ash (*Larix-Fraxinus*) and ash-elderberry-highbush cranberry (*Fraxinus-Sambucus-Viburnum*) windbreaks (about 2 m wide, with diverse understories). There was no difference in bird diversity between the treatments. 98% of the recorded birds were non-detrimental, and potentially damaging birds like crows *(Corvus brachyrhynchos)*, starlings *(Sturnus vulgaris)*, cedar waxwings *(Bombycilla cedrorum)*, and red-winged blackbirds *(Agelaius phoeniceus)* occurred in low abundance. In balancing the crop predation of detrimental birds with the pest control benefit of non-detrimental birds, the authors conclude that the windbreak probably produced a net benefit for crops. Specialty crop integration in windbreaks requires a relatively large initial investment, plus labor costs and marketing expenses are high, and small local markets can be limiting. But one analysis (Josiah et al. 2004) estimated the gross per-meter returns as high as $15 (Brandle et al. 2004). For producers with access to the right markets, that is a real opportunity.

Dix et al. (1995) review how trees affect the predators and parasitoids of crop pests. They suggest that diverse woody field edges and windbreaks provide alternate prey for predators and parasitoids, overwintering and nesting habitat, and floral resources that can enhance the fitness of crop pests' natural enemies. Lavandero et al. (2006) complicate the picture, with examples of floral resources benefiting pest organisms as well. Lu et al. (2014) discuss the importance of extrafloral nectaries in addition to nectar and pollen resources on improving parasitoid fitness. They stress the importance of finding "selective" floral resources that favor beneficial species only. One example is buckwheat, which supports the parasitoid wasp *Microplitis mediator* without benefiting its host pest, the cabbage moth *Mamestra brassicae* (Géneau et al. 2012). Lu et al. (2014) are careful to point out that selectivity can happen at the landscape scale, too: the ease with which predators/parasitoids and their prey/hosts move across various landscapes can affect the fitness of each. Future conservation biocontrol research should examine woody plants' flowers' selectivity; this can relate to extrafloral nectaries, flower morphology, nectar chemistry and secondary compounds, or benefits to predators of parasitoids. Until then, diversity, continuity of nectar availability, and other functions (habitat, caterpillar host, aesthetics, availability) will likely drive producers' choice of woody species for windbreak biocontrol.

Woody plants can also support pollinators next to agricultural fields by providing floral resources and nesting sites (Sheffield et al. 2016). Plants that flower near the bloom time of the primary crop can increase the reproductive success of native pollinators; a diverse assemblage of plants should be able to carry populations throughout the year. One analysis from Pennsylvania tracked pollinator visits to various native plants throughout the year (Russo et al. 2013). The researchers suggest that a mix of plants will support specialist and generalist bee species across the flowering seasons. Some native bees nest in bare ground, and others nest in cavities or hollow stems. Windbreaks are an ideal place to manage for a variety of habitat types that support beneficial wildlife. Details about specific habitat structures are well explained in Lee-Mader et al. (2014), and include woody debris, rock piles, un-disturbed mulch, and woody stems. Each of these is easy to incorporate into a row of trees.

### *7.4 Other Benefits of Windbreaks*

Buildings situated downwind of windbreaks use less heating energy. Other, less tangible—but very real—benefits include reduced noise and dust pollution, improved outdoor working conditions, and reduced building maintenance costs (Williams et al. 1997). Many people will be concerned about aesthetics, too. While few producers will be able to install windbreaks solely for aesthetic purposes, affinity for a particular plant can be an added factor when deciding on species composition. Proponents of windbreaks' functionality would be wise to respect individuals' preferences.

### *7.5 Windbreaks in the Northeastern United States*

The most appropriate species for windbreaks in the Northeast will vary with producers' goals and site conditions. Dense, fast-growing conifers include Norway spruce and white pine; most other hardwoods will grow well. If control over tree species is not a priority, natural regeneration might be possible, depending on what trees are in the vicinity, and what competing herbaceous vegetation is present. For small, unmown and uncultivated areas, selectively weeding out shrubs and grasses to release existing tree seedlings might be an easy way to establish a windbreak.

In the Northeastern USA, many farms already have rows of trees and shrubs along fence lines and stone walls, even if farmers aren't using the term "agroforestry." These should be valued and supplemented as needed, especially to create even density, and to make the density match the desired wind control goals. Many rows of trees alongside fields may have gaps from uneven establishment or storm or insect damage, which may be concentrating wind rather than buffering it. Fast-growing species adapted to the shade and moisture conditions of the particular gap could be planted to make these windbreaks more functional.

Windbreaks' widths vary from one to seven or even ten rows wide. The widest designs tend to have less effect on wind speeds because they encourage less eddying (Straight and Brandle 2007). Two to five rows of trees are a feasible width. This also provides an interesting canvas on which to design multifunctional systems. The simplest designs might have two rows of white pines for livestock protection. A more complicated windbreak might include one row each of red maple and black locust for early nectar resources, with a row of hemlocks in the middle for structure and wildlife cover. Willows are fast growing species that are especially adapted to higher moisture sites; several species of willow can also be marketed in the ornamental floral trade. A windbreak mixing full-sized willows with adjacent rows of ornamental willows could provide wind protection benefit and a supplemental income source. On a smaller scale, windbreaks of shrubs like elderberry (*Sambucus* spp.), hazelnut (*Corylus* spp.), nanking cherry (*Prunus tomentosa*), or crabapple (*Malus* spp.) might provide crops in a shorter time than trees, and could be easier to integrate into an agricultural landscape because of their smaller statures.

## 8 Forested Riparian Buffers

Riparian buffers are areas of vegetation managed around water bodies to intercept nutrient, pesticide and sediment runoff, stabilize streambanks, maintain cool water temperatures, and provide habitat and wildlife corridors. Many of these functions can be performed by simple perennial grass "filter strips," but the addition of woody plants provides more opportunity to be creative in meeting several management goals simultaneously. Particularly promising are the incorporation of woody floral products and other non-timber forest products like fruits and berries, and designing and managing forested buffers to enhance the beneficial effects of wildlife on agricultural operations.

The Northeastern United States faces water quality challenges from agricultural runoff, much like the rest of the country. The most common sources of excess non-point source nutrients in surface water are chemical fertilizers and manure from animal facilities. Water quality contaminants associated with agriculture include nutrients (N and P from fertilizers and animal wastes), pathogens and organic materials (animal wastes), sediment (field erosion), pesticides, salt, and petroleum products. Primary outreach is through the Natural Resources Conservation Service (NRCS) and its Environmental Quality Incentives Program (EQIP). The Connecticut Department of Energy and Environmental Protection's 5 year plan includes developing a clearinghouse for nutrient management and soil erosion control innovations (CT Department of Energy and Environmental Protection 2014).

Buffers can be forested through natural or artificial regeneration methods; the usual tradeoffs apply. Natural regeneration can be cheaper, but can be less predictable and relies on nearby seed sources. Artificial regeneration gives managers more control over the species mix, but can be more expensive (Butler 2003).

### *8.1 Design of Riparian Buffers*

The Connecticut Best Management Practices recommend riparian buffer widths from 15 m (50 ft) to more than 45 m (150 ft), depending on the slope of the land, vigor of vegetation, drainage of the soil, and size of the draining watershed (CT Department of Energy and Environmental Protection 1996). Guidelines from the University of Missouri suggest a three-part buffer: fast-growing trees closest to the stream, a combination of trees and shrubs in the next section, and perennial grasses closest to the crop field (Gold et al. 2005). Schultz et al. (2004) expand that idea, saying more flexibility in vegetation structure can benefit stream ecology and encourage producers to adapt buffers to fit their particular farms. Design considerations are well detailed in Bentrup (2008). Interestingly, buffers designed to capture runoff phosphorus should be located higher in elevation than potential floodwaters, so that the phosphorus will not be washed away during high water. Nitrogen buffers should be downslope so that they can catch the available nitrogen; the plants in the buffer use nitrogen, so it is at less of a risk for washing away.

### *8.2 Integrating Non-timber Forest products into Riparian Buffers*

There has been recent work in Virginia to encourage landowners to install riparian buffers by emphasizing the possibility of producing fruit and nuts in the buffers (K. McFarland, personal communication). Trozzo et al. (2014) found that landowners most likely to express interest in planting a buffer that included native fruit and nut trees had relatively high incomes, did not consider themselves farmers, and had bought their land relatively recently. This expands the traditional targets of buffer outreach. A new tool called Buffer$ ("Buffer Bucks," http://nac.unl.edu/tools/buffer$.htm) helps project enterprise budgets for a variety of edible or marketable riparian buffer species. Elderberries (*Sambucus* spp.) and woody florals are promising non-timber forest products that can be incorporated into forested buffers (Trozzo et al. 2012).

Riparian buffers offer a technique that can benefit water quality and improve wildlife habitat. They can also improve aesthetics and be a source of income and beneficial wildlife. They are already a recognized practice by NRCS and state conservation bodies; innovations in outreach and creative marketing of non-timber forest products are logical next steps. The agro-tourism market should be a place where woody florals can be used, and the growing vineyard industry might do well to incorporate elderberry into some unique wines. Some initial experimentation should be followed with collaborations between growers and wineries to achieve a scale that works for both parties.

## 9 Conclusions

Agroforestry presents opportunities to resolve tensions between productivity, profitability, and conservation goals held by farmers and society. Silvopastures can mitigate heat stress, improve timber value, and expand the amount of land under active management. Fodder trees can be directly grazed, and there is much experimenting to be done to ascertain the nuances of intensive silvopastures in temperate regions. Windbreaks and riparian buffers are well established conservation practices that could benefit from better promotion and support. Incorporating non-timber forest products or explicitly designing habitat for beneficial wildlife may improve these practices' appeal to farmers. Forest farming is appropriate for expanding throughout the region. Ramps, ginseng, and gourmet mushrooms can grow in previously underused farm woodlots and provide a supplemental income source to landowners of all kinds. Policymakers would do well to recognize the informal networks that are already supporting these practices. Institutions that coordinate research and communication among practitioners should continue and expand their work. Foresters and extension personnel should work with landowners to determine whether agroforestry practices might help them reach their goals. A wide spectrum of complexity and intensiveness will be useful in fully exploring the possibilities of agroforestry for a variety of applications in the Northeastern US.

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# Chapter 5
# Resilience Management at the Landscape Level: An Approach to Tackling Social-Ecological Vulnerability of Agroforestry Systems

**Dardo R. López, Laura Cavallero, Marcos H. Easdale, Carlos H. Carranza, Marcela Ledesma, and Pablo L. Peri**

## 1 Introduction

It has been estimated that more than half of the earth's natural ecosystems have been modified by anthropogenic activities for the provision of ecosystem goods (Millennium Ecosystem Assessment 2005). Both human well-being and natural ecosystems are directly affected by social activities and/or conditions, as well as by stochastic climatic events (Butler and Oluoch-Kosura 2006; Fremier et al. 2013). Agroforestry landscapes can provide a great variety of ecosystem goods and services at both farm and global levels (Jose 2009; Thompson et al. 2011). These landscapes are also home to thousands of rural people whose livelihoods depend on the forest. This dependence on the forest for subsistence strengthens the need to promote the sustainable management of native forests (Millennium Ecosystem Assessment 2005; Jose 2009).

D. R. López (✉) · C. H. Carranza · M. Ledesma
Instituto Nacional de Tecnología Agropecuaria (INTA)- Estación Forestal INTA-Villa Dolores, Córdoba, Argentina
e-mail: lopez.dardor@inta.gob.ar

L. Cavallero
Instituto Nacional de Tecnología Agropecuaria (INTA)- Estación Forestal INTA-Villa Dolores, Córdoba, Argentina

CONICET (Consejo Nacional de Investigaciones Científicas y Técnicas) - CCT Córdoba, Córdoba, Argentina

M. H. Easdale
INTA- Estación Experimental Agropecuaria (EEA) Bariloche / CONICET, Bariloche, Argentina

P. L. Peri
EEA INTA Santa Cruz-Universidad Nacional de la Patagonia Austral (UNPA), Río Gallegos, Santa Cruz, Argentina

CONICET, Buenos Aires, Argentina

 
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Sustainability is a holistic and trans-disciplinary concept, therefore a framework that integrates both social and ecological sciences is needed to understand and promote it. Despite the increase in theoretical discussions concerning coupled social and ecological systems (hereafter 'SES') over the last decades, SES have not yet been implemented as management and governance tools, possibly due to their complexity. There is a wide consensus that the analysis of alternative management strategies should focus on emergent properties of these complex systems (Folke 2006). In the face of increasing anthropogenic pressure to obtain ecosystem goods from agroforestry landscapes, management decisions taken at the local level can severely affect the resilience of SES at the landscape level, thus it is essential to adopt a broader analytical perspective, considering the potential impacts of management practices on other SES within the landscape.

In this chapter we focus on management practices of social-ecological systems at the landscape scale by using a resilience approach to reduce the vulnerability of agroforestry systems (AFS) to environmental and/or anthropogenic disturbances. We define social-ecological systems and introduce key emergent SES properties for agroforestry management. We then propose a framework to analyze social-ecological systems at a landscape scale. Finally, we demonstrate this framework with an example that shows the benefits of resolving social-ecological conflicts at the landscape scale.

## *1.1 Social-Ecological Systems*

A social-ecological system consists of a biophysical unit associated with social actors and institutions (Berkes et al. 2003). In AFS, a farming-system (e.g. households, farmers, ranchers) can be analyzed as a SES since it includes a unit of land managed by a household or stakeholder whose aim is to produce agroforestry goods and services. Thus, the farming system represents the minimum unit where management decisions are made. Hence, a farming-SES integrates the biophysical attributes of a given land unit and a rural household that manages the production unit, which is also linked with social networks (Fig. 5.1). Although household, ranch, farm, and rural-stakeholder are not synonymous, they can be viewed as complementary concepts; thus it must be noted that in this chapter the term 'farming-SES' can include any of these systems. We suggest readers use the term that most appropriately describes the SES most frequently found in each region.

From an analytical perspective, a SES can be composed of five sub-systems[1] that represent different livelihoods of rural households: natural, human, social, manufac-

[1] What we call 'sub-system' in this chapter is also called 'capital' by some authors (see more on Ekins et al. 2003; Davies et al. 2008; Easdale and López 2016).We use sub-system because the term "capital" can generate epistemological discussions from their different use by social, ecological and economic disciplines.

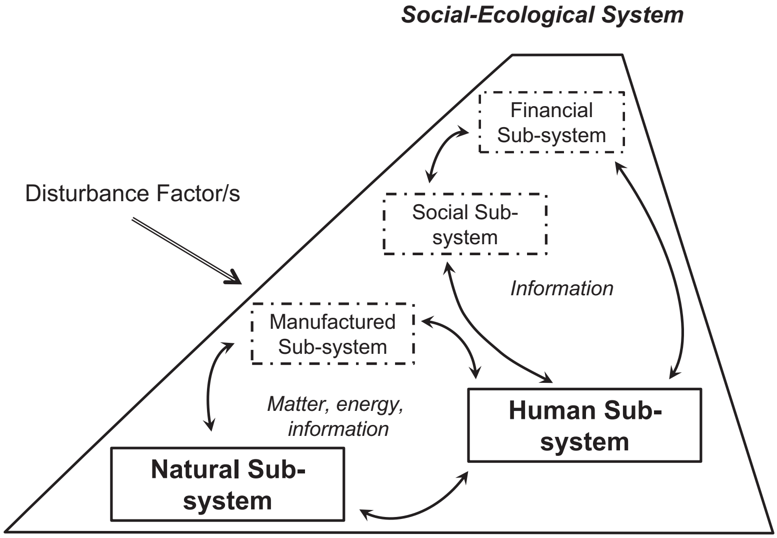


**Fig. 5.1** The household social-ecological pyramid: framework proposed by Easdale and López (2016) to analyze the Social-Ecological Systems (SES) resilience at household-scale (household-SES or farming-SES). The bottom of the pyramid is constituted by the natural and human sub-systems, since natural sub-systems represent the basis for human living, and both sub-systems are the foundations of a SES (boxes with filled lines). Towards the top of the pyramid, sub-systems that complement human well-being are organized at different hierarchical levels: manufactured, social, and financial (boxes with cut lines). Arrows connecting boxes indicate the main fluxes among sub-systems. In this scheme, an agroforestry system is defined by the interaction of the natural, human and manufactured sub-systems, among which there are flows of matter, energy and information. Human, social, and financial sub-systems mainly circulate information, except in barter economies, where products or goods are circulated primarily. The link between SESs occurs through the Social sub-system (through different social networks) (*see more* in Easdale and López 2016)

tured, and financial (Ekins et al. 2003, Davies et al. 2008; Easdale and López 2016). The natural sub-system is the base of a SES, indicating the importance of natural ecosystems to human subsistence and well-being (Daily 1997). The natural sub-system includes both environmental stock (e.g. related to soil, water, and biodiversity) and ecosystem processes (e.g. primary productivity, nutrient cycling, carbon sequestration) (Daly 1994). Ecosystem processes provide environmental goods and services, and have been classified in four categories: regulation, production, habitat, and information (de Groot et al. 2002). The human sub-system comprises all individuals' capabilities important for the pursuit of any livelihood strategy (e.g. knowledge, skills, labor capacities), while the social sub-system relates to the networks and organizations that coordinate individual contributions and actions. The manufactured sub-system comprises material or physical goods typically involved in a production process (e.g. machineries, tools, reproductive animals), while the financial sub-system is composed of monetary assets or equivalent, which contribute both to the production process and to the household financial income (more information in Scoones 1998; Ekins et al. 2003).

The five sub-systems can be nested-hierarchically and organized into the 'household social-ecological pyramid' (Fig. 5.1), which is a multidimensional and hierarchical representation of the different livelihoods of a rural household. The interactions among sub-systems and the hierarchical relationships among each other are represented in Fig. 5.1, whereas structural and functional features are implicitly included in the different boxes that represent each sub-system (see more in Easdale and López 2016). As other complex systems, agroforestry-SESs have emergent properties which have the potential to reflect the impact that management practices can cause in the system as a whole.

### *1.2 Resilience and Vulnerability: Key Emergent Properties in a SES*

A major challenge for sustainability science and management is to assess system properties that synthesize complex social-ecological dynamics, emphasizing both the relationships between system components and the functioning of the system as a whole (Gunderson and Holling 2002; Folke 2006; Nelson et al. 2007). In this sense, there is a growing consensus in the scientific-technical community that resilience and vulnerability are key properties for understanding complex system dynamics, and that they provide tangible opportunities for the integration of theory and the promotion of adaptive management (Walker et al. 2004; Miller et al. 2010; Turner II 2010; Allen and Garmestani 2015). In recent decades, deforestation, biodiversity loss, desertification, and the implications of global climate change have all motivated the study of the capacity to adapt, as well as of the resilience of social-ecological systems (Gunderson and Holling 2002; Reynolds et al. 2007; Gallopín 2006). In this sub-section, we explore the concepts of *resilience* and *vulnerability* as key emergent properties of SES.

Resilience has been the most widely analyzed property across many different systems and disciplines during the last decade, and several interpretations of resilience can be found in the literature (for a synthesis see Gunderson and Holling 2002; Folke 2006; Nelson et al. 2007). In ecological disciplines, resilience is defined as the capacity of an ecosystem to absorb and/or reorganize after a disturbance, maintaining ecosystem integrity and its structural and functional identity (Holling 1973; Westman 1978; Bestelmeyer and Briske 2012). In an ecosystem, a significant decrease or even loss of resilience implies crossing a threshold into an alternative state in response to a disturbance factor (e.g. overgrazing, forest overuse) (Briske et al. 2005, 2006; López et al. 2011, 2013). An ecosystem has therefore crossed a threshold when its key attributes and processes have been affected by one (or more) disturbance factor(s), which significantly reduce the system's capacity to return to an original or previous state (i.e. loss or significant decrease of resilience) (Groffman et al. 2006; López et al. 2011).

From a social-ecological perspective, resilience further relates to three aspects: (i) the system's ability to absorb or respond to a disturbance factor and remain within the same state, (ii) the degree to which the system is capable of self-organization (versus lack of organization, or organization forced by external factors), and (iii) its capacity to learn and adapt to future changes and/or new drivers (Folke et al. 2002; Gunderson and Holling 2002; Folke 2006; Nelson et al. 2007). Therefore, resilience is an emergent property of social-ecosystems because it cannot be maintained by a single component of a SES (e.g. by a single sub-system), but by the whole system or all sub-systems, and it can also be affected by the context. Consequently, the resilience approach aims to manage the capacity of social-ecological systems to cope with, adapt to, and shape the change. It is argued that managing for resilience enhances the likelihood of sustaining desirable pathways for development in changing environments where the future is unpredictable and surprises are likely, reducing the system's vulnerability to new socio-environmental drivers or disturbance regimes (Walker et al. 2004; Folke 2006).

Vulnerability is another key emergent property of a SES and it is also associated with resilience. It has been defined as the degree to which a system is likely to experience harm due to exposure to a disturbance factor. Thus, this concept integrates the impact of a disturbance factor as a function of exposure and resilience of the entity exposed (Turner II et al. 2003; Smit and Wandel 2006; Adger 2006). Vulnerability is an emergent property because a change in the vulnerability of a given sub-system may indirectly affect the vulnerability of other sub-systems (Nelson et al. 2007). Therefore, this concept includes an understanding of the disturbance regime and the social-ecological conditions determining resilience to a given disturbance factor (Adger 2006; Turner II et al. 2003; Smit and Wandel 2006). In recent years, the scientific community has identified some principles that are important for building resilience and reducing vulnerability in social-ecological systems. These principles include maintaining the diversity and redundancy of SES, managing connectivity, fostering adaptive systems thinking, encouraging learning, broadening participation, and promoting polycentric governance systems (Biggs et al. 2012; Resilience Alliance 2010).

Considering these theoretical advances, the structural and functional diversity (species richness and evenness, and diversity of ecosystem processes, respectively) can be used as proxies to estimate the level of resilience and vulnerability of a particular SES. In some ecosystems, increasing structural and functional diversity may enhance their capacity to adapt to disturbances, since a greater functional diversity and/or redundancy increases the ability of a system to respond to disturbance factors. Such capacity to adapt implies an increase in the SES's overall resilience to disturbance, and hence an overall decrease in vulnerability (Folke et al. 2002; Gundernson and Holling 2002; Díaz et al. 2007; Salas-Zapata et al. 2012). For instance, an increase in the diversity of the social sub-system can be associated with an increase in the number of different nodes (structural diversity) involved in a social network and/or an increase in the linkages or connectivity between nodes (functional diversity) at different organizational levels. A high diversity in network configuration may provide better alternatives for the system to respond to a given disturbance factor (Biggs et al. 2012). For example, in a context of economic crisis or price decline in agroforestry goods, the consolidation of agroforestry cooperatives may help achieving better prices for their goods than direct, individual sales (Easdale and Rosso 2010). In contrast, the total or partial substitution of a given sub-system by another (e.g. replacement of a forest by agricultural monoculture) can significantly decrease structural-functional diversity of a SES, causing a decrease in its resilience and subsequent increase in vulnerability (Easdale and López 2016).

The structural-functional diversity should be balanced within and among sub-systems at a SES level, which would depend on a trade-off among each other. For instance, AFS have already modified the pristine natural sub-system to promote the development of other sub-systems (manufactured sub-system). In particular, productive activities in agroforestry landscapes imply that manufactured sub-systems have been developed at the expense of the natural sub-system, which was modified from its pristine state. For example, an increase in the diversity of a manufactured sub-system, such as production diversification with silvopastoral and multiple forest use, can occur at the expense of reductions in the natural sub-system diversity. By replacing part of forestland with pastures, the natural sub-system's diversity is reduced. If this replacement process is large and a "manufacturing intensification" occurs with forestland degradation and/or loss, the SES moves towards an alternative state, with loss of ecosystem and productive diversity, decreasing the system's resilience and increasing its vulnerability to socio-environmental drivers.

The vulnerability of a SES can increase by modifications in one of its components, which changes its resilience, or by disturbance regimes changes. In the first case, loss of structural-functional diversity caused by partial or total replacement of a sub-system by other sub-systems to increase provision of goods (e.g. replacement of forest by pastures and/or extensive crops), causes an over-representation of some sub-systems at the expense of others, eroding the legacy of the replaced sub-system (e.g. forest loss, species extinction, migration of rural people to cities with loss of traditional-cultural knowledge). In this situation, the SES' ability to recover to the previous state significantly decreases, or becomes unlikely, and a threshold is crossed to an alternative state at the SES level (Gunderson and Holling 2002, Easdale and López 2014, 2016). In the second case, changes in disturbance regimes, such as increasing frequency, intensity, or durability, may also increase vulnerability and can trigger transitions to alternative states with lower levels of ecosystem diversity and productive capacity (Gunderson and Holling 2002; Turner II et al. 2003; Turner 2010). A loss of structural-functional diversity at the sub-system level, driven by either management decisions or by natural disturbance factors, can decrease SES resilience. These circumstances may increase SES vulnerability which can indirectly affect other farming-SES, or promote contagion or cascade effects to other SES at the landscape scale.

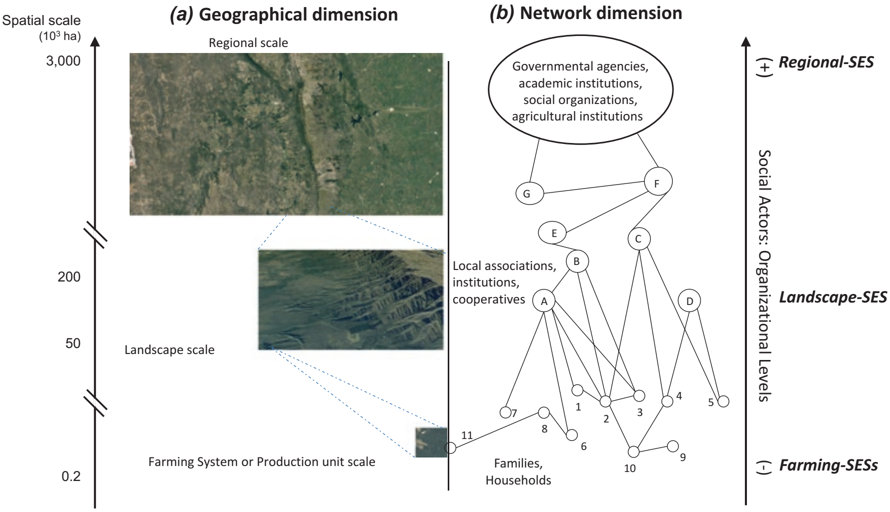


**Fig. 5.2** Schematic representation of Social-Ecological Systems (SESs) that considers geographic (**a**) and network dimensions (**b**) at different scales: *Farming-SES*, *Landscape-SES,* and *Regional-SES*. Social-ecological complexity increases from lower to higher nested-hierarchical scales, and from geographic to social-network dimensions. The higher hierarchical scales include the lower scales (e.g. farming-SESs within landscape-SES)

## 1.3 Hierarchical Scale of SES and Cross Scale Interactions

No system can be understood or managed by focusing on a single scale. All systems, and SESs especially, exist and function at multiple scales of space, time, and social organization, and the interactions across scales are fundamentally important in determining the dynamics of the system (see nested-hierarchical scales of Panarchy, Gunderson and Holling 2002). This is because farming-SES are not isolated in the landscape. Instead they share some resources and are connected by matter and energy flows, and/or by social networks with other SES that inhabit the same landscape. Therefore, different nested-hierarchical levels of SES need to be considered for agroforestry organization and management. The minimum scale of management is the farming-SES. Then, different farming-SESs that co-exist in the same landscape constitute a landscape-SES. At a higher nested-hierarchical scale, the aggregation of different landscape-SES constitutes a regional-SES (Fig. 5.2).

Within the proposed conceptual framework, the linkage between a farming-SES and a landscape-SES (or regional-SES) occurs mainly through natural and social sub-systems of different SESs in the landscape. This is because, on one hand, the natural sub-systems of distinct SESs sharing the same landscape are linked through matter and energy flows. On the other hand, management decisions are made by rural people (human sub-system) who interact in formal and informal networks (social sub-system) that connect the social sub-system among different SESs (Figs. 5.1 and 5.2).

Thus, within each nested-hierarchical level of social-ecological systems, it is possible to identify similar types of sub-systems as described in Fig. 5.1. For example, all natural sub-systems of the farming-SESs constitute the natural sub-system of the landscape-SES (Fig. 5.2). On the other hand, farming-SESs are exposed to the effects of disturbance factors, which impact directly on a given sub-system, with potential indirect effects on other sub-systems that comprise that particular SES (Easdale and López 2016). In turn, these disturbance factors can affect another sub-system of a nearby SES in the landscape through a cascade effect or spatial contagion; for example, deforestation of the upper levels of a watershed promoting water erosion throughout the landscape (Bestelmeyer et al. 2012). These cross-scale interactions are exemplified at the end of the chapter, in a case study that describes a social-ecological conflict occurring in an agroforestry landscape, between different farming-SESs, with consequences at the landscape scale in the hills of Córdoba province (central Argentina).

## 1.4 Resilience Approach and Management

Managing for ecosystem or landscape resilience focuses on maintaining key processes and relationships in social-ecological systems so that they can resist (or recover from) a great variety of external or internal disturbances at a range of ecological and social scales. It also consists of actively maintaining a diversity of functions, steering systems away from thresholds of potential concern, increasing the ability of the system to maintain structuring processes and feedbacks under a wide range of conditions, and increasing the capacity of a system to cope with change through learning and adaptation. The reinforcement of resilience implies the need for adaptive management to reduce uncertainty that ultimately allows coping with unexpected disturbances and with complex, non-linear dynamics that arise from coupled social-ecological systems (Allen et al. 2011; Bestelmeyer and Briske 2012).

We argue that management practices of social-ecological systems should focus on the landscape level by using a resilience approach to reduce the vulnerability of AFS to environmental and/or anthropogenic drivers. To reach the landscape scale, we propose a nested-hierarchical framework centered around two critical analyses: (i) analysis of structural-functional diversity for each sub-system at the farm or household level (farming-SES); and (ii) interactions between different farming-SES at the landscape level, with potential cross-scale interactions of management decisions taken at farm- and landscape-scale levels.

First, at a farming-SES level, management practices should be aimed at increasing structural-functional diversity/functional types (Díaz et al. 2007; Lavorel et al. 2011), which in turn will increase the ability of each sub-system to respond to different drivers or disturbance factors, increasing overall SES resilience. At the landscape-SES level, management practices should be coordinated with other landscape users; for example, among farming-SESs, to avoid increasing vulnerability of farming-SESs sharing the same landscape or watershed, and to prevent degradation throughout the landscape (Bestelmeyer et al. 2012).

The landscape scale perspective has the advantage of assisting management decisions by analyzing the impacts that decision making at a farming-level can have at the landscape scale. This broad scale analysis should be aimed at decreasing landscape vulnerability and reinforcing landscape-SES resilience. In the next section, we use the nested-hierarchical framework introduced above to exemplify an alternative to reinforcing resilience of a landscape-SES, with a case study of a social-ecological conflict that emerged since the 1990s in agroforestry landscapes situated in the hills of central Argentina.

## 2 Resilience Management of Agroforestry Landscapes as a Way to Reduce Vulnerability

### *2.1 Natural Ecosystems of the Upper and Middle Watershed of Traslasierra*

Traslasierra is a region located in the Córdoba province, central Argentina (31° 55′ – 32° 01′S, 64° 55′ – 65° 03′W). This area is characterized by an environmental gradient determined by the presence of a mountain range called "Sierras Grandes y de los Comechingones", whose altitude oscillates between 2790 and 500 m.a.s.l. Mean annual precipitation decreases from >900 mm at the highest elevations to <500 mm westwards due to the rain shadow effect of the *sierras grandes (high mountains)*. Precipitation is prevalent in the austral spring and summer seasons (September – March) (Karlin et al. 1994; Demaio et al. 2002; Carranza 2009), however, droughts are also frequent during these seasons. Mean summer temperature is 17 °C and mean winter temperature is 8 °C at approximately 1000 m.a.s.l., increasing to 26 °C and 17 °C respectively on the western plains of the region. Temperatures below 0 °C are likely to occur throughout the year in the high mountains.

In this region, in the lowland forests (600–1300 m.a.s.l.) the tree layer is dominated by *Lithraea molleoides* (Anacardiaceae) and accompanying species such as *Zanthoxylum coco* (Rutaceae), *Geoffroea decorticans* (Fabaceae), *Celtis tala* (Cannabaceae), and *Prosopis torquata* (Fabaceae). On warmer and drier slopes (northern aspect) *Schinopsis marginata* (Anacardiaceae), *Ruprechtia apetala* (Polygonaceae) and *Acacia furcatispina* (Fabaceae) are the woody species that dominate. In the best preserved stands, *L. molleoides* density varies between 40 and 60 adult individuals per hectare (DBH 30–50 cm). The understory is dominated by shrubs species such as *Schinus fasciculatus* (Anacardiaceae), *Acacia spp.* (Fabaceae), and *Condalia* spp. (Rhamnaceae). Shrublands occur at mid altitudes (1300–1700 m.s.a.l.) and are dominated by *Heterothalamus alienus* (Asteraceae), which is accompanied by other small trees such as *Acacia caven* (Fabaceae) and shrubs of the *Schinus* genera (Anacardiaceae) (Luti et al. 1979). Above 1700 m.a.s.l. the highlands are dominated by grasslands with high density of grasses with about 80% of ground cover, with species of *Festuca*, *Setaria*, *Nassella*, *Paspalum* and *Jarava*. Intermingled in these highlands, forest stands and shrublands of *Polylepis australis* (Rosaceae) are restricted to ravines and gorges (Demaio et al. 2002; Cingolani et al. 2008).

## *2.2 People and Social-Ecological Systems Associated with the Natural Ecosystems of Traslasierra*

Since the seventeenth century the main economic activity of Traslasierra, where most of the lands were destined for pastoral use, was livestock grazing. Following a FAO classification (Hall et al. 2001) the productive activities consist of 'extensive dryland mixed farming systems' and 'forest based farming systems'. A great number of productive units and the majority of the rural population were rural households, which would constitute a system typology of farming-SES (Silvetti 2012) (Table 5.1). This traditional farming-SES has a diversified production system consisting of breeding sheep, goats, and cows using common grazing sites, aimed to supply products to local markets and for self-consumption. Their livelihoods are complemented with both multiple forest use and small scale agriculture (about 1–2 ha per farm) (Assadourian 1983; Tell 2008; Punta 2010; Silvetti 2012) (Table 5.1). Productive activities are conducted mainly in grasslands of the highlands, using them as grazing sites for domestic animals; and in the native forests of the lowlands, which provide timber and non-timber products. The trees of the native forest are mainly used for firewood, poles, domestic utensils, beams and braces. The native forests also provide non-timber products such as aromatic plants from herbaceous and shrubby species (e.g. *Lippia turbinata*, *Mintostachys mollis*, *Erioma multiflora*), fruits of native trees and shrubs (e.g. *Geoffroea decorticans* and *Condalia microphylla*), and honey. Peri-domestic areas are cultivated with vegetables (maize, leafy vegetables, pumpkins) and fruit orchards (peach, apple, quince, figs, walnuts and vines) mainly for self-consumption, and, if there are surpluses, for exchange at local fairs (Demaio et al. 2002; Silvetti 2012).

Since the 1990s new people have arrived at Traslasierra, causing an increase in urban settlements at the expense of rural areas. These extra-territorial social actors, who are absentee landowners in the territory, constitute a new farming-SES (*new rural settlers*), which uses the land for conservation, real estate business and/or tourist enterprises, with structural-functional features very different from farming-SES of *rural households* (Table 5.1). The increasing replacement of economic activities from the agroforestry sector towards activities related to tourism-service provision has been encouraged by local policies. These policies are generally framed under the assumption that tourism provides a local developmental opportunity favoring environmental conservation. However, tourism can have unexpected effects such as generating socio-environmental conflicts, causing rural migration and natural ecosystem degradation, fragmentation, and/or replacement (Kuvan 2012).

**Table 5.1** Structural-functional features of contrasting farming-SES typologies of Traslasierra-landscape

| Farming-SES[a] | Rural households-SES[b] | New rural settlers<br>Conservation-SES[b] | Tourism/Real estate-SES[b] |
|---|---|---|---|
| Natural sub-system | (a) Most of the farm is dominated by natural ecosystems that are being grazed, and by small areas destined to agriculture for self-consumption and to livestock pens. The diversity of native species is high-medium | (a) Natural ecosystems are protected for conservation purposes. High diversity of native species | (a) Natural sub-system is replaced by housing and recreation infrastructure.<br>Low diversity of native species, introduction of exotic species |
| | (b) High-medium levels of ecosystem functions | (b) High levels of ecosystem functions | (b) Medium-low levels of ecosystem functions |
| Human sub-system | (a) High diversity, with rural families of different age strata (from producers only, to families composed of more than three generations). High level of knowledge of their habitat and their natural cycles, and of the management of natural resources | (a) Low diversity. Few people (new extraterritorial actors), with knowledge of natural ecosystems and their cycles but without knowledge aimed to agro-productive activities. There is no appreciation of the ecosystem resources, and of all the goods and services that they provide | (a) Very low diversity. Very low level of knowledge about natural ecosystems and their associated cycles |
| | (b) High work capacity and learning ability. Cultural transmission between different generations. Social reproduction and autonomy. A strong dependence on the local natural environment, which is their habitat | (b) Low work capacity. Low labor requirements. Natural environment is perceived as source for aesthetics and recreation, and some support and regulation services | (b) High labor requirements. Local natural environment used for economic resources |
| Manufactured sub-system | (a) Diversified agroforestry structure | (a) Specialized in conservation and educational purposes; without agroforestry structure | (a) Tourism infrastructure (accommodation facilities, food and beverage facilities, accompanying facilities and communication facilities) |
| | (b) Diversified production; with infrastructures, machinery, stock and input for production: livestock, forestry, fruit-horticultural, and harvesting of non-timber forest products (honey, fruits, aromatic) | (b) Without productive capacity of agro-forestry goods | (b) Touristic services (tour guides, recreational and relaxation activities) |

(continued)

**Table 5.1** (continued)

| | | New rural settlers | |
|---|---|---|---|
| Farming-SES[a] | Rural households-SES[b] | Conservation-SES[b] | Tourism/Real estate-SES[b] |
| Social sub-system | (a) Diversified, with local social networks with many rural-family nodes, very interconnected (intra-family relations); and regional networks consolidated (local markets), in which they interact: rural families, inhabitants of towns and cities | (a) Few nodes across large land-surfaces. Low participation in local networks, but high participation in regional and global networks, because they are usually extra-territorial people and/or organizations. These are usually connected to networks from where they come from (e.g. cities) | (a) Social networks beyond territorial boundaries (tourism private consortia, hotel associations) |
| | (b) In the networks mainly they exchange goods and knowledge (information on conservation, management and use of its habitat). Low capacity to develop social networks beyond territorial boundaries. Social robust networks based on local interpersonal relationships | (b) In the networks mainly exchange knowledge about nature conservation | (b) Impersonal virtual networks (only over the internet) |
| Financial sub-system | (a) The financial capital is based mainly on the monetary valuation of all its infrastructure, stock of the agroforestry system | (a) Organizations (NGOs) that buy large fields with the purpose of nature conservation. Generally, these actors are inserted in the national and / or international community of nature conservation | (a) People or enterprises with high financial capital, which invest in the real estate market with the purpose of tourism and / or future investment |
| | (b) Mainly they obtain monetary funds by the commercialization of their products in local and regional markets | (b) Financial capital depends on external financing from national and international organizations | (b) Generally, these actors are inserted in the national and / or international financial macro-economic system. Their objective is to obtain income from the real estate market or tourism |

[a]It should be noted that in reality there may be a gradient of typologies between the two SES exemplified
[b]We exemplify the main of structural *(a)* and functional *(b)* features of each sub-system

## 2.3 Social-Environmental Conflicts

The arrival of new rural settlers at Traslasierra with real estate business, tourism development, and/or conservation purposes (Table 5.1) generated a conflict of interests between different farming-SES: the traditional rural households and the new rural settlers. The new landscape configuration caused field subdivision and enclosures, which excluded or complicated the access to grazing areas that once were of common pastoral use, and also restricted water availability to rural households who live in the lowland areas of the watersheds. The increase in tourism activities and the flow of new settlers generated, in turn, a real estate valuation that in many cases put pressure on traditional rural households to sell their lands, either partially or totally. The increase in the value of real state affected the traditional farming-SESs, generating changes in the configuration of the social networks of landscape-SES. This type of conflict has been described as a growing problem for other natural landscapes where agroforestry and tourism activities coexist (Easdale 2007).

## 2.4 Environmental and Social Drivers or Disturbance Factors

Drivers are factors or processes that control, regulate, or affect the dynamics of a system. Disturbance factors are triggers that produce significant and directional structural-functional changes on the farming-SES, eroding their biophysical and/or cultural legacy. Drivers can be endogenous (biotic interactions, grazing management) or exogenous (climatic cycles, price fluctuations in national or international markets). Drivers can regulate fluctuations associated with the dynamic equilibrium of an ecosystem state (Gunderson and Holling 2002). However, depending on their intensity, frequency, duration, and/or on their interaction with other drivers, a driver can cause significant changes in the structure and function of an ecosystem, and turn into a disturbance factor (e.g. grazing can change to overgrazing during dry years).

### 2.4.1 Environmental Drivers

**Wildfires** The Mediterranean climate of Traslasierra has dry winters and dry, warm, and windy springs. The native grasslands and shrublands in the mid-altitudes of the region produce fine fuels, which dry out during the winter and increase the fire risk during the warm and windy springs. This makes the landscape prone to fires (Alinari et al. 2015; Argañaraz et al. 2015a, b, c). Fires of low intensity, frequency, and extension, can be a modulator of the spatial-temporal dynamics of the landscape (Turner 2010). However, when the intensity, frequency, and/or extent of fire increases, fire becomes a disturbance factor that triggers ecosystem degradation; for example, erosion of the biophysical legacy such as soil loss and local species extinction (Kitzberger et al. 2016).

**Grazing** With proper livestock management, using moderate stocking-rate, rotations, and efficient protection of tree saplings against herbivory, grazing can regulate dry fuel loads through forage biomass consumption (i.e. it can have a driver function). But without appropriate management, this driver can behave as a disturbance factor, causing ecosystem degradation. Specifically, livestock grazing can constrain tree species regeneration in the lowland and highland forests, through trampling and browsing (Teich et al. 2005; Renison et al. 2015; Torres et al. 2008; Torres and Renison 2016).

**Climate Change** The increases in temperature and in the occurrence of drought events predicted by general circulation models could increase fire risk in Traslasierra (IPCC 2014; Argañaraz et al. 2015a, b), which could trigger degradation in agroforestry landscapes. This new driver is a disturbance factor, which directly affects the natural sub-system and propagates throughout the SES, through the human and manufactured sub-systems (Fig. 5.3).

### 2.4.2 Social Drivers

**Legislation** National and Provincial Laws (26,331 and 9814/2010, respectively) of Native Forest Protection have placed lowland forests under the maximum environmental protection category, which means that they can be only used for conservation and management. This law is a driver that regulates the management and conservation of forests and stops deforestation. These national and provincial laws constitute social agreements, and would be a structural attribute of the social subsystem of the regional-SES which promotes processes of change in forest management and conservation (Fig. 5.2).

**Demographic Trends** Since the 1990s, there has been significant population growth which caused the expansion of urban settlements at the expense of native lowland forests. The urban sprawl occurred without strategic planning, increasing the urban-forest interface. This new driver is a disturbance factor which affects the natural sub-system both at the farm-SES and landscape-SES level in two ways: (i) replacing the lowland native forests with housing infrastructure; and (ii) increasing the urban-forest interface, which can increase the occurrence of human-set fires (Argañaraz et al. 2015a, b).

**Real Estate Pressure** The increase in the value of Traslasierra lands drives a change of social actors, and thus in dominant economic activities, causing rural-urban migration and land tenure changes. Many farmers sell their lands due to the growing restrictions to their productive activities, and because they have less negotiation capacity to deal with high land prices (see "transition from agroforestry systems to tourism-real estate systems", Easdale 2007; Rainer 2016; Easdale 2007). This kind of disturbance factor presses on the traditional farming-SES through the financial sub-system, generates changes in the configuration of social networks (social sub-system of landscape-SES), and promotes replacements of farming-SES, from rural households to new rural settlers (Table 5.1, Fig. 5.2).

### 2.5 Interactions Among Drivers and Landscape Vulnerability

The aforementioned environmental and social drivers have all occurred in the same landscape, increasing its vulnerability to fire, and compromising the persistence of native forests of low- and high-lands. When vegetation is burned in these landscapes with steep slopes, the soil is exposed, increasing the probability of soil erosion during the wet season (summer). Thus, a degradation process of the ecosystems may be triggered. Fire vulnerability increases mainly due to a higher exposure of the system to this disturbance factor, which is caused by distinct drivers such as the increase in urban-forest interface and the fine fuel loads from biomass accumulation in non-grazed grasslands, as well as by climate change, among others. These drivers can cause indirect and unexpected effects at the landscape level.

### 2.6 Cross-Scale Interactions Between Farmers' Decisions on Agroforestry Landscape Activities

The arrival of new rural settlers to Traslasierra could directly affect the livelihoods of rural households, mainly through grazing exclusion in lands subjected to tenure change (Fig. 5.3a). Traditional grazing areas of rural families were greater than their own fields, as grazing in natural grasslands had historically been the common practice used in communal lands. Therefore, field enclosure significantly decreased pastoral areas of rural households and eliminated the traditional common use of the territory.

Decisions taken at the farm level by new rural settlers directly affect the natural sub-system, and indirectly affect the manufactured and human sub-systems of rural households, respectively (Fig. 5.3a). This is because a decrease in the forage biomass available for livestock consumption compromises the productive activities of rural households, affecting their income and livelihood. This conflict can have two consequences: on one hand, it can promote migration of those farmers whose livelihoods have been affected, to peripheral areas of urban settlements, excluding several traditional farming-SES from the landscape and thus directly affecting the manufactured and social sub-systems of landscape-SES. On the other hand, this process can also cause an increase in the grazing pressure on grassland and forests, on land belonging to farmers who remain in the territory and depend on livestock for subsistence. The reduction of traditional grazing areas can increase grazing pressure on the lowland forests, thereby affecting tree species regeneration and compromising native forest persistence in the long term. This degradation of the natural sub-system can thus affect the structure and function of the manufactured subsystem of some farming-SES, because the carrying capacity of the fields of the rural households is reduced, directly impacting on livestock production (Fig. 5.3a).

These unexpected cross-scale effects are due to farm-centered management decisions, without taking into account landscape or regional consequences (Fig. 5.3a).

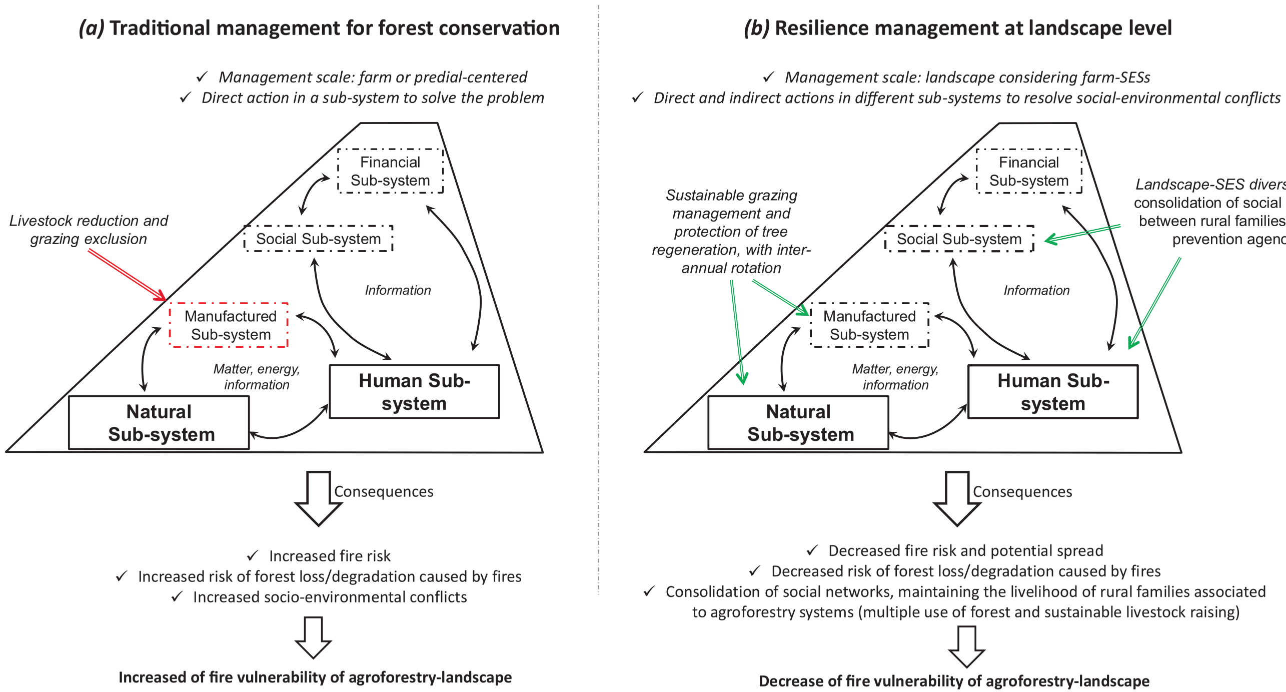


**Fig. 5.3** Schematic representation of decision-making in Social-Ecological System (SES) under: farm-centered decision making (**a**) and a resilience approach at the landscape level (**b**). Traditional management (**a**) implies direct actions on a sub-system of farming-SES (grazing exclusion in grassland areas) without considering indirect effects in other sub-systems of the same farming-SES or other farming-SES (e.g. reduced quality of livelihoods of household, or overgrazing on forestland); and may ultimately promote an increase in fire vulnerability of the agroforestry landscape (e.g. increase of fine fuel from grassland, without rural households that can prevent and/or combat the fires). Decision making in resilience approach at landscape level (**b**) contemplates direct and indirect actions on different sub-systems of SES (e.g. natural, human, and social sub-systems) and at different scales (e.g. between farming-SESs), aimed at increasing forest conservation and reducing fire vulnerability in agroforestry landscapes

In other words, management actions taken at a farm-scale can have indirect and unexpected effects at a landscape scale. For instance, farm-centered logic of the new rural settlers maintains tree species regeneration by avoiding livestock grazing in forest areas. However, this practice can indirectly affect other sub-system components of landscape-SES such as (i) an increase in socio-productive vulnerability of rural households whose livelihoods depend on native grasslands and forests; and/or (ii) an increase of fire risk at the landscape level, due to a higher availability of fine fuel loads in grasslands caused by the significant decrease in the consumption of grass biomass (Fig. 5.3a). Finding solutions to these socio-environmental conflicts requires approaches at landscape scales, considering the interactions between farming-SESs that coexist in the same landscape or territory.

### *2.7 Resilience Management at the Landscape Level*

The scenario of increased fire vulnerability of AFS in Traslasierra raises the need to manage the resilience of SES at farm- and landscape-scales, aimed at reducing their vulnerability. SES resilience at the landscape-scale could be reinforced by strengthening not only the capacities of rural households (e.g. enhancement and/or building their ability to respond to disturbance factors), but also the social networks, which allow them to anticipate and/or adapt to change (Gunderson and Holling 2002; Peterson et al. 2003; Adger 2010; Allen et al. 2011). This requires the diversification and/or strengthening of farming-SES, focusing on both the human sub-system, by increasing people's knowledge and equipment skills to improve their ability to prevent and combat fires, and the social sub-system, by building trust, consolidating and diversifying social networks, with new nodes and/or links among nodes (Easdale and López 2016) (Fig. 5.3b).

In Traslasierra, a social network is being conformed as a self-organizing process (Consorcio Champaquí[2]), where rural households interact with volunteer firefighters located in urban areas, and with other inhabitants of urban-tourist areas. In these social networks, rural households and urban inhabitants were trained and equipped in the prevention and control of forest fires by fire control agencies (Bomberos Voluntarios de Villa de Las Rosas[3]). Thus, in the social sub-system of the landscape-SES, new social-networks were conformed, with new nodes and interactions between them, where the human sub-system acquired new knowledge that gives it greater ability to respond to disturbance factors such as recurring fires (Fig. 5.3b).

Also, the collective and committed work of the "Consorcio Champaquí" has built a system of water reserves at strategic points located in the mountains where water is scarce. The water reserves have many purposes: they supply water to firefighting helicopters and to forestry firefighters, e.g. the infrastructure of manufac-

[2] http://inta.gob.ar/sites/default/files/script-tmp-inta_fortalecimiento_del_consorcio_champaqui_prevenci.pdf

[3] http://www.bomberosra.org.ar/bomberos/863-bomberos-voluntarios-de-villa-de-las-rosas

tured sub-system reinforces the functionality of human and social sub-system at the landscape-SES level. They also supply water to small agroforestry farmers to support their productive activities, e.g. strengthening the structure in manufactured sub-system of the farming-SES improves its agroforestry production and livelihoods. Consequently, rural households and other local people, working together with control agencies, play a crucial role in the prevention and control of forest fires. Rural households are dispersed along the territory where natural or human-set fires generally start, therefore they are essential for early fire detection. Moreover, because of their close link with mountainous environments, they have a detailed knowledge of the landscape and its topographic features, which helps them in identifying trails that allow them to reach risky areas for fire control.

From a landscape-scale management, it is essential that rural farmers stay in their lands. Therefore, keeping agro-productive activities is a key policy issue, which can be promoted by allowing the access of their livestock to traditional grazing areas, as in lands sold for non-agroforestry purposes, such as for real estate or tourism. In this context, adaptive management strategies aimed at enhancing resilience to fire should focus on: (i) achieving grazing agreements between the distinct farming-SESs that coexist in the same landscape, which in turn will decrease fine fuel loads in natural grasslands; and (ii) consolidating social networks among different stakeholders for fire control and prevention. This type of landscape management will reduce the vulnerability of agroforestry landscapes to fire, because it reinforces the resilience of the landscape-SES, increasing the ability to prevent and/or to control fire outbreaks, and also decreasing the occurrence of fires in grasslands. Finally, since grazing may limit tree species regeneration, the subsidies granted by the National Forest Protection Law N° 26,331 should be used to install enclosures restricted only to *Polylepis australis* stands, and to plan management practices that promote *Lithraea molleoides* regeneration, to ensure the persistence of low- and high-land forests.

## 3 Conclusions

Decisions involving management and conservation of biodiversity, provision of ecosystem services, and human well-being are complex. These decisions may rely on poorly understood processes that involve conflicts of interests and values among different groups in society. There are a wide variety of contexts in which decisions concerning ecosystem services are made. Including relevant conflicts and contexts in landscape management and/or governance requires different types of models and scenarios that can identify how social and ecological changes alter ecosystem dynamics and thus, human well-being.

Decisions are made within both social and ecological contexts. The social context includes why a decision is being made, who is making the decision, and whether that decision maker or decision making body is considered legitimate. The ecological context is shaped by the properties of ecosystem services and biodiversity being decided upon, and whether the decision is a one-off decision or part of a stream of interconnected decisions. The development and implementation of policies and practices that ensure the flow of ecosystem services to people requires that decisions are made in a social context, reducing vulnerability of social-ecological systems.

In a scenario where social-environmental conflicts are increasingly frequent, resilience management approaches at the landscape level should be used as a tool for resolving such conflicts. On the contrary, the search for solutions through decision making centered at the farming level may have direct, indirect, and unexpected effects on other SES in the landscape. Thus, integrating the local- or farming-scale perspective with a landscape-scale perspective could be useful in increasing the SES's resilience and reducing its social-environmental vulnerability. The resilience management approach of SES raises the need to evaluate trade-offs between management decisions or environmental and agricultural policies at different scales. The resilience management approach poses the challenge of thinking and planning which agroforestry landscapes society needs, in a context of uncertainty associated with climate change and an increase in anthropogenic pressure on natural ecosystems.

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# Part II
# From Subsistence to Market Oriented Systems

# Chapter 6
# Energy Analysis of Coffee Production Systems: Implications for Environmental and Economic Sustainability

**Carl F. Jordan**

## 1 Evolution of Coffee Production Systems

Until the late 1940s, coffee in Latin America was grown by the "traditional" method, that is, as an understory bush beneath tall, mixed forest trees. Coffee grown in this type of agroforestry system is "shade-grown coffee". In the early 1950s, there began a movement to modernize coffee production by planting varieties that are more resistant to coffee leaf rust. These varieties were adapted to growing in full sun, and are known as "sun-grown coffee". This system is characterized by increased reliance on high-yielding varieties, and an increase in chemical inputs, pruning, and coffee plant density (Perfecto et al. 1996). However, concerns about soil erosion, pesticide use, and loss of biodiversity in sun plantations have raised questions about the sustainability of sun-grown coffee plantations.

## 2 Objectives

Sustainability can be looked at from an environmental or an economic perspective. Environmental sustainability concerns soil erosion, nutrient depletion, and chemical pollution. Economic sustainability concerns the balance between monetary gains and losses for the local grower, the local community, and the national economy.

C. F. Jordan (✉)
Odum School of Ecology, University of Georgia, Athens, GA, USA
e-mail: cfjordan@uga.edu



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### 2.1 Objectives

The objectives of this chapter are:

- to compare environmental sustainability of several types of coffee production systems.
- to examine how the source of energy inputs to coffee systems affects economic sustainability at three hierarchical economic levels: local growers, local communities, and the national economy.

## 3 Energy Use Efficiency

All economic production systems including agriculture require inputs to produce outputs. Energy use analysis (Odum and Odum 1981) has been used to determine the efficiency with which input energy in the form of fertilizers, pesticides, and fuel is used to produce output energy in the form of food under different management and environmental conditions (Black 1971; Steinhart and Steinhart 1974; Cox and Atkins 1979; Fluck and Baird 1980; Pimentel and Pimentel 2008; Gelfand et al. 2010). When inefficiently used fertilizers contaminate streams, fertilizers become pollution. When inefficiently used pesticides kill beneficial insects, pesticides become pollution. Because wasted energy becomes pollution, energy use efficiency is useful for evaluating the environmental impact of various agricultural management strategies (Jordan 2016).

### 3.1 Agroforestry as a Thermodynamic System

Determination of energy use efficiency requires conceptualizing production ecosystems as thermodynamic systems that convert input energy into yield or its energy equivalent. There are two types of energy conversions in ecological thermodynamic systems (Giampietro 2004):

- Endosomatic, meaning conversions resulting from energy whose source is within a system. Endosomatic energy dissipates within its system of origin and therefore has no environmental impact.
- Exosomatic, meaning energy subsidies resulting from inputs originating outside of a system. The energy efficiency ratio (energy out/energy in) as an index of sustainability uses only exosomatic energy as an input. Inefficiently used subsidies are a cause of stress for the receiving system (EP Odum et al. 1979). Although sunlight energy originates outside an agricultural system, it is not a subsidy but rather the energy flux being subsidized.

## *3.2 Hierarchical Systems*

Energy flow in ecosystems and dollar flow in economies can be represented by a series of hierarchical levels, each one embedded in a higher level. As a result, energy that is endosomatic at one hierarchical level can be exosomatic at another level. Three hierarchical levels of coffee production systems examined in this chapter are: traditional agroforestry; organic agroforestry; sun plantation monocultures.

### 3.2.1 Traditional Agroforestry (Hierarchical Level – The Traditional Farm)

A traditional agroforestry system consists of a subsystem (traditional farm) embedded in the local economic community (Fig. 6.1). The farm consists of overstory trees, coffee bushes, and the community of soil organisms. An internal loop of energy flow runs from the overstory trees through the soil community to the coffee bushes and back to the overstory trees.

- Endosomatic energy in the agroforestry plots refers to energy conversions linked to physiological processes within the soil-crop system. Sunlight is intercepted by overstory trees and coffee bushes, and is transformed through photosynthesis to biomass of the trees and bushes, and to coffee cherries. Endosomatic energy is transferred from the overstory trees to the soil community by way of litter fall

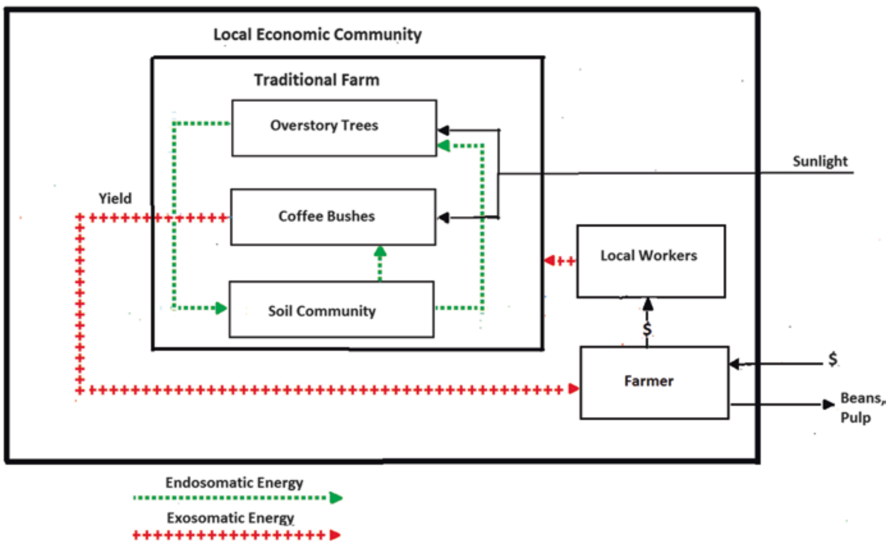


**Fig. 6.1** Energy flow through a traditional agroforestry coffee production system embedded in a local economic system

and root sloughing (Carrillo et al. 2011). Litter and dead roots are the energy source for the community of soil microorganisms that recycle nutrients into the coffee bushes and overstory trees. This feedback maintains the function of the ecosystem. In thermodynamic terms, the system is autocatalytic since the feedback is mediated by a naturally occurring mechanism.

- Exosomatic energy consists of labor for weeding and pruning by local workers to maintain structure of the system. Yield from the coffee bushes becomes exosomatic input to the traditional farm when it is converted to energy emanating from the local workers.

### 3.2.2 Organic Agroforestry (Hierarchical Level – The Local Economic Community)

The organic system (Fig. 6.2) is a local economic community in which organic agroforestry plots are embedded. A feedback loop consists of money from the sale of coffee beans that is used to pay local workers.

- Yield from the coffee bushes becomes endosomatic energy for the local economic community when part of the yield becomes pulp used as input into the organic plots, and part goes to the farmer to pay workers for separating pulp from beans and for weeding and pruning the agroforestry plots.
- For the organic plots and the local economic community in which the organic plots are embedded, mineral supplements are exosomatic inputs. They originate outside the local community.

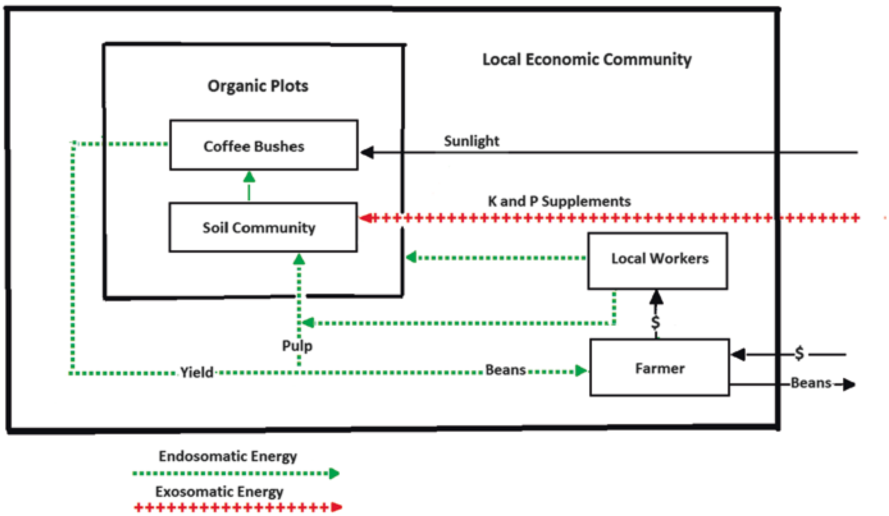


**Fig. 6.2** Energy flow through a local economic community producing organic coffee

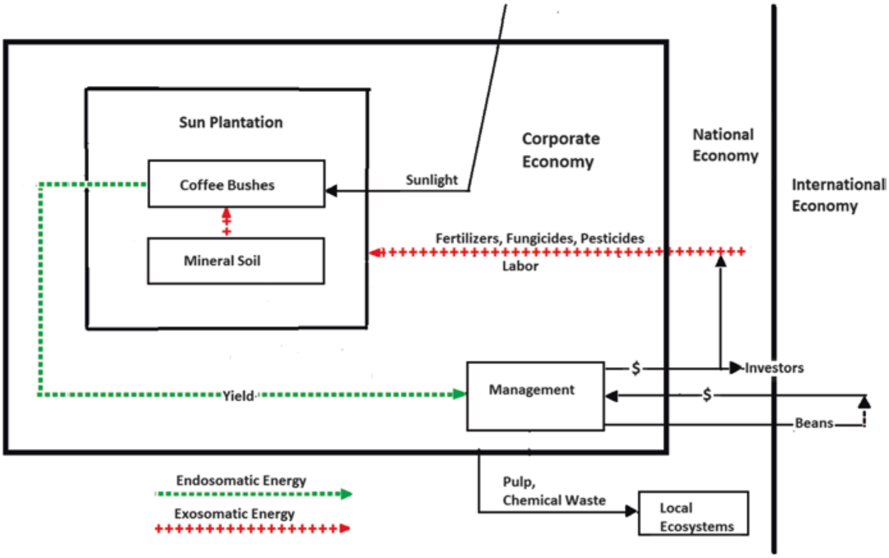


**Fig. 6.3** Energy flow through a corporate economy that embeds a sun coffee plantation

### 3.2.3 Sun Coffee Plantation (Hierarchical Level – The Corporate Economy)

Sun coffee plantations represent large scale, industrial type agriculture managed by a corporation or large scale producer (Fig. 6.3). They are characterized by high energy inputs, and are not really agroforestry systems because all trees and shrubs other than the coffee bushes have been removed. There are no internal feedback loops to produce or sustain nutrient recycling. The corporate economy is closely linked to the national and international economy. The local economic community has little involvement.

- When the beans are sold internationally, yield from the coffee bushes becomes endosomatic energy for the national economy. A feedback loop occurs at the national level.
- Exosomatic inputs include fertilizers, pesticides, fungicides, and petroleum that fuels mechanical cultivation.

## 4 Environmental Sustainability

A 10 year study comparing five coffee production systems was carried out at Centro Agronómico Tropical de Investigación y Enseñanza (CATIE) Turrialba, Costa Rica beginning in 2000 (Rossi et al. 2011; Virginho Filho et al. 2015). Data from these studies can be used to compare environmental sustainability of the systems, when energy use efficiency is used as an index of environmental sustainability. High energy use efficiency means that a relatively low proportion of input energy goes toward pollution and ecosystem degradation.

## *4.1 The Coffee Management Study at Turrialba, Costa Rica*

The five systems evaluated in the project were:

- Full sun, intensive chemical fertilization
- Full sun, moderate chemical fertilization
- Agroforestry system, intensive chemical fertilization
- Agroforestry system, moderate chemical fertilization
- Organically managed agroforestry system (coffee pulp and chicken manure for nutrient inputs)

### 4.1.1 Energy Flow Through the Organic and Sun Coffee Systems

The organically managed agroforestry system (Fig. 6.2) differed from a traditional agroforestry system (Fig. 6.1) in an important way. The organic agroforestry research was started in abandoned fields of a sugar cane plantation. The trees that eventually would become overstory were seedlings at the time the experiment started. Thus there was little endosomatic feedback from leaf litter and root decomposition as occurs in traditional systems. Endosomatic feedback in the organic system occurs at the community level, where pulp inputs to the cropping system play the same role as decomposed leaf and root litter in the mature traditional system. The labor to process the pulp and to weed the production plots is also endosomatic energy, since the workers are internal to the local community.

Exosomatic energy in the organic system consists of the potassium and phosphorus supplements. Fuel to run the pulping machine that separates the pulp from the coffee beans is also an exosomatic input, but no data are available. In the sun coffee system (Fig. 6.3), all energy inputs are exosomatic. Input subsidies in the form of fertilizers are brought in from outside the system to replace the nutrients that are lost due to coffee harvest, nutrient leaching, and volatilization. Labor crews are exosomatic when they are hired temporarily for weeding and harvesting. Labor was not measured. While land is often considered along with labor and capital as a factor of agricultural production, land (the organic matter content of the soil) is an energy stock, not an energy flow and thus does not contribute to the energy efficiency ratio. However, the stock performs a buffering role, in that the size of the stock on a unit area basis determines the stability of the energy flow.

### 4.1.2 Energy Use Efficiency and Yield of the Organic and Sun Coffee Production Systems

Data on nutrient energy inputs from the Turrialba research can be used to compare the energy use efficiency and yield of coffee production systems. The first step is to determine the energy content of nutrient inputs (Table 6.1).

The next step is to calculate the nutrient energy input per hectare for the management systems, as in Table 6.2.

For the high intensity chemical systems, input is 5.36 Gj/ha/year, and for the medium intensity, 2.68 Gj/ha/year. These are exosomatic inputs. The pulp and manure energy inputs into the organic system are 25.0 Gj and 22.6 Gj respectively. These are endosomatic inputs.

The endosomatic nutrient-supplying pulp and manure inputs for the organic system are energetically five to ten times higher than the exosomatic energy inputs for the sun coffee systems. In the sun coffee system, the pulp energy is disposed of into the environmental commons where it can become pollution. In the organic system it is recycled.

Exosomatic nutrient energy input for the organic system is 0.502 Gj/ha/year (the subtotal chemical for organic systems in Table 6.2) and a factor of 10 lower than the

**Table 6.1** Energy values for fertilizer inputs

| Type of input | Energy value of input |
|---|---|
| Coffee pulp | 12,501 Kj/kg Cubero-Abarca et al. (2014) |
| Poultry manure | 12,052 Kj/kg Quiroga et al. (2010) |
| Nitrogen fertilizer | 42 Mj/kg Hulsbergen et al. (2001) |
| Phosphorus fertilizer | 15.8 Mj/kg Hulsbergen et al. (2001) |
| Potassium fertilizer | 9.3 Mj/kg Hulsbergen et al. (2001) |
| Total NPK | 67 Mj/kg |

**Table 6.2** Energy inputs into the production systems

| Management type | Intensity of input | Gross input/ha/year | Conversion factor | Net input/ha/year | Energy content | Energy input/ha/year |
|---|---|---|---|---|---|---|
| Chemical (sun monoculture) | High | 800 kg fertilizer | 10%[a] | 80 kg | 67Mj/kg | 5.360 Gj |
| | Medium | 400 kg fertilizer | 10%[a] | 40 kg | 67Mj/kg | 2.680 Gj |
| Organic | Medium | 20 T, coffee pulp | 10%[b] | 2000 kg | 12,501 KJ/kg | 25.0 Gj |
| | | 7.5 T, manure | 25%[c] | 1880 kg | 12,052 KJ/kg | 22.6 Gj |
| | | 200 kg $PO_4$ | 10%[a] | 20 kg | 15.8 Mj/kg | 0.316 Gj |
| | | 200 kg K | 10%[a] | 20 kg | 9.3 Mj/kg | 0.186 Gj |
| | | | | | Subtotal chemical | 0.502 Gj |
| | | | | | Sum organic | 48.102 Gj |
| | Low | ½ Medium input | | | | 24.051 Gj |

[a]Assume 10-10-10 fertilizer
[b]Pulp is 90% water
[c]Chicken manure is 75% water

**Table 6.3** Yields and energy use efficiencies of the experimental systems

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|
| Overstory species | Management | Chemical energy input (Gj/ha) | Yield in 2007 kg/ha × $10^3$ | Energy use efficiency[a] col.4/col.3 | Yield, 10 year. average kg/ha × $10^3$ | Energy use efficiency[a] col. 6/col. 3 | Rank |
| *Erythrina poeppigiana* | Organic – Low intensity | 0.251 | 8.300 | 20.2 | 1.437 | 5.72 | 1 |
| *Erythrina poeppigiana* | Organic – Med. Intensity | 0.502 | 8.000 | 9.76 | 1.840 | 3.66 | 2 |
| *Terminalia amazonia* | Organic – Low intensity | 0.251 | 3.800 | 9.27 | 0.892 | 3.55 | 3 |
| *Terminalia amazonia* | Organic – Med. Intensity | 0.502 | 11.700 | 14.27 | 1.680 | 3.35 | 4 |
| Full sun monoculture | Chemical – Med. Intensity | 2.680 | 13.700 | 5.27 | 1.921 | 0.72 | 5 |
| *Erythrina poeppigiana* | Chemical – Med. Intensity | 2.680 | 6.100 | 2.28 | 1.407 | 0.53 | 6 |
| *Terminalia amazonia* | Chemical – Med. Intensity | 2.680 | 7.900 | 2.95 | 1.321 | 0.49 | 7 |
| *Erythrina poeppigiana* | Chemical – High intensity | 5.360 | 11.700 | 2.18 | 2.387 | 0.45 | 8 |
| Full sun monoculture | Chemical – High intensity | 5.360 | 13.800 | 2.57 | 2.376 | 0.44 | 9 |
| *Terminalia amazonia* | Chemical – High intensity | 5.360 | 7.900 | 1.47 | 1.826 | 0.34 | 10 |

[a]Exosomatic energy only

exosomatic input for the high intensity chemical system. The low exosomatic input in the organic systems results in relatively high energy use efficiencies. Table 6.3 gives the yield, and the ratio (coffee yield)/(exosomatic energy input) of these systems. Since the desired output of these systems is coffee beans, not energy, kg of yield is substituted for energy-out in the ratio of energy use efficiency. Systems are ranked top to bottom from highest ratio (most efficient) to lowest ratio (least efficient) from the 10 year. average data.

- Yields: Yields in the full sun monocultures and chemical input agroforestry systems averaged slightly higher than yields in the organic systems. High intensity chemical inputs for non-organic systems resulted in higher yields than medium intensity inputs. There was no yield advantage in chemical agroforestry plots compared with full sun monocultures. Since the trees were newly planted, an advantage may develop as the trees mature.

- Energy Use Efficiency: Energy use efficiency in the organic systems was always higher than that in the full sun and chemical agroforestry systems. The high energy use efficiency of the organic coffee systems suggests that organic systems provide greater environmental sustainability than systems that must import large amounts of fertilizers to maintain production.

The Audubon Society Shade-Grown Coffee Project (2004) reported that yields from shade grown coffee averaged 550 kg/ha, or about one third the yield of sun-grown coffee. Yields from the organic agroforestry systems at Turrialba were considerably higher than world-wide averages for shade-grown coffee. Differences are due in part to the quality of feedback from the soil to the plants. The high values for the Turrialba organic plots were probably a result in part of the high nutrient availability in coffee pulp and manure. The nutrient availability in organic matter in shade-grown coffee is lower, due to the high content of secondary plant compounds that are difficult for bacteria to metabolize.

### *4.2 Sun Coffee Following Deforestation*

The Turrialba plots were established on an abandoned sugar cane plantation, thus levels of soil organic matter were relatively low. When land to establish a conventional agroforestry system is cleared to produce higher yielding sun coffee, the bushes can take advantage of the residual organic matter stock in the soil from decomposing humus and the roots of overstory trees. Energy use efficiency will be high for a few years, and exosomatic energy inputs can be low. However, after a few years when this organic matter oxidizes and is not replenished, exosomatic inputs must rise to maintain high yield. Energy use efficiency in the sun plantations will decrease rapidly due to the disappearance of endosomatic energy feedback.

## 5 Economic Sustainability

An energy analysis cannot predict economic sustainability for coffee production systems. Energy analysis also cannot predict the economic costs and benefits from a particular coffee production system. However, it can always predict which type of system will give the greatest profit (or least loss) from investment, as prices of coffee and cost of inputs vary. (Yield)/(energy-input) ratios are constant for a particular environment, and are not affected by economic variables. They can be better indicators of which management system will give the highest net return on investment (profit) for a particular environment. Table 6.4 and Fig. 6.4 use yield and energy input data from Table 6.3 to illustrate how changes in price of coffee and cost of

**Table 6.4** Income per hectare and return on investment (profit/cost) of sun, organic, and shade coffee as a function of coffee price and input costs

| Economic trend | Manage-ment system | Price/Kg yield $ | Yield Kg/ha × $10^3$ | Income $ from Units Produced | Energy cost $/Gj | Energy input Gj/ha × $10^3$ | Cost/ha $ | Profit/ha $ | Profit/cost |
|---|---|---|---|---|---|---|---|---|---|
| Coffee prices going up | Sun | 2 | 1.921[a] | 3,842 | 3 | 2.680[a] | 8,040 | −4198 | – |
| | Organic | 2 | 1.840[b] | 3,680 | 3 | .502[b] | 1,506 | 2174 | 1.44 |
| | Sun | 5 | 1.921 | 9,610 | 3 | 2.680 | 8,040 | 1570 | 0.20 |
| | Organic | 5 | 1.840 | 9,200 | 3 | 0.502 | 1,506 | 7694 | 5.11 |
| Turrialba | Sun | 10 | 1.921 | 19,210 | 3 | 2.680 | 8,040 | 11,170 | 1.39 |
| | Organic | 10 | 1.840 | 18,400 | 3 | 0.502 | 1,506 | 16,894 | 11.22 |
| Coffee prices going up | Sun | 2 | 1.600 | 3,200 | 3 | 2.680 | 8,040 | −4840 | – |
| | Shade | 2 | 0.550 | 1,100 | 3 | 0.502 | 1,506 | −406 | – |
| | Sun | 5 | 1.600 | 8,000 | 3 | 2.680 | 8,040 | −40 | – |
| | Shade | 5 | 0.550 | 2,750 | 3 | 0.502 | 1,506 | 1244 | 0.83 |
| World average | Sun | 10 | 1.600 | 16,000 | 3 | 2.680 | 8,040 | 7960 | 0.96 |
| | Shade | 10 | 0.550 | 5,500 | 3 | 0.502 | 1,506 | 3994 | 2.65 |
| Input costs going up | Sun | 5 | 1.921 | 9,610 | 1 | 2.680 | 2,680 | 6930 | 2.59 |
| | Organic | 5 | 1.840 | 9,200 | 1 | 0.502 | 502 | 8698 | 17.33 |
| | Sun | 5 | 1.921 | 9,610 | 3 | 2.680 | 8,040 | 1570 | 0.20 |
| | Organic | 5 | 1.840 | 9,200 | 3 | 0.502 | 1,506 | 7694 | 5.11 |
| Turrialba | Sun | 5 | 1.921 | 9,610 | 6 | 2.680 | 16,080 | −6470 | – |
| | Organic | 5 | 1.840 | 9,200 | 6 | 0.502 | 3,012 | 6188 | 2.05 |
| Input costs going up | Sun | 5 | 1.600 | 8,000 | 1 | 2.680 | 2,680 | 5320 | 1.99 |
| | Shade | 5 | 0.550 | 2,750 | 1 | 0.502 | 502 | 2248 | 4.48 |
| | Sun | 5 | 1.600 | 8,000 | 3 | 2.680 | 8,040 | −40 | – |
| | Shade | 5 | 0.550 | 2,750 | 3 | 0.502 | 1,506 | 1244 | 0.83 |
| World average | Sun | 5 | 1.600 | 8,000 | 6 | 2.680 | 16,080 | −8080 | – |
| | Shade | 5 | 0.550 | 2,750 | 6 | 0.502 | 3,012 | −262 | – |

[a]Data from full sun monoculture, medium chemical intensity plot in Table 6.3 (10 year average)
[b]Data from *Erythrina poeppigiana*, organic medium intensity plot in Table 6.3 (10 year average)

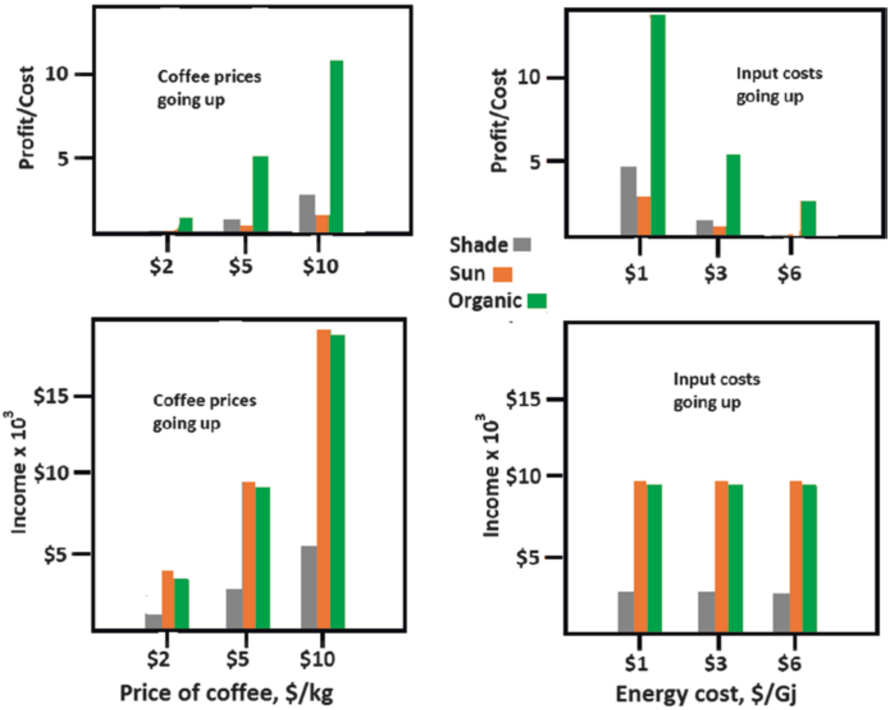


**Fig. 6.4** Changes in income and return on investment (profit/cost) for sun, organic, and shade coffee systems as coffee prices increase and as costs of inputs to the production system increase

chemical inputs affects income and return on investment (profit/cost) for selected sun, organic, and shade-coffee systems. The comparison of sun-grown coffee with organic coffee is from data of the Turrialba study. The traditional shade-grown and sun-grown yield comparison is from world data of the Audubon Society Shade-Grown Coffee Project (2004).

Price per Kg yield of coffee beans times yield in Kg per hectare equals income per hectare. Chemical energy cost times chemical energy input per hectare gives exosomatic energy cost per hectare. Chemical energy input costs for world average sun and shade were taken to be the same as for sun and organic coffee in the Turrialba study. Profit per hectare is income minus costs. Profit/cost indicates a farmer's net return on investment.

Indicated values for price of coffee and costs of input are arbitrary. They do not necessarily reflect prices and costs at any point in time. They are used only to show how income and profit are affected by trends in prices and costs. Substituting other values will change income and profit, but will not change trends.

## 5.1 Economic Trends

In both the Turrialba and world average data sets, sun-grown coffee always produced the greatest income regardless of prices or costs because sun coffee produced the greatest yield. However, organic and shade coffee always had a higher profit/cost ratio (net return on investment) than sun-grown coffee, since costs were always lower for shade and organic coffee.

## 5.2 Effect of Energy Sources on Economic Factors

### 5.2.1 When the Main Source of Energy for the Coffee Production System Is Within the Production Plot Itself

This is the case for traditional agroforestry systems, where feedback energy comes from leaf and root litter of the overstory trees. Characteristics of the system are: relatively low production; relatively low opportunity for local labor; relatively low support for the local community and local economy; low income but high return on investment.

### 5.2.2 When the Main Source of Energy for the Coffee Production System Is Within the Local Community

This is the case for the organic production system, where feedback energy comes from local labor, and the coffee pulp and chicken manure that have their source within the local community. Characteristics of the system are: relatively high production; high opportunity for local labor to collect, process, and spread inputs; relatively high support for the local community and local economy; income close to that of sun systems, but higher return on investment.

### 5.2.3 When the Main Source of Energy for the Coffee Production System Is Outside the Local Community

This is the case for sun coffee. Fertilizer inputs come from outside the local community. Characteristics of the system are: high production; low opportunity for local labor; low support for the local community and local economy; high income but low return on investment.

### *5.3 Feedback and Sustainability*

Internal feedback of endosomatic energy determines the sustainability of each hierarchical level. The traditional agroforestry system has nutrient cycling feedback within the plot itself. It is autocatalytic and thus its environmental sustainability is high. It would be the choice for an individual farmer having little capital. Organic coffee also is autocatalytic. It optimizes local economic sustainability through the energy feedback loop provided by local workers, and environmental sustainability through the nutrient feedback provided by pulp. Sun coffee would be the choice of a government wanting to increase exports to improve international balance of payments. However, the sun coffee system has no autocatalytic feedback that maintains environmental sustainability.

## 6 Conclusions

### *6.1 Environmental Sustainability*

Energy use analysis shows that traditional and organic coffee production systems are more environmentally sustainable than sun-grown systems because of the presence of internal energy recycling loops. Internal recycling builds up stocks of soil organic matter that nourish soil micro-organisms.

### *6.2 Economic Sustainability*

The profit/cost ratio determines the economic sustainability of each hierarchical level. The degree of sustainability depends on the relative contributions of "free" endosomatic energy and energetically expensive exosomatic energy. Shade-grown coffee has a high proportion of endosomatic energy, and thus promotes sustainability for the local grower. Organic coffee also has a high proportion of endosomatic energy, and thus promotes economic sustainability for the local community. There are no endosomatic energy feedbacks within the corporate sun system. Sustainability depends on low costs of exosomatic inputs and high international coffee prices.

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# Chapter 7
# Indigenous Successional Agroforestry: Integrating the Old and New to Address Food Insecurity and Deforestation

**Asha Bertsch**

## 1 Introduction

As we prepare our planet to feed a projected nine billion people by 2050 (Ash et al. 2010), our need for arable land increases, as does the threat of deforestation and forest degradation. As we face this challenge, it is crucial to consider and explore agricultural innovations that improve nutritional security and support rural livelihoods, restore degraded landscapes, and protect biodiversity. Land degraded by unsustainable agricultural practices is insufficient for future agricultural use. This renders former arable land inoperable, and encourages deforestation through demand for new farmland (Howard and Homer-Dixon 1995).

Successional agroforestry systems (SAFS) are an innovative and integrative strategy for restoring degraded landscapes while providing a diversity of agricultural and timber products for smallholder farmers. As described by Young (2017, Chap. 8, this volume), SAFS are an approach to agroforestry which attempts to replicate the spatial and temporal dynamics of forest succession. Plant species assemblages are established, maintained, and modified with time to mirror the successional stages of secondary forest development. To complement the renewed interest in this system of cultivation, it is worth reviewing the array of indigenous successional agroforestry systems (referred to as indigenous SAFS throughout this chapter), which have inspired a modern approach to SAFS. This chapter serves as a review of indigenous SAFS that have been practiced by smallholder farmers over the centuries throughout the tropics, to identify similarities in practice, diversity of uses, and economic viability, and to emphasize their importance in bridging ecology and agriculture through traditional knowledge.

A. Bertsch (✉)
School of Forestry and Environmental Studies, Yale University, New Haven, CT, USA
e-mail: asha.bertsch@yale.edu



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Mimicking natural ecosystems through agroforestry has been offered as a strategy for simultaneous ecological restoration while managing agricultural landscapes that promote biodiversity, maximize resource use efficiency, conserve and increase soil fertility, and provide increased economic stability to smallholder farmers (Hart 1980; Schulz et al. 1994; Ewel 1999; Vieira et al. 2009). In the field of restoration ecology, successional processes are often manipulated to meet goals to restore devastated landscapes (Hobbs et al. 2007). Why then, should we not implement a system of predicting and facilitating ecological succession for the paired goal of providing agriculture and restoring degraded soils and forests? By incorporating succession into the rubric of agroforestry, farmers may be able to play a key role in ecological restoration through their own agricultural pursuits. Such systems have actually been in place for centuries, practiced by indigenous groups under various names.

Many examples of indigenous SAFS are often nested within shifting agriculture, one of the oldest known agricultural practices. Shifting agriculture is a system that was once quite sustainable for the landscape and the people who practiced it, but has a reputation for depleting soils, and is heavily criticized for its role in deforestation. As the global pace of life hastens, many of these indigenous SAF systems are viewed as dated, obsolete, and destructive. In a number of cases, indigenous SAF systems have indeed suffered, as population pressure disallows sufficient time for long fallow periods and full regeneration of the landscapes. Such examples describe the slash-and-burn agriculture systems common throughout the tropics today. On the other hand, many indigenous SAF systems have withstood the test of time, have adapted to the changing needs of their local economies, and continue to be practiced traditionally with diverse cropping assemblages, long fallows, and selective planting to encourage forest regeneration.

## 2 Types of Indigenous Successional Agroforestry

Because of the wide variation in culture, location, and local naming of indigenous SAF systems, they may be perceived as unrelated agroforestry management systems. However, the consistent patterns of managed ecological succession are uncanny, and certainly, demonstrate the similarity of observation and resultant implementation of a cultivation system that is more alike than its various titles indicate. Indigenous SAF systems demonstrate a farmer's consistent recognition and awareness of tropical forest development. Astute observations and an appropriate set of successionally-based silvicultural approaches are handed down through generations to form this wealth of knowledge.

Through the description of several indigenous SAF systems, this chapter hopes to shed light on the many similarities across the multitude of differently named and unnamed indigenous SAF systems. A brief review of the literature yields abundant examples of the breadth of indigenous SAF systems worldwide. In the islands of Indonesia alone, numerous agroforestry systems with management cues inspired by natural forest succession exist: the rubber agroforests and damar (*Shorea javanica*, a tropical hardwood grown for its resin in Indonesia) agroforests, practiced by the Krui of northern Sumatra since the second half of the nineteenth century (Torquebiau 1984; Mary and Michon 1987; Michon et al. 1995), Rattan agroforests (Weinstock 1983) and Illipe (*Shorea stenoptera,* produces a substitute to vegetable oil) agroforests in Kalimantan (Momberg 1993; Sundawati 1993; de Jong 1995), the Kebun-Talun systems practiced in West Java (Michon and de Foresta 1997), and likely many more undocumented systems. In Myanmar, the Taungya system—an agroforestry system that interplants annual and perennial crops amongst timber seedlings while the plantation retains an open canopy—was developed in the early 1800s. In the northeast of India an integrative form of swidden, known as Jhum, is practiced (Ramakrishnan 2007). An equally impressive number of documented indigenous SAF systems are practiced in Latin America by the Kayapo Indians in the Brazilian Amazon (Posey 1985), the Bora of the Peruvian Amazon (Cotta 2016), and a variety of Mayan descendants, including the Tsotsil, Yucatec, and Lacandon Maya of Mexico, and the Mopan Maya of Belize (Diemont et al. 2011).

Subtle variations in indigenous SAFS management and naming systems also indicate wide diversity: Taungya and variations on swidden agriculture, such as improved fallow, fallow succession, and indigenous fallow are all examples of systems managed in ways that replicate aspects of secondary forest succession. Terms like agro-successional (Vieira et al. 2009), cyclic agroforestry and complex agroforestry (Retnowati 2003) have also been used in the literature to describe successional agroforestry systems or elements of agroforestry systems that feed into a model of ecological succession. Some systems only identify one or two successional stages, as in the case of Taungya agroforestry, oscillating between mixed-species vegetable cropping and closed canopy timber plantation. Other systems are far more complex, with some of the Mayan indigenous SAF systems identifying as many as 9 different fallow stages (Diemont et al. 2011). This listing is not exhaustive, and for the purpose of this chapter, I will explore only a subset of the more studied indigenous SAF systems.

Different practices replicate different stages of succession, and not all indigenous SAF practices integrate all stages of succession. Taungya, for example, mimics temporal change in species composition, from “pioneer-like” annual crops to late-successional perennial timber “forest”. However, the system remains relatively simple and does not typically mirror the successional changes in functional diversity, nor the full biodiversity of secondary forests. Nonetheless, it is important to recognize the detail and extent to which the selected successional stages are mimicked. Such replication of tropical forest processes is not learned in an academic setting. Farmers make these executive decisions, as informed by astute observation of the forest, by intuition and by the tailored experience of past generations. Detailed descriptive naming of fallow phases, among many indigenous SAF practitioners, demonstrates a high level of ecological understanding (see Table 7.1). Both the variations and similarities between indigenous SAF systems are striking.

**Table 7.1** Stages of SAFS succession, as identified and named by different indigenous groups (Denevan et al. 1984; Posey 1985; Christianty et al. 1986; Diemont et al. 2011)

| | Actively Cropped | "Fallow" | | | | |
|---|---|---|---|---|---|---|
| Yucatec & Tsotsil Maya | Milpa (cultivated field) | Arbusto (shrub, nurse tree planting) | Acahual (no planting, wild harvest of forest products) | Selva alta (mature forest) | | |
| Lacandon Maya | Kor (cultivated field) | Robir (shrub, nurse tree planting) | Jurup che (no planting, wild harvest of forest products) | Mahen che (forest fallow) | Nu kux che (forest fallow) | Taman che (return to mature forest) |
| Mopan Maya | Cux cul (cultivated maize field) | Cux bo'ole (mixed crops) | Mehen ca toc (managed tree regrowth) | Bega (planting nurse trees) | Nu cux ca toc (return to forest) | |
| Kayapo | Pura nu (newly cultivated fields) | Pura tuma (maturing field) | Ibê (old field) | Àpêtê (forest patches) | Bà krê ti (forest gap openings) | |
| Bora | Úmihe (cultivated manioc field) | Kapúuwa (transitional swidden) | Kapúuwa (transitional orchard) | Jia (orchard fallow) | Jia (forest fallow) | Old fallow (return to mature forest) |
| Kebun – Talun | Kebun (mixed herbaceous garden) | Kebun Campuran (mixed annual and perennial, transition to forest) | Talun (forest garden) | | | |
| Time | 0–5 years | 5–10 years | 10–20 years | >20 years | | |

## 3 Who Practices Indigenous Successional Agroforestry?

Often identified as swidden or slash-and-burn agriculture, indigenous SAF is usually practiced by some of the poorest farmers throughout the tropics. Fallow periods not only help restore soil fertility, but provide harvestable forest resources without any up-front costs. Indigenous SAF is a time and space specific practice. It is process driven as opposed to product driven, and is practiced where time, rather than fertilizer, is the more abundant resource. Indigenous groups and smallholder farmers throughout the world have independently developed SAF systems.

### *3.1 Latin America*

*Lacandon* The Lacandon Maya of Chiapas, Mexico manage succession through a series of distinctly named phases: *Milpa* (Spanish for maize field), arbusto (Spanish for shrub) *acahual* (additional shrub) phase, before being left to return to *selva alta* (high forest) (Diemont et al. 2006) (see Table 7.1). During the first 1–4 years is the *milpa* phase, a multi-cropping system consisting of up to 30 cultivated species, typically herbaceous vegetable crops for home consumption. Following the *milpa,* a diversity of fallow and enriched fallow systems may be implemented, which in some cases involves up to 4 phases of fallow. The *arbusto* phase (5–10 years) typically follows, in which nurse trees are planted to encourage forest regeneration and attract wildlife. Diemont and Martin (2005) recorded at least 18 native trees utilized by the Lacandon to accelerate forest restoration. This phase may or may not be preceded by a 3-year fallow known as *yerba* (literally meaning weeds) or *quamile.* The land is then left fallow for an additional 15 years, in what is termed the *acahual* phase. Acahual, which has no direct translation to English, describes a low secondary forest assemblage, predominantly shrubby, in which a high diversity of forest products are available (for furniture, construction, and artisanal purposes). Acahual is often divided into the subcategories robir (shrub, nurse tree planting) and jurup che (no planting, wild harvest of forest products). The final phase of fallow is recognized, *selva alta*—which allows vegetation to progress into a state of mature secondary forest, before being converted again into *milpa* (Diemont et al. 2006). During this phase, medicinal plants, valuable resins such as chicle, and timber species are harvested (Diemont et al. 2011).

Lacandon are highly selective of the species planted, deliberately managing species composition for accelerated regeneration of soil fertility (Diemont et al. 2006), and maintaining a high diversity of species offering consistent harvestable crops. Throughout all stages of succession, the farmers are able to harvest food and raw materials in the form of medicines, allowing them to keep productive land in a state of fallow for over 20 years (Diemont and Martin 2005), which is considerably longer than the 2–3 years common in many slash-and-burn systems today.

Many variations of this system exist across different Mayan ethnic groups in Mesoamerica, and though not discussed at length in this chapter, several (Mayan Mopan of Belize, Tsotsil Maya, and Yucatec Maya, of Mexico) are detailed in Table 7.1 to show the intricacy in identifying fallow phases. All mentioned groups employ long fallow periods and careful selection of trees to encourage soil and forest restoration, attract wildlife, and provide a diversity of forest products for home consumption and marketability (Diemont et al. 2011). Fallow systems are typically complemented with hunting and wild harvest of forest products.

*Kayapo* A fallow field is not an abandoned field for the Kayapo people of the Brazilian Amazon. Although not planted, the species that regenerate on fallow land play an equal role in site restoration the same way deliberately planted species would. Understanding how to take advantage of the plant and animal species that are present and can be cultivated at each phase of succession, the Kayapo are able to optimize the use of all stages without the need to repeatedly clear new land (Montagnini et al. 2000). The system begins with the clearing of a patch of forest and arranging organic matter to be burned for the release of nutrients to the soil. Root crops are planted prior to the burn, able to sustain the heat of a low intensity fire, and are given a head start against weeds that establish following the burn. While root crops can be cultivated early on, species that require high nutrients can be planted post-burn. In another example, the shrubby, weedy phases of succession, and in this case fallow, are not viewed as undesirable but are recognized for providing important habitat to the birds and mammals that are hunted by the Kayapo (Montagnini et al. 2000). Such animals are not present in the early cropping phase and are not as easy to hunt once the site advances to forest with high canopy dwelling species.

The Kayapo Indians practice an elaborate fallow management to follow the short rotations of their annual cropping systems (see Table 7.1). A diversity of crops is grown during the first 3 years of cultivation, after which the field is left unmanaged but continues to be a source of subsistence for many years. Yams, taro, and manioc continue to be harvested for 2–6 years, and papaya for more than 5 years. Bananas continue to yield for 15–20 years, *Bixa orellana* (onoto, used as a food dye) for 25, and *Cissus gongyloides* (or "Kupa", a fruit-bearing vine) for up to 40 years. The Kayapo take full advantage of their fallow fields post-crop cultivation, during which the developing secondary forest is managed to maximize harvestable forest products. In this case, the fallow takes on a more interactive role. Farmers often collect wild seedlings from neighboring forests and transplant them into their own fallow fields. Naturally regenerating species are also manipulated to encourage growth. Harvestable forest products include construction material and timber, and also many more goods including rope-making fibers, oils, paints, medicines, and body cleansers (Posey 1985).

The Kayapo also take a novel approach to site preparation. While many of the mentioned indigenous SAF systems commence with some element of slash and burn to prepare an initial site, the Kayapo take advantage of clearings made by a number of alternative means, both natural and anthropogenic. Campsites or paths that have been abandoned are viewed as new clearings, in as much as openings left by fallen trees (Posey 1985). These sites are equally taken advantage of for new cycles of cultivation, just as natural succession would ultimately claim them in time.

*Bora* The Bora community of the Peruvian Amazon practices a form of enriched fallow (see Table 7.1). Manioc, pineapples, and plantain are intensively cultivated for the first 2–3 years, followed by a passively managed fallow. Trees are not planted, but natural regeneration is encouraged. Naturally regenerating seedlings considered useful are cared for while others are thinned out (Cotta 2016). Fruit, fiber, and small game are harvested from the fallow forest *(ibid)*. Although the Bora may not engage in a management system as complex as the Lacandon one, natural succession is nonetheless encouraged and coexists with agricultural practices.

The practice of managing fallow land as it regenerates to secondary forest allows farmers to selectively guide species composition. Products that are typically wild harvested are encouraged to grow in larger numbers and in closer proximity to the farmer. This way, the farmer no longer needs to travel the distance nor spend the same amount of time searching for forest products otherwise found in an established secondary forest.

## 3.2 Asia

*Taungya* Another example of succession-mimicking agroforestry is the Taungya, an agroforestry system developed in Myanmar (Burma) that transitions from a planted mix of faster growing food crops and tree seedlings into a tree plantation harvested for timber, then back to food crop cultivation (see Table 7.1). In this sense, the system is managed as oscillating between a state of being forested and non-forested. The same Taungya system was introduced to Java around 1856. Taungya can be perceived as having advantages from two viewpoints: (1) One perception is the maximizing of space for crops intermixed with developing timber seedlings before light is lost by canopy closure, and (2) crops intermixed with tree seedlings may serve as a method of improving tree growth. In either case, Taungya systems can increase income to farmers by providing an immediate cash crop in the form of annual vegetables while awaiting the long-term investment in timber harvest (Wiersum 2004). Combined production of annual crops can also offset costs associated with reforestation, thus offering incentives for farmers to participate in reforestation programs (Schlönvoigt and Beer 2001).

*Kebun-Talun* As mentioned previously, there are numerous other SAF systems practiced in the Indonesian islands. The Kebun-Talun is a rotational cropping system that sequentially combines agricultural crops and tree crops (Christianty et al. 1986). This system operates differently from other mentioned indigenous SAF systems in that the fallow period occurs later on in the agroforestry succession as opposed to immediately following annual crop cultivation (see Table 7.1). In this case, cultivation begins with a direct transition from annual cropping to a perennial two-tiered stratified system: Marketable tree seedlings (rubber or damar) are planted amongst a pre-existing cropping system, often in newly established coffee or black pepper plantation. Such an intercropping is maintained for up to 15 years, after which point the perennial crop understory will be harvested and the tree crop will remain. In remaining years, natural regeneration is allowed to take place in the understory. As in other indigenous SAF systems, this phase is guided by selective thinning and the encouragement of desired species, as well as by enrichment plantings of additional seedlings (Christianty et al. 1986). In this scenario, it is interesting to note that the understory re-initiation phase acts as the fallow period as opposed to other mentioned systems wherein the fallow really takes place during the stem exclusion phase.

*Jhum* Another long-standing successional system is known as Jhum: an ancient method of shifting agriculture practiced by tribal communities in the northeast of India. Like many indigenous SAF systems, a forest site is typically cut, burned, and planted with annuals for several years followed by a substantial fallow period. Some traditional Jhum cycles consist of 1 year of mixed cropping followed by 50 years of fallow (Ramakrishnan and Toky 1981). However, Jhum cultivation is a prime example of a swidden system that has become unsustainable in many of its practiced locations, due to increased population pressure and decreased fallow allowance

(Krug et al. 2013). Many Jhum gardens are still maintained under a traditional 8-year fallow period. One study demonstrated significantly higher bird and plant species present in Jhum agroforests compared to neighboring oil palm and teak plantations (Mandal and Shankar Raman 2016). Cropping cycles of less than 10 years rely on tubers, rhizomes, and perennials while greater emphasis is placed on cultivation of cereals after a 10–30-year cycle (Ramakrishnan and Toky 1981). A sequential fallow is traditionally allowed to establish first with weedy colonizers, and is then replaced with sprouting rhizomes of bamboo shortly thereafter (*ibid*). Between 20 and 50 years of fallow, shade-intolerant fruit and timber trees are allowed to establish naturally before the cycle is repeated with the harvesting of trees, and slashing and burning again for a new cropping cycle (*ibid*).

In most indigenous SAF systems trees are not only planted, but encouraged through the selection of naturally regenerating seedlings. Although none of the mentioned indigenous SAF systems seem to integrate livestock of any kind into their fallow systems, the practice of attracting wild game is an important component to indigenous SAF systems.

## 4 Ecological and Social Motives Behind SAFS

Approaches and motivations around indigenous SAF systems vary. For some farmers the incentive to plant trees is to encourage desirable shade-tolerant understory species, often of handicraft or medicinal value. Alternatively, planting herbaceous crops among tree crops has been used as a strategy to promote soil fertility for planted tree species, as practiced by the Lacandon Maya of Mexico and the Kayapo Indians of Brazil (Diemont et al. 2011).

Each phase of cultivation or fallow provides a diversity of harvestable material, either for home or market use. With a patchwork of indigenous SAF systems at varying stages of succession across a landscape, farmers are able to continuously harvest a wide range of products. This allows farmers to minimize risk by planting a diversity of crops and allowing the growth of wild species of marketable and subsistence value (Cotta 2016). This complexity also aids in the biodiversity of the landscape, creating both forested and open patches of land, and providing multiple habitat types for local fauna. Indigenous agroforestry systems throughout the tropics have been shown to provide habitat and passage for a wide number of birds and mammals (Salafsky 1993; Harvey and González Villalobos 2007).

Garden hunting is also an important consideration in creating diverse habitat, especially in Latin America. Plant species are selected not only to provide for personal consumption and soil fertility, but also to attract wild game toward the gardens. Attracting wildlife serves several purposes: (1) attracts wild game that can be hunted within the garden, and provides food and habitat to ensure future generations of desired game species, (2) visiting animals deposit waste products that further improves soil fertility, and (3) by carrying fruit and dropping waste, visiting animals bring new seed sources from outside the agroforestry site. The Lacandon have also been known to integrate beehives into their fallow systems to supply themselves with honey and to encourage pollination of fruit species growing in the fallow (Diemont et al. 2011).

Another important component of indigenous SAF systems is the deliberate promotion of wild plant species and careful thinning of developing natural regeneration to promote growth. In some cases, even naturally regenerating weed species are allowed to colonize an agricultural site, with the local belief that these species will improve soil health. Such practice is documented in Jhum, Lacandon, and Kayapo cultivation practices.

## 4.1 Indigenous SAFS as Subsistence Agriculture

The term fallow is often associated with words like “passive”, “wild”, or “unmanaged”. As evident from this review, this association could not be farther from the truth. Studies of later stages in Kayapo fallows found that 94% of the plants present were of medicinal value (Posey 1985). In the same study of the Kayapo *apete* (a local name used to describe the initial phase of fallow), 85% of 140 plants collected were found to have been planted by the Kayapo (Posey 1985). Based on a figure by Cotta (2016), up to 42% of subsistence and income-generating products for Bora communities are harvested from managed fallows in the form of crops, handicraft materials, and fuelwood. Greater than half of the plant species harvested by the Bora community were shown to be available year round either in the form of fresh produce or other edible products (*ibid*). Across nearly all of the indigenous SAF systems reviewed here, subsistence cropping takes precedence during the initial phases of cultivation, while more valuable, marketable products are relied upon through naturally regenerating provisions and enrichment plantings during fallow periods of varying lengths of time.

## 4.2 Bridging Ecology and Local Tradition

In experiments mimicking successional development in tropical humid forest in Costa Rica, successional plots were able to maintain similarly high levels of organic matter, nitrogen, and cation exchange capacity in comparison to monoculture plots of the same age (Ewel 1999). The successional mimic expressed similar structural and functional qualities of root development as those of the natural successional plot. This supports the idea that successional agroforestry, in addition to providing subsistence and marketable agriculture, can also effectively replicate soil health and productivity of secondary successional forests.

What remains to be recognized is that indigenous successional agroforestry systems are fine-tuned, monitored, and regulated by their caretakers. More research is needed to bridge the gap between traditional and empirical knowledge, and to recognize the depth of complexity of indigenous SAF systems not only in spatial and temporal composition, but in recognition of the subtle management details and regular maintenance of these systems. Understanding the paired ecological and social complexities of indigenous SAF systems will be necessary if we wish to replicate these important examples of sustainable agriculture and help them transition in a changing climate.

## 5 Keeping Indigenous SAF in Today's Agriculture

### *5.1 Addressing Land Loss*

A challenge currently faced by practitioners of these indigenous systems pertains to the amount of land needed to simultaneously manage multiple stages of fallow and production. With less and less land available each year, how can farmers continue to support themselves and families with indigenous SAF practices?

Although many indigenous SAF systems utilize large areas of land to manage several different growth stages, there are examples of the same work being done on much smaller amounts of land. For example, the Kayapo make use of large areas of forestland, as they traditionally have had access to such land in the Peruvian Amazon. However, indigenous SAF is practiced with equal success in densely populated areas, and even urban areas in Indonesia. For example, the Kebun-Talun system manages an 8–15-year rotation on little more than 2 hectares providing for a single family (Soemarwoto 1984). Within a Talun (man-made forest) plot of about 2 hectares, a gap of 0.5 hectares is made to create new Kebun (garden), thus small parcels of land have been shown to be large enough to create a continuous rotation of annual and perennial crops (Soemarwoto 1984). If we consider that the average smallholder farmer in Latin America has approximately 1.8 hectares for cultivation, it is not outlandish to suggest that a similar cultivation system is feasible for smallholder farmers in Latin America and throughout the tropics (Altieri 2009).

### *5.2 How Can We Scale Up?*

The practice of indigenous SAF alone may not always be able to sustain a family, e.g. many Jhum farmers in northeast India practice indigenous SAF alongside other agricultural practices like rice cultivation. Similarly, homegardens in Indonesia supplement rice cultivation, the main form of agriculture in the country (Soemarwoto and Conway 1991). However, the diversity of crops, medicines, timber, and non-timber forest products that are provided by these systems offer important supplements to diet and invaluable economic security in the face of ever-shifting markets and environmental fluctuations.

Some strategies to keeping indigenous SAF in practice, or even scaling up, may include community forestry or the formation of farmer cooperatives. Forest cooperatives have been effective in Costa Rica, where, under shared responsibility, communal plots of forest are managed simultaneously for timber, the harvest and cultivation of non-timber forest products, eco-tourism, and even restoration (Montagnini et al. 2002). The Coope- San Juan Agricultural Cooperative in Costa Rica for example, consists of 16 families simultaneously managing multiple parcels of land for different forest resources within 400 hectares of communally owned forest (Montagnini et al. 2002). If cooperative management can enable such a diversity of practices within a shared forest, perhaps a similar model could be adapted to accommodate the variety of fallow and successional stages in indigenous SAF systems.

Community forestry, as practiced in Indonesia, could also be a viable framework for integrating indigenous SAF practices. Community based forest models in Indonesia like the Hutan Kemasyarakatan (community forests) and Hutan Desa (village forests) provide farmer groups 35-year licenses to select forests to manage and harvest from (Bock 2012). Again, such community managed forests could be managed to integrate indigenous SAF by maintaining patches of forest at varying stages of succession to improve forest health, and serve as the grounds for indigenous SAF management.

Take the scenario of homegardens in Indonesia (Soemarwoto and Conway 1991); multi-strata agroforestry systems creating series of isolated forest fragments throughout the village and even urban landscape. These typically represent only one phase of vegetative succession at a given time, consisting of a diversity of fruit trees and stratification of shade tolerant understory. However, households could form cooperatives wherein a series of homegardens could collectively be managed as a (fragmented) community forest. Households could then create a system of managing each homegarden at various stages of succession to maximize and share the diversity of products grown in each stage of fallow and succession, and provide their own homegardens with soil resting periods. In this example, farmers could keep the traditional Kebun-Talun system in practice by incorporating it into another existing structure of Indonesian agriculture.

This section can in no way claim an absolute solution for integrating indigenous SAF into modern agriculture, but it may shed light on some of the available options. The most important point is that although there are many alternatives to slash-and-burn agriculture, these systems are laden with indigenous knowledge of local forest ecology and patterns of succession that must be recognized as a resource worth saving and incorporated into, not replaced by, future models of agriculture.

## 6 Conclusions

Indigenous successional agroforestry departs from the standard farming techniques, and has the potential to facilitate ecological restoration of forest and soils throughout the tropics. Successional agroforestry has been practiced on small-scales and to varying degrees by indigenous agriculturalists, and conceptualized by ecologists. With the increased awareness of a changing and unpredictable climate, inevitable population growth, and increased push for economic development around the world, it is clear our current agricultural practices are no longer sufficient to support the many different economic, social, and environmental needs. In much of the tropics, forest conservation is in direct conflict with farmers' needs for subsistence and national pressures for economic expansion. Successional agroforestry offers an ecological solution to restore degraded soils and sustainably manage them for multifaceted agricultural production, while also acting as a stepping-stone to facilitate reforestation and restore biodiversity.

The above-mentioned indigenous SAF systems, practiced in accordance with local tradition, offer year round access to nutrition, medicines, timber, construction and fuelwood for subsistence and marketable products, and promote a wide diversity of flora and fauna. Indigenous SAF systems not only promote the re-establishment of secondary forest, but can often accelerate the process and self-subsidize the cost of reforestation.

Indigenous SAF represents a lineage of centuries old traditional agricultural knowledge that has been lost in many cultures. Although many of these systems do utilize some environmentally degrading practices to establish cultivation, they are also some of the only agricultural practices that take long-term forest processes into consideration, and assist in the regeneration of secondary tropical forests in the long term.

As scientists and policy makers move forward with the task of designing agricultural systems that both support food sovereignty for smallholder farmers and aid in forest restoration, it is imperative that we continue to understand the past and the present, and find ways to effectively integrate these indigenous systems into modernity without losing their integrity.

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# Chapter 8
# *Mimicking Nature:* A Review of Successional Agroforestry Systems as an Analogue to Natural Regeneration of Secondary Forest Stands

**Katherine J. Young**

## 1 Introduction

Agroecological systems can be designed to mimic nature (Alvim and Nair 1986; Ewel 1999; Somarriba et al. 2001; McNeely 2004; Malézieux 2011). One agroecological strategy that seeks to facilitate tropical forest recovery by mimicking patterns and processes of natural succession of native forests is *successional agroforestry* (Götsch 1992; Schulz et al. 1994; Peneireiro 1999; Ashton and Montagnini 2000; Dufty et al. 2000; Vaz 2000; Vieira et al. 2009; Schulz 2011). Successional agroforestry systems (SAFS) are composed of stratified multifunctional species assemblages that collectively appear to have a similar structure to native forests. Management of SAFS emphasizes building species assemblages that contain functional characteristics of key natural successional stages to diversify functional groups, promote tree-growth and crop productivity, and offset reforestation costs (Götsch 1992; Peneireiro 1999; Vaz 2000; Vieira et al. 2009; Schulz 2011).

The concept of SAFS integrates indigenous knowledge of intercropping multipurpose subsistence species (Nair 1991; Schulz et al. 1994; Senanayake and Jack 1998; Senanayake and Beehler 2000), modern agroforestry techniques (Alvim and Nair 1986; Ashton and Montagnini 2000; McNeely and Schroth 2006), and assisted natural regeneration (Parrotta et al. 1997; Shono et al. 2007) to emphasize biodiversity, and the use of ecological succession to establish a productive forest system (Senanayake and Jack 1998; Dufty et al. 2000; Senanayake and Beehler 2000; Schulz 2011; Dickinson 2014). Much like the adaptive management of assisted regeneration of forest stands, mimicking natural ecosystems in agroecosystems requires the knowledge of species-specific survival, growth, functional traits, and niche resource requirements in order to appropriately select multi-functional species

K. J. Young (✉)
School of Forestry and Environmental Studies, Yale University, New Haven, CT, USA
e-mail: katherine.young@yale.edu



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and to develop ideal spatial arrangements for stratified stand structures (Ewel 1999; Somarriba et al. 2001; Kraft et al. 2008).

Conceptual theories have drawn parallels between natural succession models of forest stand development and management of successional agroforestry systems (Perera and Rajapakse 1991; Senanayake and Jack 1998; Ashton and Ducey 2000; Dickinson 2014). However, to date, studies on SAFS are limited to conceptual papers and descriptive case studies without replication, most often featured in the grey literature (see Götsch 1992; Peneireiro 1999; Vaz 2000; Vieira et al. 2009).

In this chapter, information is first summarized from publications that have advanced our understanding of natural succession. The chapter reviews theoretical frameworks that have contributed to the development of the biomimicry concept, and introduces a silvicultural approach to agroforestry systems highlighting analogue forest hypotheses. Case studies from current agroforestry systems in Latin America are provided, demonstrating the theory of successional agroforestry systems as anthropogenic analogues to secondary forest stand development, and its potential to regenerate severely disturbed agricultural landscapes to bountiful, biodiverse agroforestry systems.

## 2 Conceptual Background

### *2.1 Theory of Natural Succession*

Succession refers to the changes observed in an ecological community following a disturbance. Successional processes of natural regeneration are driven by the type, intensity, timing, and duration of a disturbance to a site; pre- and post-disturbance of propagules; climate; and species competition for resources such as sunlight, water, and nutrients (Gleason 1939; Egler 1954; Connell and Slatyer 1977; Halpern 1989; Camp and Oliver 2004). Within mixed species stands, each species responds to microenvironmental changes in resource availability and stress through time, while competing with neighboring plant species for access to limited resources (Gleason 1939; Egler 1954; Connell and Slatyer 1977; Halpern 1989). In his botanical field studies, Gleason observed:

1. Every species of plant has reproductive powers in excess of its need;
2. Every species of plant has some method of migration;
3. The environment in any particular station is variable; and
4. The development of a vegetational unit depends on one or the other of two conditions, the appearance of new ground or the disappearance of an existing association (1939).

Over time, associations between groups of plants in natural succession are temporary and fluctuating—dependent upon their origin, structure, and the particular disturbance in the environment and surrounding vegetation (Gleason 1939).

Conventional interpretation of "old-field plant succession" has followed the idea of *relay floristics*– involving a succession of incoming and outgoing plant associations, each group establishing itself and out-competing predecessor plant groups. This model suggests each plant groups modifies or "prepares" the site for a subsequent group. Alternatively, in the *initial floristic composition* (IFC) hypothesis, species representing all guilds colonize soon after an initial disturbance but reach dominance at different times according to their growth rates and longevities. Egler (1954) found evidence for both models in old fields, however, relay floristics was less frequent: "several instances are now known where the incoming relay is responsible for less than 5% of the eventual forest stand. Conversely, 95% was determined years before, at the time of abandonment, and developed completely independently of the grasslands and shrublands that have temporally preceded them." IFC is largely dependent upon the availability of seeds lying dormant in the soil and/or from seed trees adjacent to the site, and to the necessary conditions to break the seed coats for germination. In a successional agroforestry system, these seeds and/or seedlings are purposely introduced by the manager, rather than being naturally present in the site following a disturbance.

In a seminal 1977 paper, Connell and Slatyer proposed alternative models for natural succession: the *tolerance* model, the *inhibition* model, and the *facilitation* model. Mechanisms that determine changes during succession (such as interactions with herbivores, predators, and pathogens) and the relationship between succession and community dynamics were explored. Papers published before 1977 all agreed that certain species will usually appear first because they have evolved "colonizing" characteristics (such as the ability to produce large numbers of propagules). The models differed in *how* new species appeared later in the sequence. In the *facilitation model*, species *modify* the environment making it more suitable for other species to invade and grow. In the *tolerance model*, new arrival of species from modifications in the environment neither increased nor decreased the rates of recruitment and growth of later colonizing species. Examples include shade tolerance, and resilience to other environmental factors such as moisture, nutrients, allelopathy, or grazing. In the *inhibition model*, species do not grow to maturity when previously established species are present; they only appear later because they live longer and gradually accumulate as they replace earlier species. Early species are killed by local disturbances or by natural enemies (herbivores, parasites, pathogens, etc.).

The *facilitation model* can be seen in primary succession (newly exposed sites), such as weedy species with quickly spreading roots or umbel-like flowers that disperse wind-blown propagules rapidly and far, quickly covering the ground. This maintains moisture and adds organic matter, which is critical for nutrient cycling and nitrogen fixation. This is the dominant model in agricultural fallows following slash-and-burn (swidden) agriculture, but is unlikely to be found in forest stands. The *tolerance model* is supported by evidence that late successional species are often able to establish without any preparation of the site by earlier species. This is true in timber plantations, or in the installation of native tree species for reforesting disturbed forests in tropical regions. This is also true for simple agroforestry systems, where trees that are highly tolerant to poor soils and high UV (such as

*Mangifera indica*, *Citrus spp.*, *Inga spp.,* and *Eugenia uniflora*) establish well in former agricultural fields without prior preparation/modification to the environmental conditions. However, species that are less tolerant to extremes (*Theobroma cacao, Persea spp., Cinnamomum zelanicum,* or other genus in the Malvaceae or Lauraceae families) may require some modification of the environment (shade, leaf litter accumulation, water infiltration and soil quality) to establish strong root systems and healthy shoots, foliage, and fruits.

In management of SAFS following agricultural fallows, selective removal or thinning of flora can produce new plant assemblages (IFC) by modifying the environment, and can also open up niches for plants with complementary structures to thrive. Management approaches of SAFS are consistent with the individualistic concept of plant associations, whereby plants are selected for individual phenological traits (timing of flowering, shade tolerance, drought resistance, etc.) and structural traits (height, growth rate, etc.) and are interplanted with other multifunctional species with complementary traits. Rather than monocropped plantations, successional agroforestry techniques seek to take advantage of individual plant traits and adaptively manage the variation in the environment.

## *2.2 Theory of Biomimicry*

The idea of simulating the diversity of the forest for agricultural purposes—or biomimicry—has been debated since the 1960s (Geertz 1963; Harris 1971; Nations and Nigh 1978; Beckerman 1983; Vickers 1983; Eden 1987; Ewel 1999; Malézieux 2011). Citing examples from indigenous forest cultivation practices in Indonesia and Japan (Geertz 1963), Venezuela and New Guinea (Harris 1971), and Mexico (Nations and Nigh 1978), researchers suggested that using traditional methods of shifting cultivation (clearing and burning forest land to cultivate a short period of mixed cropping, followed by an extended period of forest fallow) as a strategy to intercrop subsistence products in gaps, develops complex, polycultural community structures that protect the soil from leaching and erosion, and directly utilize nutrients stored in living matter— much like a tropical forest (Geertz 1963). Subsequent studies challenged this hypothesis, citing evidence from indigenous communities in tropical South America (Beckerman 1983; Vickers 1983) to argue that while many crop species may be present in swidden agriculture, the distribution and composition is often patchy, 'zoned', and dominated by the crop of primary subsistence (such as manioc), and therefore is not comparable to the native forest (Beckerman 1983; Vickers 1983; Eden 1987). Recent research has attempted to bridge the arguments to demonstrate how productive agricultural systems can better mimic native ecosystems by developing a working framework of high species diversity, complex structure, low management intensity with minimal inputs, and diversified output of yields (Perera and Rajapakse 1991; Ewel 1999; van Noordwijk and Ong. 1999; McNeely 2004; Malézieux 2011).

Agroforestry systems have borrowed from biomimicry theory since the 1970s and have been promoted as a land use strategy for addressing food security and sustainable agricultural production (Nair 1993; Somarriba and Beer 2011), biodiversity conservation (Nair 1993; McNeely and Schroth 2006; Bhagwat et al. 2008), and restoring connectivity to fragmented landscapes (Nair 1993; Laurance 2004; McNeely 2004; Schroth 2004; Montagnini et al. 2011). Integrating indigenous practices of intercropping non-timber, multi-purpose tree species, and managing long fallow periods (e.g. traditional homegardens and swidden agriculture) into modern techniques that fit within linear conventional agricultural systems (e.g. alleycropping, windbreaks, and living fences), agroforestry techniques range from simple systems that intercrop one tree species with one agricultural crop species to systems that interplant tree crops of high value under existing or introduced canopy cover (e.g. *cabruca* cacao or shade-grown coffee systems). However, many conventional agroforestry systems do not necessarily mimic native forest structure and biodiversity. Trees are the primary focus in plantation agroforestry (e.g. cacao, *Theobroma cacao;* coconut, *Cocos nucifera;* rubber, *Hevea brasiliensis;* and oil palm, *Elaeis guineensis*), however the contributions of other forest components (such as herbs, shrubs, lianas, epiphytes, etc.) are often ignored (Ewel 1999). It should be noted that non-tree biodiversity has important roles to play in enhancing sustainability and structural stability of landscapes (Dufty et al. 2000), and also provides many high market value products such as culinary and medicinal herbs, berries, vanilla, and fibers.

## 3 Mimicry Hypotheses in SAFS

Several studies have shown the potential for agroforestry systems to better mimic natural ecosystems, whose components are the results of natural selection and are therefore sustainable models on which to base the design of new systems of land use.

### *3.1 Three Case Studies Testing the Biomimicry Hypothesis in Agroforestry Systems*

In 1986, Alvim and Nair examined intercropping of cacao with rubber, clove, black pepper, and coconuts on various farms in the cacao-producing region of Bahia, Brazil. They found that overall, crop combinations were preferred most with clove and least with coconuts, which reflects the synergistic growing requirements of cacao and clove. The authors point to further examples of highly productive intercropping that includes: coffee, passion fruit, papaya, clove, peach palm, beans, patchouli, cardamom, and vanilla—which all have high market value. Yields were measured in pure stands (conventional, un-shaded cacao production; improved management; experiment station sites) and mixed stands of rubber and cacao. The paper suggests that benefits to crop combinations include: more efficient use of labor and equipment over a relevant time and space, reduction of weeding, more efficient use of soil fertility resources, decrease in erosion hazards and increase in land's total productivity. Socio-economic benefits included increasing overall economic yield and protecting against threats of pest/diseases. The authors also identify management considerations, such as choosing appropriate intercrops, identifying their agronomic requirements, developing adaptive management practices for crops with varied needs over time and space, and ensuring marketability of the various products (Alvim and Nair 1986). Overall, the authors found that complex crop combinations are more demanding in labor, capital, and technical/managerial skills.

Ewel (1999) articulated the 'mimicry hypothesis' when he argued that "agricultural systems should benefit from imitating the structure and function of natural ecosystems, since components of the latter result from natural selection towards sustainability and the ability to adjust to perturbations" (as cited by van Noordwijk and Ong 1999). Van Noordwijk and Ong extended that hypothesis on structure and function to include a second mimicry hypothesis: "agroecosystems shall benefit from resembling the diversity of natural ecosystems" (van Noordwijk and Ong 1999). Both hypotheses refer to the potential benefits of combining different plant life forms in the place of monoculture:

(i) Larger total production with staggered harvests throughout the year
(ii) Higher efficiency (particularly labor) over time, as less effort is needed to achieve the same results where one works 'along with' rather than 'against' natural processes;
(iii) Reduction of downstream effects (e.g. groundwater flow patterns can be grossly affected by both additional and reduced water use) if the total resource use (water, nutrients, biodiversity) simulates that of the natural system of which it replaces;
(iv) Improved maintenance of environmental service functions in the landscape.

Ewel (1999) examined plant communities designed to imitate the structure and function of secondary succession in humid tropical lowlands over 5 years. Comparing natural succession vegetation following slash-and-burn of existing vegetation; a monoculture maize field; an "imitation system" ("investigators' attempted to build [a system that contains] the same mix of life forms that appeared in the successional vegetation [i.e. dominated by herbaceous vegetation, shrubs, or trees], but which consisted of species alien to the site [*Zea mays, Manihot esculenta,* and *Cordia alliodora,* respectively], selected and planted by the scientists (naturally occurring colonists being weeded out"); and species-enriched treatments ("in which vast quantities of seeds were regularly added to natural successional vegetation in an effort to assess the functional responses of further enrichment of diversity"); and measured responses to pests, productivity, and soil fertility. The findings indicated that the imitation system performed on par with the natural succession plot in respects to pests and soil fertility. However, the imitation system was not as productive as the successional vegetation, although much more productive than the monoculture maize at times.

A subsequent study (Somarriba et al. 2001) advanced Ewel's findings to compare six production systems: (i) *taungya* under inga (*Inga edulis*), acacia (*Acacia mangium*), or in association with crops cycles consisting of three cycles of maize (*Z. mays*), one cycle of ginger (*Zingiber officinale*), followed by permanent installation of a perennial fruit shrub, araza (*Eugenia stipitata*); (ii) new cacao plantings (*Theobroma cacao*) under the shade of valuable tropical timber trees such as laurel (*Cordia alliodora*), inga (*Inga edulis*), tropical almond (*Terminalia ivorensis*), and rosy trumpet tree (*Tabebuia rosea),* with laurel and cacao planted simultaneously with maize (*Z. mays*), cassava (*M. esculenta*) and pigeon pea (*Cajanus cajan*) as temporary shade for the cacao; (iii) old cacao plantations, (iv) cacao-laurel-plantain (*Musa* AAB) systems, (v) line plantings of laurel, *A. mangium* and *Tectona grandis* compared with five trials of laurel, *T. ivorensis* and *Eucalyptus deglupta*; and (vi) pure plantations of just laurel (*C. alliodora*). The authors evaluated mortality, growth, site index and site variables and found that the laurel growth was highest in the intercropped cacao-laurel-plantain system, followed by *taungya*, new cacao plantations, old cacao plantations, line plantings, and pure plantations, respectively. This study suggests that intercropping valuable timber in agroforestry systems benefits growth when planted in association with other species.

Also in 1999, van Noordwijk and Ong tested the two "mimicry" hypotheses ((i) *Agricultural systems benefit from imitating the structure and function of natural ecosystems and relative components of natural succession*; and (ii) *Agroecosystems benefit from resembling the diversity of natural ecosystems*) in the savannah zone of sub-Saharan Africa, an area where agriculture and native vegetation are difficult to maintain due to temperature extremes, limited water source, and other disturbances such as wind, grazing pressures, and human disturbance. The authors sought to understand how diversity of species might be used to design or improve agroforestry systems for sub-Saharan Africa. To answer this question, they examined the structure and function of sequential fallow-crop rotation agroecosystems in the savannah zone, comprised of gum arabic (*Acacia senegal*), desert date (*Balanites aegyptica*), shea butter nut (*Vitellaria paradoxa*) and néré (*Parkia biglobosa*), and studied species competition and diversity, and structure and function of the African savannah ecosystem (dominated by thorny shrubs and trees in the Acacia genus such as *Acacia senegalensis;* long-lived canopy trees such as the baobab, *Adansonia digitata*) and elephant grass (*Pennisetum purpureum*). Van Noordwijk and Ong concluded that agricultural systems do benefit from imitating the structure and function of natural ecosystems, but the relative benefit from resembling the diversity of natural ecosystems is dependent upon the perspective and ability of farmers to derive value from a complex system with many components (van Noordwijk and Ong 1999). These findings echo the warnings of other studies that acknowledge the challenges of designing ecologically intensive agroecosystems due to the necessity of in-depth knowledge of biological processes (Alvim and Nair 1986; Malézieux 2011), and the knowledge-intensive management required for each tree species to be selected based on the site conditions and an understanding of survival, growth, and other dynamics (Alvim and Nair 1986; Perera and Rajapakse 1991).

In an opinion paper published in *Trends in Ecology and Evolution,* Bhagwat et al. (2008) examined the role of agroforestry systems in maintaining biodiversity, and argued that agroforestry systems can re-connect fragmented landscapes such as nature reserves to human-dominated landscapes, reduce resource-use pressure from these forests, and provide habitats outside formally protected land. The authors introduced the concept of conservation in human-dominated landscapes by challenging conceptions of "untouchable wilderness" through their analysis of landscape management practices known from ancient, pre-Columbian civilizations (i.e. the Maya in Mesoamerica, and native populations in central Amazonia) and hunter-gatherer societies in Cameroon and Papua New Guinea. They reviewed recent research in tropical agroforestry *vis a vis* a literature search (185 references, using keywords 'agroforestry' and 'biodiversity'), and found that many studies sampled multiple taxa in forest and agroforestry landscapes: 36 articles made a direct comparison between agroforestry systems and neighboring forest reserves, and 12 types of agroforestry systems and 9 taxa were represented in 14 tropical countries. For each agroforestry study, the authors calculated the species richness as a percentage of the species found in the neighboring forest reserve, and examined the similarity in species composition between the two system types. This work demonstrated: (i) many agroforestry systems are important for the protection of species and habitats outside protected areas; (ii) agroforestry systems maintain heterogeneity at the habitat and landscape levels; (iii) trees in agroforestry landscapes reduce pressure on protected forests (Bhagwat et al. 2008). Agroforest matrices provide a rich habitat for native species to survive outside the confines of a nature reserve.

## 3.2 Theory of (Agro)Forestry Analogues

*Are successional agroforestry systems analogous to natural regeneration of native forests?* An Analogue Forestry system is defined as "an environmentally sustainable land management approach that assists farmers in developing multi-species plots of both native and exotic crop species that, over time, mature to approximate the structure, ecological functions and environmental integrity of a natural forest" (Senanayake and Beehler 2000). Analogue Forestry uses organic principles to produce a suite of high-value foods, spices, herbs, and medicinal plants, as well as fuelwood and timber stratified amongst canopy trees, vines, understory shrubs and herbs without compromising biodiversity (Senanayake and Beehler 2000). The choice and placement of each species is determined by its contribution of specific ecological and economic functions. Creating multi-strata agro-forests improves wildlife habitat, thus becoming ideal buffer zones with multiple functions (ecological, economic, etc.). Benefits include increased ecosystem services from a mature forest system; economic opportunities from the production of timber and non-timber forest products; social benefits stemming from exchange of information, best practices, and strategies among practitioners (Senanayake and Beehler 2000; Dickinson 2014). Each of these principles is consistent within SAFS.

*Can silvicultural management of forest stands be applied to successional agroforestry models?* Because the dominance of long-lived, woody trees and shrubs in agroforestry systems adds structural and functional complexity over a long period of time, successional agroforestry is best understood from a silvicultural perspective, in which multistoried stand structures are managed for complexity (Ashton and Montagnini 2000). Successional processes of natural regeneration are driven by the type, intensity, timing and duration of a disturbance to a site; pre- and post-disturbance of propagules; weather conditions; and individual species competition for limited resources such as sunlight, water, and nutrient availability (Gleason 1939; Egler 1954; Connell 1978; Tilman 1985). In successional agroforestry, these disturbances are largely anthropogenic management interventions (such as burning, planting, pruning, thinning, coppicing and pollarding), and therefore require an understanding of forest stand dynamics to manage them appropriately.

Management of forest stand development has been described as occurring in four phases: (i) stand initiation, (ii) stem exclusion, (iii) understory re-initiation, and (iv) oscillating steady state or "old growth" (Oliver and Larson 1990; Kozlowski 2002; Camp and Oliver 2004) (Table 8.1). In recent years, conceptual theories have been proposed that draw parallels between management of secondary forest stands (Oliver and Larson 1990; Ewel and Bigelow 1996; Kozlowski 2002; Camp and Oliver 2004) and management of *successional* agroforestry systems (Perera and Rajapakse 1991; Senanayake and Jack 1998; Ashton and Ducey 2000; Ashton and Montagnini 2000; Kelty 2000; Jones 2001).

Following the conceptual model proposed by Ashton and Ducey (2000), the *nurse phase*—combining annual crops and perennial agroforestry species—is analogous to "stand initiation"; the *training phase*—establishing timber, fuelwood, fruits, spices, and medicines in multistoried stands of trees—is analogous to "stem exclusion"; and the *shade tree/crop* phase—preferentially managing valuable overstory timber species and understory perennial crops such as cacao or coffee—is analogous to the "understory initiation" of stand development (Ashton and Ducey 2000; Kelty 2000) (Table 8.1). As gaps in the understory and canopy are filled with multi-functional agroforestry species, and management efforts shift over time from planting (stand initiation), to thinning/pruning (stem exclusion), to installation of understory crops (understory re-initiation), towards harvesting and maintaining the system (oscillating stable state/old growth), silvicultural management of SAFS may resemble silvicultural management of multi-species forest stands (Perera and Rajapakse 1991; Senanayake and Jack 1998; Ashton and Ducey 2000; Kelty 2000; Dickinson 2014).

**Table 8.1** Parallels between successional stages of forest stand dynamics (Oliver and Larson 1990; Camp and Oliver 2004) *and analogue agroforestry* (Senanayake and Jack 1998; Ashton and Ducey 2000; Kelty 2000)

| Forest stand dynamics | Analogue (agro-)forestry |
|---|---|
| Stand initiation | Nurse phase |
| Stem exclusion | Training phase |
| Understory re-initiation | Shade-tree crop phase |
| Old growth | Management for harvest/ structural diversification |

Mimicking natural ecosystems in agroecosystems similarly requires development of multi-strata, multi-functional species stand structures based on age, size, spatial arrangements, functional traits, and species-specific niche requirements of plants (Kraft et al. 2008) as well as a clear definition of desired stand structures based on developmental stages. These systems combine the horizontal arrangement of complementary species with vertically overlapping species, mainly determined by light needs and the available rooting zone (Schulz 2011). Through the mixture of trees, shrubs and herbs or crops, a broader spectrum of functionally different species can lead to a more efficient use of the available nutrients, solar energy and water, giving more stability to the system and reducing the need for external inputs (Schulz et al. 1994; Schulz 2011).

### 3.3 The Missing Link?: Functional Diversity Theory

*What traits and environmental variables are most important in determining fundamental niches of agroforestry species?* To answer this, we can look at agrobiodiversity in terms of functional traits that are present in the dominant species in a successional age class. The functional biodiversity of the system emphasizes dynamics at various levels and can reveal implications for its functioning as a whole (Callo-Concha 2009). Within mixed species stands, each species responds individually to niche micro-environmental changes in resource availability and stress through time, while competing with neighboring plant species for access to limited resources (Gleason 1939; Ashton and Larson 1996). Changes in species composition and diversity will affect the functioning of ecosystems most strongly when species differ in their effects on ecosystem processes or in their response to environmental change (Chapin et al. 1997; Huang et al. 2002; Lavorel et al. 1998; Lavorel and Garnier 2002; McGill et al. 2006; Lebrija-Trejos et al. 2010). Ecosystem functioning is the end result of multiple stages of filters that, by assembling individuals with appropriate responses (functional traits), result in communities with varying trait composition (Huang et al. 2002; Lavorel et al. 1998; Lavorel and Garnier 2002; McGill et al. 2006). As species richness increases, productivity and biomass of the system also increase (Chisholm et al. 2013).

Functional biodiversity is operationalized by identifying functional groups, indicating productive, ecological and operational functions in the ecosystem (Lavorel et al. 1998; Tilman 2001; Callo-Concha 2009). Plant functional groups are classified by functional traits that reveal their strategies in varying environments and in the face of changing resources (Tilman et al. 1997; Lavorel et al. 1998; Tilman 2001; Cornelissen et al. 2003; Lebrija-Trejos et al. 2010; Lohbeck et al. 2012). Plant functional groups are cohorts of species that share similar functioning at the stand level, and demonstrate similar responses to environmental factors and/or similar effects on ecosystem processes (Tilman et al. 1997; Lavorel et al. 1998; Tilman 2001; Cornelissen et al. 2003; Lebrija-Trejos et al. 2010; Lohbeck et al. 2012).

## *3.4 Successional Agroforestry Systems (SAFS)*

Incorporating a range of agroecology and agroforestry techniques as a transition phase early in forest restoration could be used to overcome socioeconomic and ecological obstacles to restoring these lands (Vieira et al. 2009). The management practices used in SAFS parallel those used in many forest restoration efforts. A range of agroforestry systems could be used as a transitional phase in restoration that simultaneously helps provide for human livelihoods, reduces the initial costs of restoration, and extends the time period of management of restoration. *What does this look like, conceptually?*

In a typical agricultural production system following disturbance using slash-and-burn methods of clearing land prior to cultivation (known as swidden agriculture), short-lived perennials (such as cassava) are planted after slash-and-burn. Fires intentionally ignited for agricultural management are a lethal or sub-lethal disturbance to the site for short-term agricultural production purposes (Fig. 8.1). Immediate consequences include the loss of plant and animal diversity from removal of habitat and, may also result in soil erosion and nutrient leaching, ultimately posing an ecological, nutritional, and economic threat to farming communities.

In contrast, SAFS seek to imitate the structure of natural ecosystems and take advantage of ecological interactions among species to mimic patterns of natural regeneration to provide long-term food security. Management of SAFS focuses on the selection, combination, and management of crops, and managing structural and functional diversity to promote complementary ethnobotanical plant associations, mitigating negative relationships such as allelopathy, and harnessing positive relationships such as cycling of carbon and nitrogen (Schulz et al. 1994). As such,

**Typical swidden agricultural production in the tropics**

**Before:** *Severe anthropogenic disturbance (slash and burn)*

**After:** *Short-lived perennials (such as cassava) are planted after slash and burn*

**Fig. 8.1** Management transition of swidden agriculture


**Fig. 8.2** Potential for SAFS to regenerate degraded agricultural systems

SAFS have been identified as an adaptive socio-ecological management approach that has the potential to improve tree-growth, stabilize crop yield productivity, regenerate degraded landscapes, and offset reforestation costs by providing seed sources (Schulz 2011; Vieira et al. 2009; Kelty 2000; Vaz 2000; Peneireiro 1999; Götsch 1992) (Fig. 8.2).

Silvicultural management of forest stands may be applied to SAFS models by following analogous phases of natural regeneration in adjacent native secondary forest stands to favor high-value ethnobotanical species and cash tree-crops, maximizing nutrient cycling and vertical growing space (Fig. 8.3). In successional agroforestry management, enriching the growing site with leguminous annuals and perennials mimics stand initiation by planting species tolerant to high UV radiation and poor soil quality (A). Nitrogen fixing woody trees, shrubs, and leguminous herbaceous ground cover can be integrated into the understory to provide ecosystem services (preventing erosion, moderating topsoil temperatures and soil moisture, and supporting nitrogen cycling for surrounding woody species—critical in tropical soils such as oxisols and alfisols), while also providing a food source (e.g. beans) for humans or livestock, and/or a source of seasonal income. Leguminous ground covers benefit the stand initiation of young agroforestry species by providing nutrients and moderating extreme temperatures and weather events. The shade from the newly established trees and shrubs also create an ideal "nursery" for the establishment of valued trees—such as fruit, nut, or timber species (B). As the system matures, available growing space is filled, and sunlight, water, and soil nutrients may become limited by heavy competition—much like in the stem exclusion phase of forest stand dynamics. This is the stage in which adaptive management and tree training (such as pruning, coppicing, pollarding, and thinning the stand) becomes critical to support the growing space and nutrient needs of high-value species (C). In the analogous "understory re-initiation" phase of SAFS, native secondary or selectively planted leguminous overstory trees (such as *Inga spp.* or *Erythrina spp.*) may serve as a shade-tree phase, promoting the establishment of high-market value understory crops (such as cacao, *Theobroma cacao;* coffee, *Coffea arabica*; yerba

| | | |
|---|---|---|
| A.<br>**Stand initiation/ Nurse phase I**<br><br>*Anthropogenic disturbance opens growing space for high-UV tolerant species.*<br><br>*Short-lived perennials tolerant of high UV and poor soils are planted after disturbance.* |  |  |
| **B.**<br>**Stand initiation/ Nurse phase II**<br><br>*Intensive enrichment plantings of herbaceous, nitrogen-fixing ground covers, short-lived perennials (e.g. bananas, cassava) and long-lived perennials (e.g. fruit or nut trees)* |  |  |
| **C.**<br>**Stem exclusion/ Training phase**<br><br>*Intensive pruning, coppicing, and pollarding (up to 95% of leaf canopy), and/or selective thinning. Trimmings are "chopped" into smaller pieces and "dropped" under high-value species to promote decomposition, moisture retention, and biomass production of regrowth to support light, moisture, and nutrient requirements of high value species at each vertical strata of the system.* |  |  |

**Fig. 8.3** Management transitions (A-E) of SAFS following successional analogues

| | | |
|---|---|---|
| **D.**<br>**Understory Re-initiation/ Shade-tree crop Phase**<br><br>*Natural regeneration of seedlings are permitted in understory until saplings surpass understory strata. Integrative and adaptive management (intensive pruning, selective thinning) is repeated [C]to maximize benefits of biomass accumulation and light, moisture, and nutrient requirements between complementary plant associations.* |  |  |
| **E.**<br>**Target goal: Diversified, agroforestry Systems**<br><br>*Multi-strata perennial polycultures maximize available growing space, nutrient resources, and diversify multiple harvests per year.* |  |  |

**Fig. 8.3** (continued)

mate, *Ilex paraguariensis;* or cardamom, *Elettaria cardamomum*) (D). Many conventional agroforestry systems stop there, but this is where SAFS stands apart. Niche micro-environments in mature agroforestry systems can be advantageously exploited to fill the spaces with additional species, diversifying the system with both ecological and economical outputs from other valuable woody and herbaceous species to spread the potential yields of food, fuels, fibers, medicines, precious timbers, and livestock fodder across the seasonal harvest periods and over time (E). As such, short term gains from annual crops and fruit harvests *and* long-term investments into precious hardwoods (such as mahogany, *Swietenia macrophylla;* teak, *Tectona grandis;* and rosewood, *Dalbergia spp.*) are achieved.

Many farmers focus on one or two harvest seasons per year with yields from just one or two crops, but they could spread out the returns in their yearly income to profit from a diversified harvest regime. While the management of a complex agroecosystem requires complex planning and initial investment, raising initial opportunity costs (particularly for smallholder farmers), single-species cropping systems are a risky business: they are highly susceptible to threats such as pests, diseases, and seasonal irregularities associated with climate change. SAFS offer an integrated, adaptive management approach to reduce ecological damage from intensive farm management, while diversifying yields and reducing the risks of harvest losses. All these translate into potential gains over time in farm income.

Management of SAFS can be designed to better mimic the structure and function of natural secondary successional development in native forests by selecting productive species that share the same functional traits within a plant functional group. Careful observation of both native forests adjacent to the agroforestry system and of the specific species chosen for the SAFS has the potential to increase agrobiodiversity, conserve native ethnobotanical species, add ecological complexity to strata structure and provide ample functional traits to maintain important ecosystem services such as nutrient cycling, soil quality, and water retention, as well as building biomass and habitat for animal species. For proper design and management of successional agroforestry systems it is vital to understand individual species requirements and how to pair them in successional plant associations to improve the functioning of agroforestry systems.

## 4 Case Studies of Successional Agroforestry Systems

*What does a theoretical SAFS that mimics the structure and function of secondary forest regeneration look like at the farm level?* Below, three experimental case studies are presented that highlight the theory of successional agroforestry principles in practice, and examine the limitations of further adoption of these systems.

### 4.1 Bahia, Brazil: Fazenda Olhos d'Agua

Successional agroforestry systems (SAFS) have been promoted by agronomist Ernst Götsch in Bahia, Brazil over the last 30 years as an approach for regenerating degraded soils and improving productive agro-ecosystems in degraded agricultural landscapes. In 1994, B. Schulz and B. Becker collaborated with Götsch to highlight the management of Fazenda Olhos d'Agua—Götsch's 500 ha farm in the Gandu District of southeastern Bahia. The farm was converted in 1985 from degraded pasture and secondary forest—with remnant fragments of primary forest—to 100 ha of cultivated agroforest over a 10-year time period (at time of 1994 publication). Initially, the farm was planted with cocoa as the main cash crop; however, due to the crash in the cocoa economy from the witch's broom fungus outbreak in the late 1980s, bananas became the primary source of income (Schulz et al. 1994). Management decisions were guided by the following objectives:

1. Protection of the soil from direct influence of weather (sun, wind, rain), resulting in reduced erosion and increased microbial activity.
2. Decrease of water loss by reduced run-off, improved drainage, higher water retention capacity, and decreased evaporation.
3. Humus accumulation.
4. Maximization of nutrient cycling.
5. Management of light and space for the cultivated species.
6. Management of positive and negative growth inhibition effects.

Plant selection followed two primary strategies: (i) *Native species without commercial value [were] deliberately left in or incorporated into the system,* and (ii) *A portion of the native species [were] substituted by eco-physiologically similar cultivated ones*. Management of the agroforest system was further guided by Götsch's two "working hypotheses": first, there is a *"growth reducing effect of maturing plants at the end of their life cycle on their neighboring plants,* and (conversely) *there is a growth stimulating effect by young plants on the vegetative development of adjacent plants"*. This likely refers to Connell and Slatyer's (1977) "inhibition" model (*growth reducing effect*) and the "facilitation" model (*growth stimulating effect*), which may be correlated with nutrient cycling associated with particular plant combinations. The latter assumption is echoed by Götsch's second working hypothesis: "*There is a positive relationship between carbon and nitrogen cycles within the cropping system and its productivity*." According to Schulz, Becker, and Götsch, removing plants just before they reach maturity may accelerate succession by "shortcutting the homeostatic phases of the different succession stages", removing any antagonistic growth reduction. In Götsch's system, 6 ha of land are managed at a time. Overstory species are intensively pruned (up to 95%) each year, and the trimmings are cut into smaller pieces and evenly distributed on the ground with larger branches placed on contour to prevent erosion. Intensive pruning regimes stimulate high biomass production (increasing foliar growth and fruit production), intensifies photosynthesis, increases moisture retention in soil and moderates ambient temperatures. Additionally, mulching made from "chopping and dropping" selected plants (such as banana stems, and maturing plants at the end of their life cycles) provides organic material from which microbiological activity can rapidly mineralize nutrients, building a rich topsoil supporting *in situ* nutrient cycling—much like a natural forest under assisted regeneration.

*What methodology is needed to quantify the validity of these claims?* Schulz, Becker, and Götsch attempted to estimate the annual amount of i) natural litter fall and plant material cut during cocoa (*Theobroma cacao)* cultivation in Götsch's SAFS, and ii) compared yields to conventional cocoa plantations of neighboring farms (Table 8.2). Results indicated that the 'forest garden' cacao management approach provides cocoa yields without the need for external inputs "at a level which, in the surrounding cocoa plantations, can only be attained by the use of considerable amounts of fertilizer and pesticides" (Schulz et al. 1994).

Whereas assisted natural regeneration relies upon seed trees and release methods of natural regeneration as the primary sources of seed dispersal and seedling establishment, SAFS like Götsch's use existing seed trees as nurse trees, and interplant collected seeds or seedlings from ethnobotanical and cash crop plants to occupy the gaps in the understory and fill in canopy levels over time. Natural regeneration of saplings in the understory beneath the cacao is left to grow until it has either i) surpassed the cacao, or ii) is occupying horizontal or vertical space. The natural regeneration is then incorporated into the system, either as a long-term investment for timber, or integrated into the intensive pruning regime. As such, SAFS rely on both active observation and keen knowledge of the particular site, as well as future trajectories based on physiological characteristics of the timber and non-timber forest crops.

In 2011, Schulz, J. compared two climatic regions in the northeast of Brazil, where smallholders have applied successional agroforestry methods. Schulz found that at the start, the SAFS had been very difficult to manage, as very limited yields of the plot coincided with a high workload. The first years of development of the successional system could only be supported by a newly introduced honey produc-

**Table 8.2** Annual litter and harvest yields and associated input quantities from a successional agroforestry system, a conventional cacao production system, and as noted in literature recommendations

| | *Fazenda Olhos d'Agua: SAF Cacao System* | Conventional Cacao Plantation | Literature recommendations |
|---|---|---|---|
| *Dry matter/mulch* (t/ha/year) | 8–16 | 1.5–5 | 5–20[a] |
| *Cocoa yield* (kg/ha) | 110–370 | 225[b] | – |
| *Inputs:* | | | |
| Fertilizers | 0 | 130 kg/ha (N)[b] | – |
| Pesticides | 0 | Fungicides[b] | – |

[a]Beer (1988)

[b]CEPLAC (Commissao Executiva do Plano da Lavoura Cacaueira), the Brazilian Cocoa Research Center

tion initiative, with the help of a local NGO (Schulz 2011). The workload of the system decreased proportionally with the development of the perennial plants and after 10 years the system required only low maintenance efforts, leaving sufficient time for the processing of food. After 10 years, the regeneration of the site had been achieved, enabling the provision of a wide variety of food for the subsistence of four persons, as well as sufficient supply of construction timber and firewood (Schulz 2011). Results suggest that degraded agricultural lands can be regenerated with SAFS. At the same time, crop diversification and increases in agricultural production lead to the regeneration of the subsistence basis of smallholder farmers.

## *4.2 Toledo District, Belize- Maya Mountain Research Farm (MMRF)*

Maya Mountain Research Farm (MMRF) is a registered NGO and research/training center in southern Belize that promotes the imitation of primary forest structure and services to create complex agroforestry systems as a means of ensuring food sovereignty and (agro)forest regeneration. MMRF is located approximately 3.2 km west from the predominantly K'ek'chi Mayan village of San Pedro Columbia in the District of Toledo in the foothills of the Maya Mountains, which range from 244 to 400 m.a.s.l. where limestone hills meet the plains. It is situated between a large unbroken tract of forest reserve (Columbia Forest Reserve) to the north and the Columbia branch of the Rio Grande to the south. The population of the Columbia Forest Reserve's fringe is composed almost entirely of K'ek'chi and Mopan Maya Indians. Sixteen villages are considered as being within daily communication distance, approximately 8 km from the management area. All are subsistence and/or cacao-producing farming communities, practicing some livestock grazing and rearing pigs, chickens, and some ducks. The local population in the Toledo District is home to the Garifuna, mixed communities with creole, Hispanic, East Indian, American, European, and further inland to the K'ek'chi and Mopan Maya.

MMRF was founded in 1988 by Christopher Nesbitt (Director of MMRF) first as a family homestead and later developed into an applied agroforestry experimentation farm. MMRF now manages approximately 28 ha of land, which functions as a genetic seed bank for indigenous species and as a buffer zone to the adjacent Columbia River Forest Reserve with his wife, Celini Logan. The only entrance is by foot trail or canoe. Across the river from MMRF is K'ek'chi Maya land in a reservation system, under the "alcalde" (town mayor) system introduced from Guatemala. In addition to agroforestry development, MMRF managed the Belizean Maya Ethnobotanical Research Project for the University of Florida, hosts interns, students, groups and volunteers, works with local NGO/CGO's, and, from 1997 to 2004, Christopher managed the Toledo Cacao Growers Association on behalf of the Green & Black Chocolate Company. MMRF currently provides training in renewable energy and holds an annual Permaculture Design Course for local, regional, and international students.

In the 1940s to late 1950s, the land was a "mahogany works" or area just used to harvest mahogany, being run by a family of creole/East Indian descent. Prior to MMRF, the site was cleared and planted as a citrus plantation, and used for grazing cattle until the soil was so leached and compacted that the intensive management supported very little production. Other disturbances included anthropogenic fires (swidden agriculture) and frequent hurricanes (in 2001, the area was devastated by Hurricane Iris).

MMRF's restoration strategy is to emulate the form and function of the primary rainforest (Fig.8.4). Since 1988, management at MMRF has focused on "induced patchiness", with concentrations of species in certain areas to facilitate easier harvesting, especially of seasonal crops, and better rates of pollination. MMRF is divided into different management and restoration strategies defining four different zones: (i) *wamil* (secondary forest), (ii) multi-level ("stacked") polycultures/complex agroforestry systems; (iii) sheep pasture; and (iv) alley cropping. Much of the food they eat themselves, and most of the food they raise is also used to feed their animals (pigs, chickens, ducks). By utilizing perennial crops, they maximize the "calorie production to energy expended" ratio (Heichel 1976). With a total of 28 ha, 12 ha are under adaptive management (primarily agroforestry). Of those 12 ha, approximately 11 ha are over 20 years old and consist of over 500 mixed species used for food, fiber, biofuels, firewood, precious timber, medicinal crops, marketable crops, and ornamentals. Approximately 1.4 ha has been cleared for sheep pasture. The remaining 12 ha are native secondary forest stands. Future plans include 4 ha of future sheep pasture for Barbados black belly sheep, comprised of humidi-

**Fig. 8.4** Diverse polyculture with native and exotic fruit and timber trees (Photo by Christopher Nesbitt)

cola (*Brachiaria humidicola*) and brizanta (*Urochloa brizantha*) grass for forage. Of the 28 ha, MMRF actively manages approximately 10 ha of land at a time.

Cacao (*Theobroma cacao*) production at MMRF is the main cash crop, providing high quality heirloom Mayan cacao varieties for local chocolate production. The seed parents of these rare varieties were collected by Nesbitt in the upper Bladen watershed with helicopter support from the British Army in 1999 as a way to address the devastation of the witch's broom fungus (*Taphrina betulina*) on hybrid cacao varieties introduced by USAID to southern Belizean K'ek'chi and Mopan Mayan growers in 1986 to foster sales to Hershey Foods. Cacao is an integral part of the agroforestry system at MMRF, and is placed beneath the shade of many species, including inga (*Inga edulis*). Amidst the cacao and inga, caimito (*Chrysophylum caimito* and *C. mexicanus*), banana (*Musa spp.*), jippy jappa palm (*Carludovica palmata*), coconut (*Cocos nucifera*), biriba (*Rollinia deliciosa*), avocado (*Persea americana*), coffee (*Coffea arabica*), cardamom (*Elettaria cardamomum*), bukut (*Cassia grandis*), and Pride of Barbados (*Ceasalpinia spp.*) are planted.

In MMRF's SAFS, diverse polycultures are created with fruit and timber trees. Both native timber species such as mahogany (*Swietenia macrophylla*), cedar (*Cedrela odorata*), guanacaste (*Enterolobium cyclocarpum*), mayflower (*Epigaea spp.*), and "samwood" or laurel (*Cordia alliodora*), and exotics such as teak (*Tectona grandis*) are utilized to maximize utility and value. Between timber trees, fruit trees such as mango (*Mangifera spp.*), avocado (*Persea americana*), mamey sapote (*Pouteria sapota*), *Rollinia spp.*, soursop (*Annona muricata*), noni (*Morinda citrifolia*), breadfruit (*Artocarpus altilis*), breadnut (*Brosimum alicastrum*), golden plum (*Spondias dulcis*), lime (*Citrus aurantifolia*), etc. are interplanted and, amongst those, understory species such as coffee (*Coffea arabica*), cacao (*T. cacao*), jippy jappa palm (*Cardulovica palmata*), coconut (*Cocus nucifera*) and other species fill micro-environment niches to maximize utility of sunlight, shade, and leaf litter decomposition. At the ground level, ginger (*Zingiber officinale*), pineapple (*Ananas comosus*), coconut (*C. nucifera*), turmeric (*Curcuma longa*), and leguminous plants like wild peanuts (*Arachis pintoi*) and *Desmodium* spp. are planted, and other herbaceous perennials such as banana and papaya (*Carica papaya*) serve as pioneer species, and are placed in the system where conditions are favorable for them, giving a quick return and providing biomass to the farm when harvested. MMRF demonstrates optimum SAFS management, whereby farmers carefully observe species' niche growing requirements, growth heights, widths, and rates, to take advantage of spatial niches and temporal windows of access to sunlight (or shade), rainfall, airflow (to prevent fungal disease), and leaf litter decomposition below and amongst species. In this way, MMRF maximizes use of vertical and horizontal space and potential for both short- and long-term returns.

In 2013, MMRF pioneered a former "wamil", or second growth, and converted it into "food forest" using *Erythrina spp.*, golden plum (*Spondias dulcis*), banana, polly redhead (*Hamelia erecta*), sugarcane (*Saccharum barberi*), coconut (*C. nucifera*), peach palm (*Bactris gasipaes*), mango (*Mangifera spp.*), laurel (*C. alliodora*), and interplanted with "pioneer-like species" such as cocoyam or taro (*Xanthosoma sagittifolium*), cassava (*M. esculenta*), banana (*Musa spp.*) and plantain (*Musa x* *paradisiaca*). The back is a section of existing agroforestry, formerly citrus, with cacao, coffee, turmeric, vanilla and ginger, amongst others, underneath.

To achieve their goals, MMRF starts disturbances to create niche environments to grow their agroforestry species of choice (Fig. 8.5). Using a method called "chop and drop", existing vegetation is cut by hand (machete) and "dropped" in place to allow for decomposition and prevent loss of biomass and nutrients from leaving the site. The newly cleared site is established with leguminous woody shrubs such as pigeon pea (*Cajanua cajan*). To mitigate erosion and slow water flow, pineapple (*A. comosus*), lemongrass (*Cymbopogon citratus*), and vetiver (*Chrysopogon zizanioides*) are planted on contour with banana, plantain, and Anjali (*Artocarpus hirsutus*). Lemongrass is planted in between rows of pineapple to stagger (or "stack") complementary structural profiles, and is particularly useful for holding the soil with its deep taproots, while also providing pest control with high aromatic oil content. *Arachis pintoi* is planted in alleys below this. When the rainy season begins, MMRF adds *Caesalpinia spp*. Each tree is mulched with lots of biomass (mostly dry leaves, but also some banana stems, a small amount of biochar and compost) in a "V" shape—a method known as "Mascarenhas Mulching method" after Kevin Mascarenhas, whom developed this specific application at MMRF in 2009. This shape slows the movement of water from uphill, dropping nutrients in the form of soil, manure, leaves, dirt, clay, flowers, stems and fruit, in the areas beneath the newly establishing trees where


**Fig. 8.5** MMRF restoration strategies and management

it is needed most. This mulching approach fosters healthy mycorrhizal fungal communities at the intersection of soil and decaying biomass.

Currently, monitoring is done daily (harvesting, site walks, installations), seasonally, and yearly. However, data are limited to qualitative evidence of growth/health of indicator species, an increase in soil litter, biomass, soil moisture retention and/or drainage, and forest cover and gap dynamics. Nevertheless, empirical evidence demonstrates that from 1989–2016, MMRF has achieved an increase in biomass (critical for carbon sequestration), improved soil fertility and soil moisture retention, the creation of wildlife habitat in a previously severely disturbed agricultural landscape, and has mitigated flooding. One critical indication for improved ecosystem functioning was discovered in 2014, when MMRF observed their vanilla plants had been naturally pollinated and were producing large quantities of valuable vanilla beans. This suggests the restoration strategies have successfully regenerated the habitat necessary for the vulnerable bee species (*Melipona spp.*) associated with naturally pollinating vanilla.

MMRF demonstrates that agro-reforestation using successional agroforestry principles can restore ecosystem services, improve soil quality, mitigate soil erosion, and provide food sovereignty. However, limitations in quantitative data hinder a clear understanding and evaluation of the effects of the management strategies over time. To improve assessment of the efficacy of management strategies, a consistent monitoring and evaluation protocol should be established. Additionally, market development may be addressed by working with pre-existing producer cooperatives for other non-timber forest products to increase economy of scale at the landscape level. These cooperatives could also put resources towards cooperatively managed tool "libraries", transportation, and processing into value-added products (such as dried fruit, etc.). Other potentials for incentivizing the adoption of successional agroforestry systems for biodiversity conservation and food sovereignty include payment for ecosystems services.

### *4.3 Isla de Ometepe, Nicaragua- Project Bona Fide*

Project Bona Fide is a multi-strata agroforestry research and demonstration farm that seeks to promote food sovereignty and an example of integrated agro-ecological design systems that mimic native forest structure and function. It is located in the southwest corner of Nicaragua, on a twin-peaked volcanic island in the tenth largest fresh water lake in the world (Lago Nicaragua). The island is home to approximately 40,000 inhabitants. Project Bona Fide seeks to be an experience-based learning center that aims to inspire local partners and people from all over the world to undertake their education through hands-on learning experiences with permaculture design, agroforestry, and community collaboration. Additionally, Project Bona Fide runs an organic agroforestry nursery with over 250 species of rare and/or endangered tropical fruits, nuts, hardwoods, and other multifunctional tree species. This nursery serves to provide the farm and community valuable seed and seedling stock, and is shared with local farmers from the island at their annual seed and plant exchanges during the rainy season. Saplings from the nursery are also sold to reforestation and landscaping projects throughout Nicaragua to earn additional income to support staff members.

In 2001, Michael Judd puchased a 10.5 ha property on the south-eastern side of Volcán Maderas on the twin-peaked volcanic island Isla de Ometepe. The site had been abandoned by local farmers, who had cleared the land of timber, and practiced swidden agriculture (primarily for maize and sorghum) until the land could no longer support agriculture. It was then heavily grazed with cattle until compacted and eroded, and no longer provided adequate nutrition for the cows. Judd cover-cropped approximately 7 ha with cow pea *(Vigna unguiculata L. Walp.)* and divided the property into five different management zones. In 2002, Christopher Shanks joined Judd to further develop agro-restoration strategies into more than a dozen different experimental management zones, to assay species suitability in the creation of niche micro-environments through initial windbreaks and dense plantings (Table 8.3).

Project Bona Fide's management approach for a newly opened site is to create "triangulated guild systems" to promote nutrient cycling (particularly nitrogen) through the introduction of leguminous groundcovers, and multifunctional shrubs and trees; build rapid biomass through selection of short-lived perennials (such as bananas or pigeon pea) and fast-growing woody species (ideal for firewood), that can be used to "chop and drop" branches and leaves for rapid *in situ* mulching around valuable fruit, nut, or hardwood trees planted on contour. The nitrogen-fixing shrubs or trees (such as *Gliricidia sepium*) provide wind protection and shade, fix nitrogen, *and* provide firewood and stakes through coppice and pollarding. The short-lived perennials also provide shade and windbreaks, and bananas have the added benefit of maintaining moisture in soil, providing moisture-rich organic material for mulch, *and* provide edible fruits. Once the desired trees begin to establish (approximately the same length of time it takes the bananas to lose their production), the bananas are chopped and dropped around the trees and removed. The gaps in the system are filled with other non-timber forest product species (fruits, nuts, oils, forage, etc.) and/or native or non-native timber species. Below, Fig. 8.6 illustrates this "guild" planting technique after one year of planting and seven years later.

Current practices of monitoring and evaluation follow adaptive management most appropriate to farmers. Daily farm walks, seasonal observations of weather events (such as heavy rains or extreme droughts) allow the farmers to tailor their management approach for the following season. Water flow has been directed to areas of species with higher moisture requirements and, with contour planting, has helped to keep soils from eroding. After 15 years of experimentation with both native and non-native timber and non-timber forest species, Project Bona Fide provides an example of how interplanting species of value can provide an extremely biodiverse agroforestry system that in time resembles a multi-strata forest. Future goals include developing systems to support the harvest and export of their products.

Like with other SAFS, management is focused on the daily operations of the farm. Therefore, data available on the performance of this system are limited to qualitative evidence of growth/health of indicator species, an increase in soil litter,

**Table 8.3** Project bona fide experimental zones and species

| Experimental zones (year began) | Principal species | Supporting species |
|---|---|---|
| Mixed agroforest (2002) | Malabar chestnut (*Pachira aquatic*), pejibaye (*Bactris gasipaes),* coffee (*Coffea arabica, C. robusta),* banana (*Musa paradisiaca),* plantain *(Musa x paradisiaca)*, mango (*Mangifera indica*), tamarind (*Tamarindus indica)*, cashew (*Anacardium occidentale),* ackee (*Blighia sapida),* guanabana (*Annona muricata)*, custard apple (*Annona reticulata),* cinnamon (*Cinnamomum zelanicum)*, nispero (*Manilkara sapota),* jackfruit (*Artocarpus heterophyllum)*, canistel (*Pouteria campechiana),* star apple (*Chrysophyllum cainito)* | |
| Mango with palm overstory (2002) | Mango (*Mangifera indica*, var. Ford, Hayden, and Baptista), palma real *(Sabal mexicana*), coconut (*Cocos nucifera*), pejibaye (*Bactris gasipaes*) | Nitrogen-fixing trees: Madero negro (*Gliricida sepium*),<br>Other: madroño (*Calycophyllum candidissimum*), coffee (*Coffea arabica* and *C. robusta*), and cacao (*Theobroma cacao*) |
| Citrus trials (2002) | Many *Citrus spp.* hybrids (grafted) and seedling trials (3–9 varieties of each): orange, grapefruit, mandarins, limes, lemons, kumquat, pomelo, calamondin | Nitrogen-fixing trees: *Leucaena spp., Cassia siamea, Gliricidia sepium, Delonix regia*<br>Other: *Moringa oleifera* |
| Research triangle (2003) | Grafted citrus, Wampi (*Clausena lansium*), Pink wampi (*Clausena excavata)*, Atemoya (*Annona annona x atemoya*), Bael fruit (*Aegle marmelos*), khirni (*Manilkara hexandra*), Natal plum (*Carissa grandiflora*), Pomegranate (*Punica granatum*), curry tree (*Murraya koenigii*), Bignai fruit (*Antidesma bunius*), grafted nispero (*Manilkara huberi*), grafted canistel/ross sapote (*Pouteria campechiana*), white sapote (*Casimiroa edulis*), grafted jackfruit (*Artocarpus heterophyllus*) | Nitrogen-fixing trees: Leucaena (*Leucaena leucocephala*), pheasantwood (*Cassia siamea*).<br>Other: Moringa (*Moringa oleifera*) |
| Bamboo alley windbreak (2005) | *Dendrocalamus spp.*, *Bambusa stenostachya*, *Gigantachloa atter*, *Guadua spp.*, *Bambusa textilis*, *Bambusa oldhamii*, *Dendrocalamus giganteus*, *Bambusa dolichoclada*, and one unknown *Bambusa spp.* | Other: Canistel (*Pouteria campechiana*), mamey (*Pouteria sapota*), ackee (*Blighia sapida*), nispero (*Manilkara huberi*), and caimito (*Chrysophyllum caimito*) |

(continued)

**Table 8.3** (continued)

| Experimental zones (year began) | Principal species | Supporting species |
|---|---|---|
| Guanabana and avocado (2006) | Guanabana (*Annona muricata)*, avocado (*Persea americana)*, coconut (*Cocos nucifera)* | Nitrogen fixing species: Malinche (*Delonix regia*), *Erythrina spp., Leucaena spp., Bauhinia spp* |
| Pig forage system (2005) | Avocado (*P. americana*), coconut (*C. nucifera*), jackfruit (*A. heterophyllus*), star fruit (*Averrhoa carambola*), canistel (*P. campechiana*), guanabana (*A. muricata*), jocote (*Spondias purpurea*), Mayan breadnut (*Brosimum alicastrum*), citrus, guajilote (*Paramentiera edulis*), Malabar chestnut (*Pachira aquatica*). | *Erythrina spp., Gliricidia sepium, Leucaena spp.* |
| Breadfruit and palmyra (2006) | Breadfruit (*Artocarpus altilis*) and Palmyra palm (*Borassus flabellifer*) | *Leucaena spp.*, banana (*Musa spp*.), *Hibiscus tiliaceus* |
| Jackfruit and pejibaye (2007) | Jackfruit (*A. heterophyllum)*, pejibaye (*Bactris gasipaes*) Brazilian firetree (*Schizlobium parahybum*) | Cacao *(Theobroma cacao),* False mangosteen (*Garcinia xathochumus*)*, Cassia siamea, Erythrina spp., Albizia guachapele* |
| Resilient salad perennials (2007) | Chaya (*Cnidosculus chayamansa),* moringa (*Moringa oleifera),* katuk (*Sauropus androgynous),* Haitian basket vine (*Trichostigma octandrum),* sunset hibiscus (*Abelmoschus esculenta),* Brazilian spinach (*Alternanthera sisoo)*, Okinawan spinach *(Gynura crepioides),* cranberry hibiscus *(Hibiscus acetosella)* | |
| Mixed agroforest (2007) | Biriba (*Rollinia deliciosa*), Custard apple (*Annona reticulata*), Amla fruit (*Phyllanthus emblica*), Nispero (*Manilkara zapota*), Rose apple (*Syzygium jambos*) | Brazilian firetree (*Schizlobium parahybum*), Mountain sugar apple (*Annona spp.*)., Jinocuavo (*Bursera simaruba*), Yellow bamboo (*Bambusa vulgaris*) |
| Homestead nut system (2008) | Candlenut *(Aleurites molucan*a), jackfruit (*Artocarpus heterophyllus*), Mayan bread nut (*Brosimum alicastrum*), pejibaye (*Bactris gasipaes*), Malabar chestnut (*Pachira aquatica*), rubber tree (*Hevea brasiliensis*) | *Schizlobium parahybum*, coffee (*Coffea arabica* and *C. robusta*) |
| Sapotaceae conservation area (2009) | Pan de vida fruit (*Pouteria hypoglauca)* | *Gliricida sepium, Delonix regia, Leucaena leucocephala* |

(continued)

**Table 8.3** (continued)

| Experimental zones (year began) | Principal species | Supporting species |
|---|---|---|
| Annual alley croppping (2010) | *Leucaena spp., Caesalpinia velutina, Gliricidia sepium, Acacia albidia, Sabal mexicana, Delonix regia,* Yellow trumpetbush *(Tecoma stans),* Madroño (*Calycophyllum candidissimum)*, vetiver (*Chrysopogon zizanioides*), Moringa (*Moringa oleifera*) | Maize (*Zea mays)*, Sorghum (*Sorghum bicolor*), Pigeon pea (*Cajanus cajan)*, velvet bean (*Mucuna pruriens),* coconut (*C. nucifera*) |
| Heritage Jocote Conservation (2010) | *Spondias purpurea* (both cultivated and wild) | Native groundcovers |
| Coffee, cinnamon, and coconuts (2010) | *Coconut nucifera, Coffea arabica, Cinnamomum zeylanicum* | Turmeric (*Curcuma longa),* palma real (*Sabal mexicana),* leucaena *(Leucaena leucocephala),* and Brazilian firetree (*Schizlobium parahybum*) |
| Oil polyculture (2010) | African oil palm (*Elaeis guineensis*), South American oil palm (*Elaeis oleifera*), and Jatropha (*Jatropha curcas*) | Malinche (*Delonix regia*), *Gliricidia sepium,* pigeon pea (*Cajanus cajan)* |
| Tree cereals trials (2011) | Malabar chestnut (*Pachira aquatica),* Maya nut or *ojoche (Brosimum alicastrum*), Ackee (*Blighia sapida*) | *Gliricidia sepium* and *Delonix regia* |
| Pulasaan and Pili nut (2011) | Pili nut (*Canarium spp.),* Pulasaan (*Nephelium mutabile)* | *Acacia mangium, Leucaena spp.,* cassava (*Manihot esculenta),* taro (*Colocasia esculenta)* |
| Surinam cherry slope (2011) | Surinam cherry (*Eugenia uniflora*) | Papaya (*Carica papaya*), *Citrus spp.* |
| *Psidium* collection (2011) | Strawberry guava- yellow and red (*Psidium cattleianum*) Cas guava (*Psidium friedrichsthalianum),* common guava (*Psidium guajava),* Brazilian guava (*Psidium guineense)* | Pheasantwood (*Cassia siamea),* rose apple (*Syzygium jambos)* |
| Plantain orchard (2011) | Plantain (*Musa x paradisiaca*), red sapote, nispero, canistel (*P. campechiana*), *Bambusa spp.,* caimito, and Maya nut (*P. aquatica)* | Nitrogen fixing species: Malinche (*Delonix regia*), *Erythrina spp.*, *Leucaena spp*., and *Bauhinia spp.* |
| Mesoamerican tree crop conservation (2011) | Maya nut (*P. aquatica)*, canistel, jocote, caimito, sugar apple (*Annona squamosa)* | Neem (*Azadiracta indica),* elephant grass, nitrogen fixing trees |
| Rambutan trial orchard (2012) | Rambutan (*Nephelium lappaceum)* | *Leucanea leucocephala,* pheasantwood (*Cassia siamea), Moringa oleifera* |

(continued)

**Table 8.3** (continued)

| Experimental zones (year began) | Principal species | Supporting species |
|---|---|---|
| Jackfruit and nitrogen-fixer windbreak (2012) | Jackfruit (*Artocarpus heterophylum), Cassia siamea, Delonix regia* | Taro and Moringa |
| Agro-silvopasture (2012) | Native pasture grasses, elephant grass (*Pennisetum purpureum)*, canistel (*P. campechiana*), mamey (*P. sapota*), red sapote, jackfruit (*A. heterophyllus)*, nispero (*Manilkara sapota)*, Mayan breadnut (*Brosimum alicastrum*), Malabar chestnut (*P. aquatica)* | *Delonix regia, Leucaena spp., Moringa oleifera* |
| Native bamboo conservation (2012) | *Guadua amplexifolia* | |
| Greywater forest garden (2014) | Taiwan grass (*Pennisetum purpureum),* Citrus (*Citrus spp.),* Soursop (*Annona muricata),* vetiver grass (*Chrysopogon zizanioides),* banana (*Musa paradisiaca),* Surinam cherry (*Eugenia uniflora)* | *Acacia mangium* and *Flemingia spp.* |

**Fig. 8.6** Triangulated guild technique at initial planting (left) and 7 years later (right)

biomass, soil moisture retention and/or drainage, and forest cover and gap dynamics. Nevertheless, empirical evidence demonstrates that from 2001–2016, Project Bona Fide has achieved an increase in biomass (critical for carbon sequestration), improved soil fertility and soil moisture retention, mitigation of erosion and flooding, wildlife corridor connectivity, the creation of wildlife habitat in a previously severely disturbed agricultural landscape, and food sovereignty**.**

## 5 Conclusion

Successional agroforestry has great potential to (i) promote biodiversity in agricultural systems, (ii) reduce risks associated with mono-cropped commodities, (iii) regenerate degraded agricultural landscapes, and (iv) reconnect fragmented landscapes to native forest stands of vulnerable ecosystems. The concept of successional agroforestry integrates indigenous knowledge of intercropping multi-purpose subsistence species, modern agroforestry and horticultural techniques such as alley cropping and intensive pruning, and applications of assisted natural regeneration to emphasize maturity, biodiversity, and the use of ecological succession to establish a productive forest system. Various succession models and silviculture practices give us insights into managing SAFS.

Much like the adaptive management of assisted regeneration of forest stands, mimicking natural ecosystems in agroecosystems requires the knowledge of species-specific survival, growth, functional traits, and niche requirements in order to appropriately select multi-functional species and to develop ideal spatial arrangements for stratified stand structures. For its successful adoption, agroforestry managers must have a working knowledge of natural successional development and tropical forest stand dynamics to manage their system appropriately. Experimental case studies from SAFS indicate a dearth of quantitative data, critical for understanding long-term effects of management approaches. These systems are highly complex, and knowledge and labor intensive—particularly during the first five to ten years of establishment—until management focuses on thinning, pruning, coppicing, and pollarding for improved harvest. Without quantitative evidence of the socio-economic and ecological benefits for adopting a more complex agroforestry system at the farm level, adoption by local farmers will continue to be limited. Data on soil erosion, nutrient leaching, soil quality, crop yields, and farmer income before and after agroforestry development as compared to other local/regional data would be an important first step along these lines.

Ultimately, widespread adoption is undoubtedly hindered by poor local and regional infrastructure (such as processing and transportation), and by a lack of local, regional, and global market incentives. Markets are currently unable to support the high biodiversity of farm yields that do not reach economy of scale, thus attention is needed to harness cooperative approaches to address these economic and infrastructure limitations. Farmer-to-farmer field school models, utilized in more conventional agricultural development, may prove promising for addressing the knowledge gap to attract new adopters of SAFS at the local and regional levels—thereby achieving economy of scale at the landscape level. Nevertheless, despite these current limitations, SAFS show great promise as an innovative approach to increase agro-biodiversity, regenerate severely disturbed agricultural landscapes, diversify harvest yields, and reduce ecological and economic risks associated with conventional agricultural systems.

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# Chapter 9
# Small-Scale Açaí in the Global Market: Adding Value to Ensure Sustained Income for Forest Farmers in the Amazon Estuary

**Leonora Genya Pepper and Lívia De Freitas Navegantes Alves**

> **"O açaí para os Paraenses é sagrado."**
> (For the people of Pará, açaí is sacred.)
> – Carlinhos
> Curralinho, Marajó
> October 28, 2015

## 1 Introduction

Today we often hear about the damages inflicted on the environment and on traditional communities by conventional agriculture. The way we grow our food, fibers and fuels calls for the rampant use of agrochemicals, leads to the disappearance of topsoil, drives loss of biodiversity and in some places causes desertification. Small farmers often lose out as land ownership is concentrated and commodity markets favor mechanization and economies of scale.

A far cry from this bleak picture are the floodplain forest systems managed for açaí production in the Amazon estuary. Açaí agroextractivism yields an abundant,

L. G. Pepper (✉)
Fulbright Commission, Brazil 2015

Yale University School of Forestry & Environmental Studies, New Haven, CT, USA
e-mail: leonora.pepper@yale.edu; leonora.pepper@fulbrightmail.org

L. De Freitas Navegantes Alves
Núcleo de Ciências Agrárias e Desenvolvimento Rural, Universidade Federal do Pará, Belém, PA, Brazil
e-mail: lnavegantes@ufpa.br



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**Fig. 9.1** Family farmers beneath the canopy of an açaí agroextractive forest (Photo: L. Pepper)

calorie-rich crop from within the shade of native floodplain forest (Fig. 9.1). This system is *de facto* organic—without synthetic inputs or pesticides—and lucrative enough to provide the chief source of income to the rural population on a regional scale (Brondizio 2008).

In the Amazon estuary, açaí fruit has long been a dietary staple for rural populations. In fact, açaí seeds have been found in archeological sites on Marajó Island that date back thousands of years (Smith 2002). Today, açaí comprises more than half of a typical rural family's caloric intake (Brondizio and Siqueira 1997). At rural tables, the menu may include a spread of fresh shrimp, fish, rice, manioc flour or other fare, but without bowls of smooth purple açaí pulp, it quite literally may not be considered a meal. In the city, discussions on the best way to enjoy açaí never get old; some people mix in sugar or manioc flour while others prefer it plain and unadulterated.

Beyond its importance to regional identity, açaí cultivation and sale provide the cornerstone of income generation for a multitude of people. Small-scale forest farmers, hired hands who scale the palms to harvest açaí, boat operators who ferry baskets of the fruit to market wharfs before dawn, workers at regional processing plants, and the *batedores* who sell the pulp by the liter from small storefront stands (Fig. 9.2)—estimated at more than 3000 in Belém alone (Cialdella and Alves 2014)—all make up the vast web of commerce that supplies açaí to the region and the world (Fig. 9.3).


Fig. 9.2 Açaí stands in Belém sell açaí by the liter until the day's supply runs out (Photo: L. Pepper)

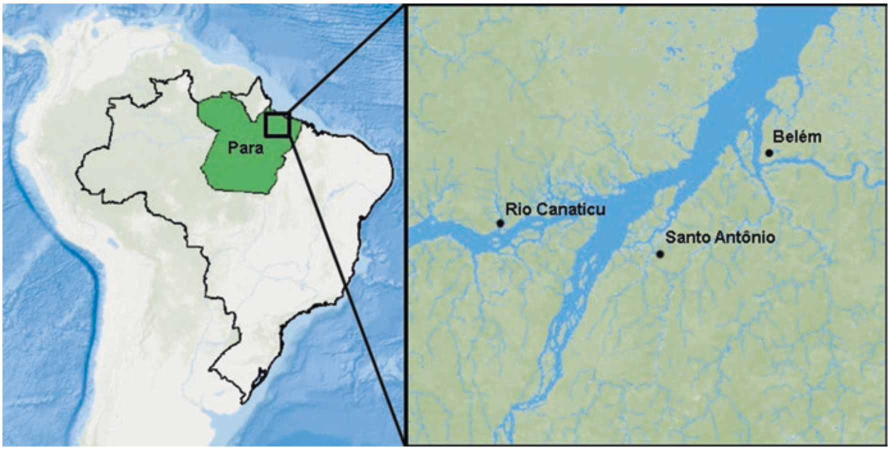


Fig. 9.3 Amazon estuary and study field sites. GIS data used for map based on: World Ocean Base – Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors

The livelihood of each of these stakeholders rests on the enduring viability of traditional açaí production in the estuarine region. However, "the increasing number of companies concerned with targeting volume rather than quality neglects the importance of close relationships existing between producers, intermediaries and traditional market points" (Cialdella and Alves 2014). Thus it remains to be seen whether traditional açaí production will be outcompeted by agribusinesses, or whether it will diverge from the emerging industrial agriculture trend as a higher-quality product. Will buyers beyond the Amazon region recognize that not all açaí is of equal quality? Will açaí cultivation endure as an economically viable occupation for a large part of the rural population? Will it continue to represent an ecologically sound production model on the estuary floodplain?

A key opportunity in this complex equation lies in certification. Certification can open new marketing channels, enable entry to more competitive markets, generate a price premium, facilitate greater access to capital, and encourage biodiversity conservation; these benefits, however, can remain out of reach for family farmers and small cooperatives due to the high costs of implementation (Braga 2015). In Brazil, few certification programs are tailored to the realities of the Amazon region, much less to the relatively little-known floodplain forests of the estuary. However, new opportunities for certification are emerging.

This chapter examines the possibilities and limitations of existing certification programs within the context of small-scale floodplain açaí production. Drawing on field observation and interviews in two açaí-producing river communities, it addresses the utility that river farmers see in certification and presents several certification options accessible to this demographic of forest farmer. In considering the potential of certification as a tool for setting apart small-scale, island-grown organic açaí from açaí of lesser quality, and for facilitating access to buyers willing to pay a premium for higher quality fruit grown under environmentally sound forest management, this research seeks to contribute to the pursuit of marketing options adapted to the realities of the small-scale production of açaí and other non-timber forest products of the Amazon estuary.

## 2 Traditional Açaí Production

The açaí palm is native to the Amazon region of Brazil. It is one of many plant species that comprise the traditional mix of forest products cultivated in the floodplain forests of the Amazon estuary, called *várzea*. High above the ground, açaí's marble-sized purple fruits grow in bunches hand-harvested by forest farmers of the floodplain river communities.

Açaí is traditionally produced in agroextractive systems called *açaizais* (singular *açaizal*). This term, according to Brondizio and Siqueira (1997), "encompasses different intensities of management, population densities, vegetation structure, as well as a wide range of species composition." These systems can include other palms such as pupunha *(Bactris gasipaes)* and miriti *(Mauritia flexuosa)*, as well as plants used for fiber, oil producers such as andiroba *(Carapa guianensis)* and virola (also known as ucuúba) *(Virola surinamensis)*, and a wealth of fruits including cacao, cupuaçu *(Theobroma grandiflorum)*, bananas, citrus, guava, papaya and mango.

Areas of açaí cultivation blend the boundary between forest and agroforest because of the wide range of management intensities. As açaí is native to the floodplain forest, it occurs naturally and can be harvested purely "extractively", with no direct management. Small-scale producers in areas of várzea often manage for higher densities of trees, such that density is highest in the area directly surrounding their houses and diminishes moving further into the forest, depending on the size of pro-

**Fig. 9.4** Boat moored in front of a river family's house framed by açaí palms (Photo: L. Pepper)

duction (Fig. 9.4). In other cases, the "açaízal" can be a short canoe ride away. Thus the boundary between cultivation and extractivism is fluid and difficult to pinpoint.

This fluidity is reflected in the várzea ecosystem where açaí characteristically grows. Here the boundary between forest and river is tenuous. Flooding can be daily, with the tides, or seasonal during the rainy part of the year (Montagnini and Muñiz-Miret 1999). Floodwaters vary greatly in salinity depending on the ratio of rainfall to estuarine tidewater, and even freshwater from the river varies in nutrient content and color. It can be clear, whitish from high clay and silt content, or stained dark from the tannins in leaf litter. Because of salinity and periodic inundation, várzea tends to have lower tree species diversity than upland forest (Montagnini and Muñiz-Miret 1999; Brondizio 2008).

Across the estuary region, freshwater bays and rivers both small and mighty rise and fall according to the tidal rhythms of the open ocean downriver. From the front docks of dwellings on the Amazon's innumerable small offshoots, it is possible to observe a moment of stillness when the river is "full", and then witness the current switch direction as it begins to empty. Daily inundations of the floodplain forest during the growing season bring a flush of nutrients that provide natural fertilization to the açaí agroextractive systems. Here mechanized equipment is ineffective, and applications of herbicide and insecticide would be quickly washed away.

Within traditional floodplain production, management practices are evolving. *Euterpe oleracea* Mart. differs from other closely related palms in its multiple stems that grow from one base clump (Jardim 2002). This characteristic shapes management techniques and facilitates the extraction of heart of palm as a by-product. An açaí clump can include numerous stems, but best management practices now

**Fig. 9.5** Ripening açaí fruit (Photo: L. Pepper)

recommend limiting each clump to approximately four stems—two tall, one intermediate and one emerging (Herraiz and Ribeiro 2013). When one of the tall stems is deemed too tall or otherwise structurally unsound (thus presenting harvesters with greater risk of falling), it is cut, allowing the younger stems to replace it.

The harvest season stretches over a three to six-month period each year, offset slightly across the expanse of the estuary. Beginning in July on the eastern side, the small round fruits clustered at the top of each açaí stem begin to deepen to a purplish black (Fig. 9.5). By August, harvest season is in full swing.

From the ground, açaí producers are experts in assessing whether a particular bunch of fruit, high in the canopy, is ripe and ready for harvest. This is a critical moment in determining the quality of the açaí. To deliver the best flavor when pulped, the round fruits cannot exhibit any lingering green; in the words of countless producers, it must be "bem preto" (very black). Even more highly valued are the fruits that have progressed beyond the glossy dark purple to display an ashy bloom on their skin. This "açaí tuíra" is the finest harvest. A high quality product therefore requires meticulous selection, an ability acquired through dedicated time and experience. River families are well accustomed to this discerning task, as consuming the best açaí is both habit and a point of pride.

The best time of day to harvest is in the early morning. Açaí fruits have higher moisture content before the sun reaches full strength, making for higher quality and yield. Furthermore, after around 10 o'clock the stems heat up until a person harvesting risks burning the arches of his or her bare feet with the friction of the descent (Fig. 9.6). All able-bodied family members help with the harvest, ascending three to eight meters into the canopy or waiting below to strip the fruit into wicker baskets. These baskets, when full, weigh approximately 14 kg and are the standard transport container and unit of trade for açaí on the rivers and portside markets (Fig. 9.7).

**Fig. 9.6** A producer reacts to attempting the ascent up an açaí stem with boots on (Photo: L. Pepper)

**Fig. 9.7** Harvested açaí ready for transport (Photo: L. Pepper)

# 3 Açaí Market Growth

Beginning in the 1960s, a widespread rural-urban migration brought demand for açaí to the cities (Brondizio 2008). People arriving from rural areas were accustomed to açaí as a main part of their diet, and they retained this custom even after settling in urban areas. This migration can be seen as having generated the first wave of growth in demand for açaí outside the rural areas where it is cultivated. Now the juice is widely consumed across the general population in the eastern Amazon, both rural and urban, and holds cultural importance as a symbol for regional identity.

The next wave of market growth occurred in the 1990s when açaí became popular in the South of Brazil. It is now commonly frozen and shipped throughout Brazil and internationally, where it is consumed as pulp or juice and used as an ingredient in an array of specialty food products. Claims to its energetic and antioxidant powers have led to its characterization as an Amazonian "super food" (Cialdella and Alves 2014), while Brondízio has broadly referred to it as a "fashion food" (2004, 2008). With global demand, annual açaí production in Brazil has grown significantly; between 2000 and 2011, production increased from 121,800 to 215,381 tons (IBGE 2000, 2011) and has since remained at approximately 200,000 each year.

The recent expansion in demand for açaí across Brazil and internationally has presented small-scale açaí producers with the opportunity to earn significant income from a commodity that, until not too long ago, didn't reach beyond local markets. Demand for açaí continues to increase, as does the number of processing plants in Pará state where the lion's share of açaí is grown. In fact, according to the Brazilian Institute of Geography and Statistics (IBGE), açaí is now Brazil's main agroforestry food product by value, and second only to yerba mate in quantity (IBGE 2011, 2012, 2013, 2014). According to Brondizio (2008), açaí fruit "has become the most important income source for a vast majority of riverine households." As such, it has been an key catalyst for the conservation of floodplain forest throughout the Amazon estuary, in some cases driving an increase in forest cover (Brondizio 2008; Padoch et al. 2008).

In spite of the opportunities presented by the growing global demand, small-scale producers face several significant challenges in the cultivation and sale of their açaí.

# 4 Emergent Challenges

## *4.1 Açaí Ecology and Land Use*

For forest farmers, açaí promises income that no other crop can currently match. The result is higher densities of the açaí palm within the floodplain forest. Meanwhile, other tree species are cut or phased out little by little to make way for more açaí seedlings (Cialdella and Alves 2014). Consequently, some parcels that were once covered with a mixed-species floodplain canopy now more closely resemble açaí monoculture (Fig. 9.8). Because açaí cultivation is so widespread,

**Fig. 9.8** An intensified açaizal has few larger canopy trees for shade, habitat and forest diversity (Photo: L. Pepper)

this increasing intensity presents a threat to the biodiversity of floodplain forest on a regional scale.

Besides supporting less biodiversity, parcels dominated by açaí represent a step away from forest and toward more conventional, single-species agriculture. They bring inherent risks of monoculture systems, such as the possibility of heightened vulnerability to pests (Ratnadass et al. 2012).

Some farmers are cognizant of the importance of retaining forest structure. An intact overstory provides shade down to the forest floor and habitat for várzea wildlife. There are those who maintain that a shaded system is good for production—the resulting açaí has superior flavor and better yield once it is pulped. A producer on the Canaticu River, Marajó, explained that roughly half of his family's area of production is under native tree cover while the other half consists mostly of açaí. The fruit growing in the latter, more exposed area has been drying out before it is ready to be harvested. This is one reason to maintain or reintegrate a mixed composition of trees in the açaizal.

In the more diverse açaízais, açaí palms are interspersed with a profusion of valued species including citrus, mango and other fruits, medicinals, and trees and palms for timber, paddle making, roofing and basket weaving. Trees such as andiroba, murumuru *(Astrocaryum murumuru)* and copaiba *(Copaifera langsdorfii)* produce oil-rich seeds valued for use in industrial and artisanal cosmetics. Also present are rubber trees (*Hevea brasiliensis*), relics of the rubber boom, which still display repeating V-shaped scars at the bases of their trunks.

A disadvantage to this diversified approach to açaí cultivation is that the palms only begin producing fruit once they are relatively tall. In contrast, in the parcels with higher densities of açaí and fewer canopy trees to cast shade, the palms produce when their crown is only a couple of meters above head height. This makes harvesting a much easier affair. Under a shady canopy, the taller stems present a heightened risk of falling to those harvesting the fruit.

### 4.2 *Informal and Marginalized*

Much of the regional açaí economy is informal. Açaí processing plants in Belém, Castanhal, Macapá and smaller local cities rely heavily on small-scale producers to supply their raw material but in most cases have no formal agreement or contract with them. Middlemen who do the direct negotiating with both parties facilitate this anonymity. Furthermore, local governments capture tax revenue from only a fraction of this booming regional market: in the state of Pará, açaí only generates tax revenue within the formalized industry of processing plants. Municipalities lose out on the enormous volume of daily transactions surrounding açaí that play out informally in local ports and markets (Fig. 9.9) (Brondizio 2011).

According to the president of Santo Antônio, Igarapé-Miri, the municipal government does not keep track of the amount of açaí produced, while there are family producers who keep incredibly detailed records of their management, production and sale of the fruit. He maintains that if even R$0.50 (approximately $0.15 USD) were captured from each basket of açaí, Igarapé-Miri would be the richest municipality in this part of Pará.

**Fig. 9.9** Empty 14-kg baskets accumulate behind dockworkers unloading açaí (Photo: L. Pepper)

Despite the magnitude of the market that revolves around açaí, traditional producers remain marginalized, their role largely undervalued in the public eye. Muñiz-Miret et al. maintain that production of non-timber forest products is commonly misunderstood and assumed to "not involve any manipulation of the natural forest" (Muñiz-Miret et al. 1996). Similarly, Brondízio argues that the term "extractivist" carries historic cultural connotations that suggest passive appropriation of a natural resource. The term therefore disregards the enormous role that açaí producers play in feeding the region and shaping its ecology. A better term is "forest farmer", as it better acknowledges producers' expertise and role in actively shaping the natural environment for food production (Brondizio and Siqueira 1997; Brondizio 2008). Alternatively, "agroextractivism" also encompasses the social and economic importance of this active and specialized production system.

### *4.3 Access to Market*

For many, the geography of the estuary continues to pose difficulties in accessing the market. Producers on remote river tributaries often depend on intermediaries to transport their harvest, by boat, to urban centers or processing plants, typically within 24 h after harvest. Because it is so perishable, açaí produced closer to these consumption centers fetches higher prices. In more remote areas, such as the southern part of Marajó Island, the value of the harvest depreciates in the time it takes to reach the buyer.

Luckily, açaí is "one of the rare products for which demand is greater than supply" (Cialdella and Alves 2014). A producer on the Canaticu River confirmed this, saying that açaí "is maybe the only product that doesn't face competition, even during the harvest season. There's no way. As long as you've got it, you can sell it." In all but the most remote corners of the estuary, competition among intermediaries prevents them from being too cutthroat in their pricing. Even so, this step in the supply chain is one of the factors that limits the income return to producers (Jardim 2002).

In some communities, the implementation of collective marketing models is shifting the way producers connect to the growing global market. Aggregation of the açaí harvest can allow member producers to bypass intermediaries and sell directly to industrial buyers, in this way gaining access to differentiated markets.

### *4.4 Expanding Production and Market Competition*

In light of the economic opportunities presented by domestic and international demand for açaí, a lot of investment is currently going into its cultivation. Small-scale farmers are not the only ones increasing production area and intensity. Larger landowners and enterprises are also investing in large-scale plantations in areas of upland “terra firme” (Cialdella and Alves 2014). Some ranchers are even converting cattle pasture to açaí production.

While this is a small shift away from an exceptionally detrimental use of land in the eastern Amazon, these upland plantations differ dramatically from the várzea systems. They tend to be sun-drenched monocrops of açaí planted in easily mechanized rows. Terra firme is drier, and has a different forest profile than the “várzea” floodplain forests where the largest populations of açaí naturally grow (Montagnini and Muñiz-Miret 1999). Without the daily flooding that occurs in its forest of origin, the palm requires irrigation, as well as synthetic agricultural inputs that are entirely absent from traditional cultivation (Cialdella and Alves 2014). These systems therefore do not conform to organic standards.

With the expansion of upland production, the Brazilian Agricultural Research Corporation (EMBRAPA) has gone so far as to develop a dwarf açaí cultivar, “BRS Pará”, which is specifically adapted to cultivation on terra firme (Fioravanti 2013). BRS Pará produces early, at only 3 years, and its squat height lends well to mechanized harvest.

Is there a resulting difference in quality between floodplain and plantation grown açaí? Undoubtedly. In Belém, the capital city of Pará, signs outside açaí stands advertise “Açaí da Ilha”, a term bestowed on açaí originating from the várzea islands surrounding the city. This is the choicest açaí, and local purveyors each source from their preferred island of origin. City inhabitants, in turn, tend to be adamantly loyal to their favored purveyor. On the industrial side, however, the situation is different.

Zones of terra firme tend to be more geographically accessible to mainland processing plants than production areas in more remote, floodplain forest (Cialdella and Alves 2014). Due to this accessibility, as well as the larger scale of production, many buyers don’t mind that quality doesn’t match that of the traditionally grown island açaí. A common complaint of traditional producers is that companies that buy and process açaí don’t care at all about quality, being preocupied exclusively with meeting their quotas (personal observation, Igarapé-Miri PA, 2015; Cialdella and Alves 2014). In this context, the high quality of small-scale várzea açaí goes unrecognized and unrewarded.

Family farmers in the river communities have no choice but to confront the changes stemming from this new wave of investment in the market. Linking to markets for other fruits, oils and fibers growing in their agroextractive systems will keep them from being solely dependent on income from açaí while also safeguarding the ecological diversity of the estuary forests. Successfully marketing a differentiated açaí, a step above the general supply, will help them maintain a place in the market. Certification is an important potential mechanism for garnering recognition and added value for the differentiated product, as described later in this chapter.

## 5 Comparative Study: Santo Antônio and Canaticu River Communities

From where they lie on opposite sides of the Bahia de Marajó (Marajó Bay), and separated geographically by upwards of 10 h of travel by boat, açaí producers of the Canaticu and Santo Antônio river communities are working to address similar challenges arising from the expanding market. The geographic and historical contexts particular to each inform how they grow and market their açaí, and shapes the avenues by which they interact with the global market. Fieldwork carried out by the authors in 2015 on the Rio Canaticu, municipality of Curralinho, Marajó, and in the community of Santo Antônio, Igarapé-Miri, forms the basis of this study.

### *5.1 Santo Antônio*

Southeast of Marajó and 2 h from the city of Belém, the community of Santo Antônio enjoys the fame awarded to the açaí of its municipality, Igarapé-Miri. Açaí coming in from Santo Antônio's port is sought after as some of the best quality açaí in the estuary. Residents credit açaí with lifting the community out of poverty.

> "*We need biodiversity; the açaizal has to be a consortium, otherwise the soil and harvest dry out. Many people are replanting trees*." (Santo Antônio açaí producer)

In the face of the seemingly endless demand, there is a strong tendency here toward açaí monoculture. Misguided advice early on from extension workers did not help: they recommended cutting out of the açaizais anything that wasn't açaí. Later, producers noticed drying and altered flavor in their harvest; many are now working to reintegrate more diverse tree cover.

The region is relatively close and accessible by road to the açaí juice and pulp industries. Local buyers are competing more and more for the fresh commodity—they no longer wait for middlemen to arrive with truckloads of wicker baskets filled with the fruit but send their own fleets to Santo Antônio's port, the connecting point between surrounding river communities and the road to nearby industry. Some buyers go as far as to send boats out to communities, catching the product at its source.

Still, many açaí growers in Santo Antônio feel the lack of direct contracts with larger companies. These days the community's harvest enters the general mix, the majority trucked off to processing plants in nearby Castanhal. Producers of the older generation remember the late 1990s–2000s when contracts with the juice manufacturers Sambazon, Bolthouse and Bony Açaí brought considerably higher prices and income security to the community. These farmers lament the fact that buyers sourcing açaí for regional factories don't care about anything beyond filling their trucks. They hope for a future relationship with an export company that recognizes and rewards their carefully cultivated açaí.

### *5.2 Canaticu*

The Canaticu River is located near the town of Curralinho on the southern tip of Marajó Island. Marajó rests at the mouth of the Amazon River, between two state capitals—Belém to the east, and to the northwest Macapá, capital of Amapá. Situated between these two regional centers, Marajó chronically lags in development indicators (Brondizio 2011) and lacks the infrastructure for processing açaí locally. Açaí from Marajó, even of high quality, depreciates over the greater distances traveled to market. Nevertheless it plays an important part in the local economy.

> "*My daughter is a schoolteacher, it's been two months since she's gotten her paycheck. Imagine if we didn't have açaí!*" (Canaticu açaí producer)

Compared with Santo Antônio, the açaí export industry on the Canaticu River is more nascent. One resulting advantage is the possibility to learn from mistakes and misdirections that have already played out in Baixo Tocantins. As producers in Santo Antônio work to reestablish forest biodiversity to guard against drying and other issues manifesting in their açaí-dominated systems, producers in Curralinho never lost that biodiversity in the first place. Their best practices include maintaining 50% of native tree cover in order to preserve the forest structure and guarantee higher quality açaí.

The emphasis on quality of the açaí currently goes unrecognized. Nearly all of the community's harvest travels north to a single export company in neighboring Amapá state. Producers worry about being so dependent on one buyer. At the same time, they only deal directly with the intermediaries whose large boats are equipped for the passage. There is therefore no formal interface between the company and these producers—no accountability, no certification, no contractor benefits and no return for high-quality raw material.

In the past few years, small local producers associations along the Canaticu River have organized into a larger umbrella cooperative. The cooperative, Sementes do Marajó (Seeds of Marajó) has plans underway to build a processing plant on site. The hope is to achieve a branding of higher-quality açaí and eventually supply directly to the international export market.

> "*The biggest bottleneck we're having is the lack of certification.*" (President, Sementes do Marajó)

Early on in our fieldwork, the president of Sementes do Marajó expressed that certification is a knowledge gap the cooperative wants to fill as it looks to break into international markets. In response to this conversation, we began investigating options for certification that would be appropriate for traditional agroextractive açaí production, on the Canaticu River and beyond.

## 6 Methodology

Research was conducted between March and November 2015. Qualitative data were gathered through open interviews with açaí producers, community leaders and presidents of local cooperatives during field visits lasting 2–6 days. An effort was made to observe, and participate when possible in all aspects of life around açaí production and culture: management of the açaizal, proper technique for ascending a palm, açaí at mealtime, communities' annual açaí harvest festivals, soccer games played in a clearing in the açaizal.

Quantitative data were collected during the 2015 harvest season (July through October) using semi-structured surveys. Sixty surveys were conducted in total, with thirty producers each in the river communities of Santo Antônio and Canaticu. These surveys consisted of questions including: (1) what the producer's family's primary source of income is, (2) what additional sources of income they have beyond açaí, (3) whether the farmer believes s/he receives a fair price for the harvest and, if not, what would have to happen in order to attain fair pricing, (4) whether s/he has heard of certification, and if so, has her/his açaí ever been certified, (5) does s/he believe there is any advantage in obtaining certification, and (6) whether s/he is satisfied overall with açaí as a livelihood.

Data were also gathered on third-party certifiers in Brazil and the programs they offer that would best fit small-scale agroextractive production in the Amazon estuary, as well as alternative avenues for certification available through the Ministry of Agriculture.

## 7 Results

### *7.1 Income*

Results from the field surveys paint a compelling picture of the composition of income sources on the Santo Antônio and Canaticu rivers. In both communities, açaí provides the primary source of income for the majority of farmers interviewed

(27 and 26 of the 30 interviewees in Santo Antônio and Canaticu respectively). Striking differences between the two communities arise, however, vis-à-vis income derived from government aid programs and diversified production.

Several government aid programs provide important income to rural families in Pará. Bolsa Família, a social welfare program launched in 2003, provides small cash transfers to low-income families across Brazil on the condition that their children attend school and receive regular vaccinations and health checkups; it also requires health checkups of pregnant and lactating mothers (Lindert et al. 2007). Bolsa Verde, operating since 2011, provides R$300 (approximately $92 USD) each trimester to families practicing the sustainable use of natural resources within areas including extractive reserves, national forests and federally designated sustainable development reserves (Ministério do Meio Ambiente n.d.). The Seguro Defeso program, administered by the Brazilian Ministry of Agriculture, provides a monthly minimum wage stipend to artisanal fishers during the months of breeding season when fishing is prohibited (Instituto Nacional de Seguro Social 2016).

Overall, 18 of the families interviewed on the Canaticu River reported receiving government support through the Bolsa Família, Bolsa Verde or Seguro Defeso programs (Fig. 9.10). Of these 18 families, nearly 40% received income from two or more programs simultaneously. In Santo Antônio, in contrast, only 13 of the families interviewed reported receiving support from any of these program; those that did received only from Bolsa Família.

While the grand majority of the farmers interviewed in Santo Antônio rely primarily on açaí production to support themselves and their families, they also reported a more diverse assortment of products that they market for additional income (Fig. 9.11). These products encompassed fish, shrimp, heart of palm from culled açaí stalks, and other NTFPs (non-timber forest products) including coconut, citrus, cacao and cupuaçu, as well as seeds whose oil is valued for use in cosmetics (murumuru, miriti, andiroba, ucuúba). Farmers on the Canaticu River topped those in Santo Antônio only in the fishing category.

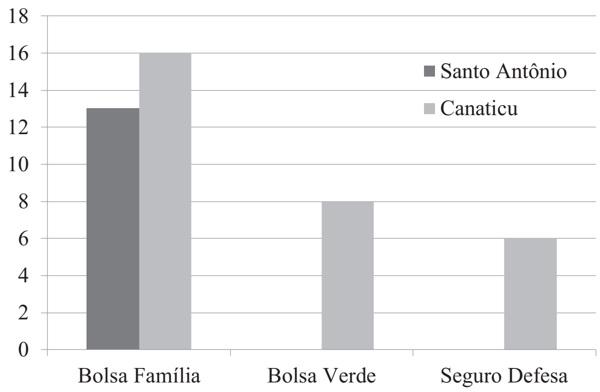


**Fig. 9.10** Government aid: Number of families in each community receiving income from government aid programs

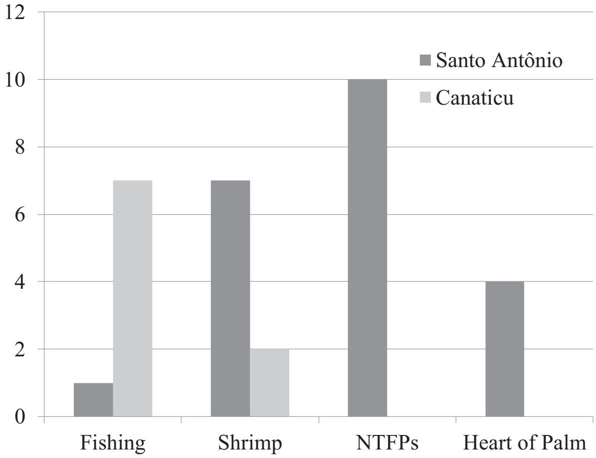


**Fig. 9.11** Additional income: Number of families supplementing açaí production with income from other products

## *7.2 Value of Açaí*

Based on data collected in the Santo Antônio and Canaticu communities, from the point of view of the farmers, the price they receive for açaí is not a fair one—74% of the 60 farmers interviewed consider their compensation too low given the time, energy and other resources invested over the year (Fig. 9.12). Dissatisfaction was higher among Canaticu farmers overall. When asked how much the price paid for their açaí would have to increase to constitute a fair one, Santo Antônio and Canaticu farmers cited an average increase of 62% and 69% respectively. In the context of the 2015 harvest season, when a 14 kilogram basket was bringing in approximately R$14 (Brazilian reais, or approximately $4.30 USD) during October on the Canaticu River, a fair price would be closer to R$24 ($7.35 USD).

It is important to bear in mind that 2015 brought a decline in the market compared to the 2014 season, when local açaí prices were at their record highest. Whether due to a drier spring season, the Brazilian financial crisis or a combination of factors, farmer dissatisfaction with the value of the açaí harvest is likely in part a response to this downturn. At the height of the 2014 harvest season, a basket of açaí on the Canaticu River was valued at a staggering R$40.

> "*With Sambazon and Bolthouse it was good, we negotiated a fair price. Today companies aren't interested in negotiating with cooperatives.*" (Santo Antônio açaí producer)

When asked what would have to happen in order for them to receive fair prices, farmers in both communities cited the need above all to organize. Also significant was the need to add value by processing açaí on site, through the cooperative, rather

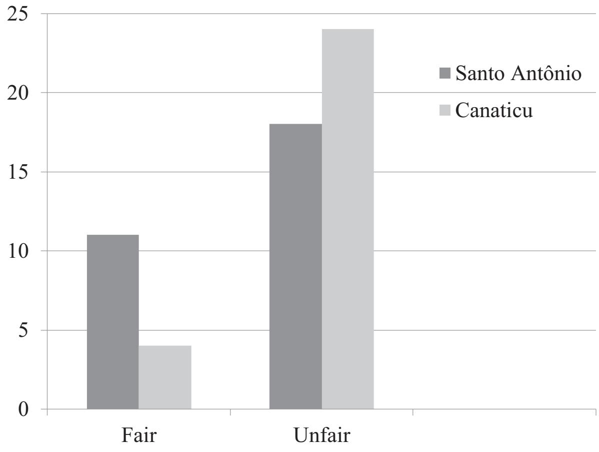


**Fig. 9.12** Fairness of price: Number of farmers who consider the price at which they sell their harvest a fair/unfair reflection of the time and labor invested

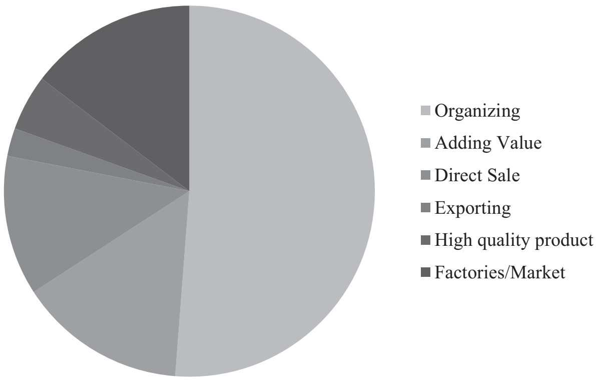


**Fig. 9.13** Increasing the value of açaí: Factors that farmers cited as necessary to achieving a fair price

than selling it in its raw form. Canaticu farmers mentioned, in addition, selling a high quality product, cutting out intermediaries to sell directly to factories, and reaching the export market. In each community a handful of individuals expressed that determining the value of açaí was out of their hands, dependent instead upon factories or the market (Fig. 9.13).

### *7.3 Certification*

Of the farmers interviewed, 66% had heard of certification, and 32% currently have or have had certification in the past. Of those who had heard of certification, 92% consider it advantageous, primarily as a route for achieving higher valuation of their açaí (Fig. 9.14).

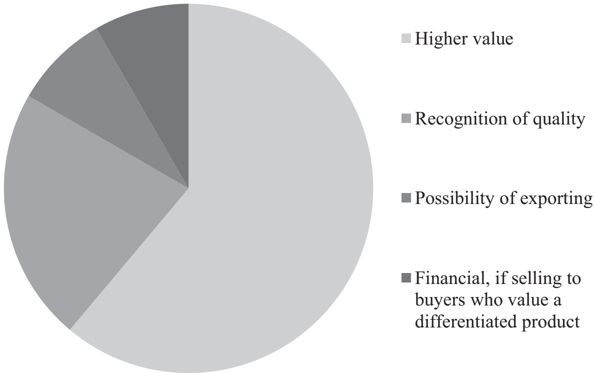


**Fig. 9.14** Advantages of certification: Primary benefits perceived by farmers of securing certification for açaí

Farmers in Santo Antônio offered perspectives on where and when certification might—or might not—be advantageous. One observed that certification benefits açaí factories and not so much the producers who supply them with açaí. Overall, certification is advantageous assuming that there is a factory willing to pay a premium for a differentiated product. If not, producers don't stand to benefit financially. In that case, certification might elicit higher environmental and agroecological standards and bring technical training to producers, but won't bring a higher price. These sentiments were echoed by one Canaticu farmer: "Up to now we've just been selling to the middleman, not to the factory, so for us on the Canaticu there's no advantage [to certification] in practice. If the cooperative were to negotiate with a company that exports, *then* it would be of interest."

This is exactly the aim of the umbrella cooperative, Sementes do Marajó, according to its president. The cooperative's leadership is looking into establishing a contract with a German company. Such a direct relationship would allow the cooperative to pursue and maintain certification specific to the European market.

Overall satisfaction with açaí production as an occupation was high in both communities. 96% and 72% of respondents said they were satisfied with the açaí context in Santo Antônio and Canaticu respectively. In the words of a few of these farmers, "Açaí freed us from things like the sugar plantations, digging clay for brickmaking; we were practically slaves. Not so today—we work autonomously, make a better living." "By 10:00 am we're back at home, with our R$120 [approximately $37 USD] already made." "If we were to stop and think, we live in a paradise. We wake up in peace, we're not subordinate to a boss. My father worked under the owner of sugarcane plantations." "What would become of us without açaí?"

## 8 Product Differentiation Through Certification

One way for family producers in floodplain areas to continue to benefit from the global demand for açaí, even as the market evolves and without having to compromise their management methods, is to connect to markets that value traditional and more ecologically aligned cultivation over industrialized production. Buyers in these markets may be willing to pay a premium for a differentiated product, despite it coming from more remote areas lacking the economies of scale inherent to larger, intensified production.

These extra efforts go unrewarded economically if the harvest is then sold to intermediaries, thus being thrown in with the general mix. If, however, the harvest reaches markets that recognize and value these measures, it can potentially generate a higher sale price. Certification that recognizes and guarantees the qualities that set this açaí apart would give these producers an edge in international specialty markets.

As the current president of the Rio Canaticu cooperative pointed out, 10 years from now the açaí market will be very different. Considering the trajectories of other Amazonian commodities that have come and gone in the all-too-familiar cycle of boom and bust, "the force and speed of açaí's entrance in the market may result in a loss of control for traditional producers in the sector" (Cialdella and Alves 2014). Given how much is currently being invested in large-scale production, certification that recognizes açaí grown and harvested under traditional management in floodplain agroextractive systems may be crucial.

Possible certification categories include organic, fair trade, and sustainable agriculture/forest management. Organic certification would recognize what traditional growers already practice—cultivation without any synthetic inputs or pesticides. Socially conscious consumers in the US and beyond are often willing to pay a premium for products labeled Fair Trade.

Certification of sustainable agriculture or forest management has the potential to open the door to compensation for environmental services. This option might resemble, for example, the "Bird Friendly Coffee" certification developed by the Smithsonian Migratory Bird Center (Smithsonian Migratory Bird Center n.d.), which guarantees organic production of coffee under full shade in systems that support bird life and other biodiversity. Certification could also facilitate the development of place-based branding recognizing açaí of várzea origin, or a wider appreciation for "açaí da ilha".

Certification applied to the land area under management rather than a specific product could support producers' aims to diversify sources of income. Under such a system, any agroforestry product—including oils sourced from andiroba, pracaxi *(Pentaclethra macroloba)*, murumuru, virola, patauá *(Oenocarpus bataua)* and miriti, as well as cacao and other fruits, and select timber extraction—might fetch a higher price. By allowing producers to market various products grown within the area as organic and sustainably managed, this type of certification could also encourage the preservation of biodiversity within production plots.

## 9 Possibilities for Certification

Many of the certification programs offered in Brazil by third-party certifiers make the most sense for large-scale individual producers or cooperatives of industrial farmers. Some certification companies have begun to offer programs that could be

**Table 9.1** Certification for international markets

| Certifier | Certification | Target sector | International standards |
|---|---|---|---|
| ECOCERT Brasil | Organic agriculture | Production: organic products | Various |
| | Fair trade | Supply chain: fair trade and organic products | Various |
| IBD certifications | Organic | Production: organic products | Various |
| | EcoSocial all fair | Production: fair trade and organic products | ILO[a], IFOAM[b], quality insurance international |
| | Sustainable agriculture network | Production, supply chain: agriculture | Rainforest alliance |
| IMAFLORA | Small-Scale Low Intensity Forest Management (SLIMF) | Production: small-scale forest extractivism | FSC[c] |
| | FSC supply chain | Supply chain: forest products | FSC |
| | Sustainable agriculture network | Supply chain: agriculture | Rainforest alliance |

[a]International Labour Organization
[b]International Federation of Organic Agriculture Movements
[c]Forest Stewardship Council
Select certification programs offered by third-party certifiers in Brazil appropriate for small-scale, traditional açaí production, which facilitate access to international markets

applied to the production and marketing structures of small-scale açaí producers and their cooperatives. Table 9.1 presents a few of the options offered by three leading certifying entities in Brazil: ECOCERT Brasil, IBD Certifications and IMAFLORA.

Internationally recognized third-party certification is essential if a farmers' cooperative intends to supply açaí to international markets. In this case, the cooperative can pursue the particular certification program that best fits the specific market they anticipate reaching. Depending on the size of the cooperative and its available capital, however, certification fees and annual renewals can keep this approach to certification out of reach.

If supplying to international markets is not the goal, there are more accessible options available to organic family farmers in Brazil. Offered through the ministry of agriculture, these are (1) Social Guarantee for Direct Sale without Certification, and (2) Participatory Guarantee Systems. The first option is applicable for producers selling directly to the final consumer. This works in the context of community-supported agriculture, farmers' markets, and for the national school lunch program.

The second option emphasizes collective accountability, and allows farmers to work with other local stakeholders including distributors, industrial processors, consumers, and public and private organizations to form an entity to keep producers accountable. This participatory process permits the farmers to use Brazil's official organic logo. While it may carry less clout than certification from independent third-party certifiers, participatory guarantee offers an accessible option to producers' cooperatives looking to market locally and domestically.

## 10 Conclusions

On days when traditional açaí producers sell açaí through the conventional routes, to the intermediaries who travel by boat from community to community, the high quality of their harvest generally goes unrewarded. Meanwhile, açaí cultivation is expanding to large landholdings in upland areas that can take advantage of economies of scale and greater geographic accessibility to capture market space. Food sovereignty and continued participation in the market that provides the bulk of income and economic opportunities are what is at stake for the estuary's riverine populations.

Local consumers in the region's towns and capitals recognize the value of várzea-grown açaí; for now their demand for açaí continues to support the livelihoods of small-scale producers. Still, these producers could benefit greatly from linking to export markets that value traditional production, with its high quality and more ecologically sound management practices (Fig. 9.15). Tapping into such markets would certainly provide a boost to the prices family farmers currently have access to as their harvests compete with large volumes of plantation açaí.

**Fig. 9.15** Açaí intermixed with other floodplain species on a várzea riverbank

By facilitating the collective sale of açaí, local producer associations and cooperatives offer the potential for alternative points of sale with greater possibility of recognizing a higher quality product. Certification guaranteeing higher quality as well as ecologically sound management could facilitate sale of açaí to specialty export markets. In combination with the direct sale made possible by aggregating the harvest through producer cooperatives, certification holds the potential to help sustain the livelihoods of family farmers of the Amazon estuary as they confront the evolving market.

"*We're happy knowing that today the whole world is buying açaí.*" (Canaticu açaí producer)

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# Chapter 10
# Ecological Indigenous (EIK) and Scientific (ESK) Knowledge Integration as a Tool for Sustainable Development in Indigenous Communities. Experience in Misiones, Argentina

**Patricia Rocha, Fernando Niella, Héctor Keller, Florencia Montagnini, Ruth Metzel, Beatriz Eibl, Julieta Kornel, Fabián Romero, Lucas López, Jorge Araujo, and Juan Barquinero**

## 1 Introduction

Approximately 60 million indigenous people worldwide depend today on forests (CBD Secretariat 2009), and 350 million people living in a forest or nearby have customary rights over these forest areas. Indigenous peoples, communities, local governments, as well as mining, logging and industrial companies, are claiming rights over the same forests, thus creating conflicts of different magnitudes. Many countries lack the mechanisms or tools needed to address these conflicts, to implement reforms in land tenure systems or to allow participation of indigenous peoples and local communities in forest management. These mechanisms are necessary to achieve sustainable forest management.

The inclusion of traditional knowledge in the Convention on Biological Diversity (CBD), more than 20 years ago, has opened the possibility of integration of ecological indigenous knowledge (EIK) and ecological scientific knowledge (ESK) in biodiversity management. The CBD recognizes, particularly in Article 8j, the need to respect the "indigenous and local communities embodying traditional lifestyles rel-

P. Rocha (✉) · F. Niella · H. Keller · B. Eibl · J. Kornel
F. Romero · L. López · J. Araujo · J. Barquinero
Facultad de Ciencias Forestales, Universidad Nacional de Misiones,
Eldorado, Misiones, Argentina
e-mail: procha910@gmail.com

F. Montagnini · R. Metzel
School of Forestry and Environmental Studies, Yale University, New Haven, CT, USA
e-mail: florencia.montagnini@yale.edu; ruth.metzel@yale.edu



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evant for conservation" as well as the need to "promote equitable sharing of benefits arising from the use of such knowledge innovations and practices."

Ecological indigenous knowledge (EIK) can make a significant contribution to sustainable development. Most indigenous communities inhabit areas where the vast majority of plant genetic resources in the world are located. Many of them have cultivated and used biological diversity in a sustainable way for thousands of years. Their skills and techniques provide valuable information to the global community and a useful model for biodiversity policies (www.biodiv.org/2009). Increasingly, Article 8 (j) and other articles of the Convention on Biological Diversity (CBD) stress the fundamental role of traditional knowledge in the conservation of biological diversity and the need for its implementation at local and international levels. However, Professor Teodora Zamudio, of the Department of Law of Indigenous Peoples of the University of Buenos Aires (UBA), in a recent interview for the magazine Pachamama (www.cbd.int/idb/2009) stated that "researchers have not been trained in the philosophy of the Convention, they are completely unaware of it...or if they have heard rumors on the subject, consider Article 8 (j) as a threat to the development of their task, as a burden...that no one has showed them how to comply. In addition indigenous communities are not prepared -in the majority of cases- to address this relationship with the scientific community". The gap between indigenous and scientific knowledge does not seem to provide possibilities of some kind of unification. The defined parameters of scientific knowledge do not allow the inclusion of any other science that does not conform to its guidelines. The respect for the existence of two different worldviews (EIK and ESK) should promote the search for favorable conditions toward the establishment of a fruitful relationship between these two types of knowledge.

Based on these assumptions, the aim of our study was to conduct an analysis of national and international experiences in implementing projects on natural resource management that include the integration of EIK and ESK. In addition, we conducted a case study in Misiones, Argentina, to analyze the local integration of EIK and ESK.

The present chapter first introduces the concepts of EIK and ESK and the role of ethnosciences in their integration. A section on conservation and environmental services in intercultural settings (IS) follows, then successful cases where indigenous non-timber agroforestry products have been integrated to the local economy are described. Finally, the chapter discusses the national and local legislation regarding natural resource restoration, and presents a local case study on EIK-ESK integration.

## 2 Ecological Indigenous and Scientific Knowledge: Differences and Need for Integration

The indigenous knowledge (IK), also known as traditional knowledge (TK), and as local knowledge (LK), or ecological indigenous knowledge (EIK) is defined as the knowledge that a local indigenous community has accumulated through generations living in a particular environment (www.unep.org/IK). The EIK also connotes knowledge systems held by traditional communities and based on their experience and adaptation to a local culture and environment (Makinde and Shorunke 2013).

Dei (2000) identifies three aspects of IK: (1) traditional knowledge which is the intergenerational knowledge transmitted from generation to generation; (2) empirical knowledge based on observations of the environment (nature, culture and society); and (3) revealed knowledge that comes through dreams, visions and intuition. EIK is comprehensive and includes both the physical and spiritual aspects of life.

Tella (2007) states that EIK is important for a number of reasons: (1) it provides problem solving strategies for communities; (2) it contributes significantly to global knowledge on development; (3) it is relevant to the development process; and (4) it is an underutilized resource in the development process. However, Ocholla (2007) states that indigenous knowledge continues to be marginalized in development plans, and this has led to its limited use in the development process. One of the reasons why the EIK has been marginalized is because of its tacit nature. EIK resides in memory of the people and is spread primarily by word of mouth. This means that it is, in many ways, endangered when cultural custodians (which are often elderly) die and those who remain do not have full understanding of the history of that EIK.

Dei (2000) notes that the problem arises from the separation of traditional and modern knowledge as if they had no bearing or impact on each other. Many writers tend to invoke the differences between indigenous knowledge and Western knowledge systems in order to explain what IK is. IK is portrayed as holistic, communicated orally, stemming from experience in nature, and closely linked to spiritual and social values. On the other hand, the Western knowledge system is portrayed as narrowly written, theoretical and value-free; while the IK is affected by and affects other forms of knowledge, which seems to point out the need to combine or synthesize the two knowledge systems.

Several authors argue that many of the natural habitats that we know are actually "cultural landscapes" modified by human action (Reyes-García 2009). Manipulations of the environment by indigenous groups range from total or partial domestication of plants and animals to the application of techniques for soil conservation, water collection, handling fire or gathering wild fruits, resulting in natural ecosystems that are the product of human management. For this reason, the abandonment of environmental management practices based on EIK affects the conservation of several ecosystems.

Regional strategies have been implemented to mobilize the CBD negotiations on issues such as sovereignty of biodiversity, access to natural resources and traditional knowledge, intellectual property rights on innovations based on natural resources, the right of traditional communities and indigenous peoples to develop, and the right of researchers to freely perform their research on biological material for the benefit of humanity. These have been identified as important issues, and have become the object of public policy. In this context, all the different branches of academic science with an interest in natural resources (botany, pharmacology, anthropology, biology, forestry and chemistry), should consider indigenous knowledge and skills and how to interact with ancestral knowledge on managing biodiversity (Kleiche-Dray 2012).

Globally, the relevance of the 'indigenous' and 'local' forms of knowledge for sustainable development has been amply demonstrated, especially in regard to the management of natural resources (biodiversity, water, soil) and to the prediction of responses to ecosystem disturbances (Rist and Dahdouh-Guebas 2006). The fundamental role played by the Ethnosciences, Ethnoecology and Ethnobiology in the integration of knowledge for sustainable management of natural resources should be stressed.

## 3 EIK and ESK, the Role of Ethnosciences

The ethnoscientific approach developed by the Anthropology of Knowledge or cognitive anthropology can contribute valuable criteria for addressing the relationship between EIK and ESK. Some of its disciplines, such as Ethnobiology and Ethnoecology have been and remain nowadays particularly relevant for addressing EIK. Therefore, it is worthwhile to present the epistemological framework in which they were originated and where they currently operate.

Ethnoscience can be defined as the study of the content and organization of knowledge about nature by traditional societies (Beaucage 2000). In its ontogenetic evolution, it has been the subject of numerous controversies between relativistic and universalistic positions. The first one is sympathetic to the notion that ethnic knowledge about the environment can only be explained in terms of the society where it is developed (Conklin 1955; Murdock and Withe 1969; Hunn 1977); while universalist positions suggest that knowledge concerning living things (plants and animals) is structured similarly in all societies and cultures (Berlin 1972, 1973, 1992). Nevertheless, long before the development of ethnotaxonomy by Berlin, the Universalist position was already adopted as a rule by some early ethnobiologists who worked with indigenous groups in the Southern Cone of South America, including Bertoni (1940) who suggested that "the Guarani race uses a scientific binomial nomenclature, and assigns names to plants and animals in egalitarian and democratic assemblies."

In a way, the Relativistic and Universalistic positions are closely related to the preferential use of the EIK and ESK. In this sense, it has been suggested that each element of a culture can be studied from two points of view, the **emic** and **etic**, related to EIK and ESK, respectively. The most immediate, the **emic**, held by the members of the culture, reflects the linguistic and cultural context (subjective). The second view, **etic**, is the exterior and reflective view, adopting science (Pike 1956). Relativists emphasized these peculiarities of traditional (emic perspective) systems, while Universalists, based on comparative studies, insisted more on the commonalities (etic perspective) (Beaucage 2000).

### *3.1 EIK and ESK in Ethnobiology*

In 1896, Harshberger proposed the word Ethnobotany to describe the study of plants and their uses by different populations of the world. The importance of Ethnobotany and Ethnozoology led scholars of biocultural issues to coin the word "ethnobiology" to include these two fields (Castetter 1944; Clement 1998). Murdock and Withe (1969) used the word Ethnobotany in the context of ethnosciences or cognitive anthropology. Currently ethnobiology is defined as the study of knowledge and concepts on biology, or rather "about life and living things" developed by any culture (Posey 1987). To date, ethnobotany is one of the most important fields of ethnoscience, followed in importance by ethnozoology (Beaucage 2000).

As the most prolific discipline within the ethnociences, ethnobotany has also been subject to a diversity of perspectives and definitions. It has been defined as "the study of direct inter-relationships between humans and plants in dynamic systems" (Alcorn 1995). Currently, the discipline includes the study of the interrelationships of human societies with nature (Alcorn 1995; Alexiades and Sheldon 1996). The latter definition, somewhat ambitious, is inadequate since it detracts prominence and importance from EIK. From our perspective ethnobotany should be defined as a subordinate to ethnobiology which studies the knowledge on organisms and plant life developed by traditional human societies.

Ethnobiology and related disciplines have been branded as romantic and reductionist, figurative attributes that constitute the two strongest criticisms of these approaches. The label of "romantic idealism" has been given by deterministic orientations to circumvent the ethnoscientific approach of the cognitive anthropology (Harris 1979; Durand 2000). Social scientists who mechanically adopt a perspective aligned to these criticisms are at risk of default on the analysis of the socio-political and environmental complexity of the EIK and thus, often unwittingly, contribute to the consolidation of a unilateral approach (Keller 2013).

The most Universalist approaches of ethnobiology driven by Berlin (1973) have been criticized for trying to assess indigenous knowledge with Western science parameters (Descola 2001; Hviding 2001). This criticism suffers from being generalist in its views on a polymorphous discipline, but has increased in popularity dramatically in recent years. According to Reynoso (1986), since its foundation in 1956, cognitive anthropology has continued to enrich and diversify.

Another aspect that has been the subject of uncertainty and suspicion is the scope or the pragmatic value of EIK that has been documented by ethnoscientists. As expressed by Reynoso (2014) in his critique of Perspectivist Anthropology, "far from being exhausted in the classification of plants or ingredients, the ethnosciences are closely oriented practices and knowledge of great strategic importance, not only to anthropologists but to UNESCO, the World Bank and to multinational health food technology companies that have had their eye in it and have already begun to take advantage of it." The documentation of EIK by the ethnosciences has confused ethnobiology with bioprospecting. The bioprospective resemblance awarded to ethnobotany has also been extended to a historical level, linking this discipline to the practice of inventorying resources from the colonies to provide the colonialists with alternative benefits (Ruiz 1805). This research has been documented in such works as the "Days Náuticas" by Fray Jacinto de Carvajal (1648), and works by Ortega (1996), the "Ethnobotanical News" by Augusto Guinnard (Martínez Crovetto 1963), containing an analysis on useful plants made in the nineteenth century (Guinnard 1864).

Ethnobiologists have responded in a precautionary manner, suggesting the omission of publications on taxonomic identity of medicinal species (Prance 1991). However, to defend the intellectual property rights of communities, it is better that EIK is documented and attributed correctly in scientific publications, which may become publicly available documents before any leases by pharmaceutical companies. As expressed by Hersch-Martínez (2002), the protection of traditional knowledge, the struggle for self-determination and other rights that local communities and indigenous peoples claim for themselves should not be ignored.

## *3.2 EIK and ESK in Ethnoecology*

Following Toledo (1990), Ethnoecology is defined as the discipline which studies the conceptions, representations and knowledge on nature that allow indigenous societies to produce and reproduce the material and spiritual conditions of their social existence through proper management of natural resources and ecosystems. Toledo and Barrera-Bassols (2008) propose a conceptual framework for the study of traditional knowledge, based on the Cosmos-Corpus-Praxis complex where Cosmos represents the belief system or world view, the Corpus is the full repertoire of skills or cognitive systems, and the Praxis symbolizes the set of productive practices including different uses and management of natural resources.

Ethnoecology is currently defined as the study of local ecological knowledge understood as a complex form of adaptation and habitat modification, the result of the process of co-evolution between culture and nature. It is a discipline which contributes value to local ecological knowledge systems, underlining their potential to improve the well-being of today's society (Reyes-García and Martí Sanz 2007). Indigenous ecological knowledge, as a key component for the management of natural resources, also has the potential to contribute to human welfare and rural economic development (Reyes-García and Martí Sanz 2007).

Based on his personal experiences in accompanying participatory research and development processes, Ardón Mejía (2001) proposes a multidisciplinary approach from an ethnoecological perspective. He points out that participatory methods applied to ethnoecological research start with the recognition of the integrity of the individual and human groups, from a perspective that does not set rigid boundaries between material, social and spiritual aspects that, through a historical process, have shaped the environmental, social and economic reality in the daily life of individuals and human groups to the present day.

## 4 EIK and ESK in Education

In a time characterized by uncertainty and complexity it is important not to forget that the sophisticated knowledge of the natural world is not limited to what is recognized as a science or ecological scientific knowledge (ESK). Human societies have also developed ecological knowledge and explanations from rich experiences in their surrounding environments. The terminology adopted here to refer to these knowledge systems of indigenous groups is ecological indigenous knowledge (EIK).

The EIK is relevant because it has stimulated scientific thought over time, contributing to science in general, and to the conservation of biodiversity and management of natural resources in particular. Moreover, it has promoted innovation based on such knowledge. As examples, one can point to the commercialization of agricultural technologies such as permaculture, water and soil conservation, or marketing of many products such as handicrafts, pesticides, beauty products, seeds and medicines based on EIK.

EIK should be considered as valuable knowledge in educational programs. One wonders then, how EIK is integrated into educational programs that focus on ESK that has long been established and valued as formal educational knowledge.

As pointed out in previous sections, EIK is the result of a cumulative and dynamic process of practical experiences. Unlike ESK, EIK is local, holistic and carries a worldview that integrates physical and spiritual aspects (Toledo 1990). Therefore, some sectors related to scientific communities consider learning this knowledge as unimportant because they argue that it is anecdotal and imprecise. This attitude is a key obstacle to incorporating EIK into formal education.

Added to the epistemological differences in perspectives, the loss of indigenous languages and values that accompanies acculturation is a major cause of EIK loss. As generally EIK is not taught in schools, the time and resources invested in formal education are not invested in the acquisition of EIK (Sternberg et al. 2001).

EIK loss is the result of a long process of erosion of social, political and institutional structures sustained by local systems of natural resource management. The factors behind this erosion range from specific factors such as changes in land use, loss of local dialects, acculturation and schooling, to more widespread changes such as industrialization, rural migrations, market integration and cultural homogenization processes linked to globalization (Turner and Turner 2008). Educational institutions often do not promote EIK recovery and its integration with ESK, but rather limit any expression of diversity, heterogeneity and variety, particularly multiculturalism.

Multiculturalism involves cultural identity. Various authors hypothesize that the loss of cultural identity should be a major cause of loss of EIK (Marín 2002; Diez 2004). A pedagogical approach based on an intercultural education perspective, mainly with indigenous communities, can be an alternative to recover EIK and integrate it into formal education. In this sense, Marín (2002) believes that intercultural education is one of the key considerations in the development of programs that can give value to indigenous languages and cultures, combining them with elements of Western culture.

Regarding the application of the intercultural approach in Peru, Argentina and the rest of Latin America the fragmentation of intercultural education programs has unfortunately weakened its original founding principles. Intercultural bilingual education has failed to be broadly implemented because it remains isolated from the mainstream educational system (it is considered education for Indigenous peoples), and is not articulated with proposals and actions in other sectors. It has also failed to facilitate the participation of underrepresented sectors in planning or decision-making. In many cases, it is implemented as a focused and vertical proposal, which does not usually encourage alternative ways to manage diversity and difference (Diez 2004).

Moreover, the pedagogical work with this approach is complex because it requires training of teaching staff that is not only limited to the technical-pedagogical aspect, but also demands an awareness and sensibilization work of the process of teaching and learning, a culture of interdisciplinary work, and the recognition of the cultural rights of indigenous peoples.

Another element to consider in this analysis is that EIK is passed down from generation to generation and the elderly play an essential role in the adaptive learning process. The incorporation of new generations of indigenous groups and rural communities into the globalized market economy changes the implementation of activities linked to the production stage, alienating them from nature. This interferes with the dynamics of the transmission of EIK and the possibility of programming the integration of EIK and ESK in formal education.

To summarize, it is clear that indigenous peoples have extensive knowledge of how to live sustainably. However, formal educational systems have disrupted the practical aspects of everyday life of indigenous knowledge and ways of learning, replacing them by abstract knowledge and academic ways of learning. Today, there is a serious risk of indigenous knowledge being lost and, along with it, valuable knowledge about sustainable livelihoods.

## 5 Conservation and Environmental Services in Intercultural Settings (IS)

Biodiversity sustains the functioning of the ecosystems, which provide a broad set of services to human societies. Therefore its constant loss brings serious consequences for the present and future well-being of human populations. The provision of food, fiber, medicines and fresh water, crop pollination, filtering of contaminants and protection from natural disasters are some of the ecosystem services that can be threatened by the decrease and changes of biodiversity. Cultural services such as spiritual and religious values, opportunities for education and learning, as well as aesthetic and recreational values are also threatened by losses of biodiversity (CBD

2010). In this section we discuss the importance of maintaining ecosystem biodiversity for the provision of environmental services to human populations and present strategies for conservation.

### *5.1 Importance of Biodiversity for Human Populations*

Biodiversity is the variation that exists not only among species of plants, animals, microorganisms and other life forms of the planet, but also within a single species (genetic diversity), and at the ecosystem level, where all species interact with each other and the physical environment. This diversity is of vital importance for people because it sustains a great variety of ecosystem services on which human societies have always depended on, although its importance is frequently underestimated or completely unknown. When some element of biodiversity is lost, ecosystems lose their ability to recover and the services they provide are threatened. Ecosystem services can be classified into four categories:

**Provision services,** providing goods that benefit people directly and generally have a direct monetary value, such as fuelwood, medicinal plants, fish;

**Regulation services**, including the whole spectrum of vital functions sustained by the ecosystems which are generally not assigned monetary value in conventional markets: climate moderation, carbon storage, elimination of contaminants, protection from natural disasters such as landslides and coastal storms;

**Cultural services**, which do not offer direct benefits but contribute to satisfy certain society needs and thus influence the desire to cover the costs of their conservation, for example, the spiritual value of certain ecosystems such as sacred forests, or the aesthetic beauty of landscapes and coastal areas that attract tourists;

**Support services**, which do not benefit people directly but are essential for the functioning of ecosystems and are thus indirectly responsible for the other services, such as soil formation and the processes that support plant growth.

It is important to note that generally the regions of greater concentration of diversity are home to indigenous populations. Some biological endemisms can be linked to specific linguistic expressions, which can be considered "linguistic endemisms". Likewise, "endemic traditional knowledge" is a highly valuable resource among indigenous populations that needs to be preserved (Boege 2004; Nabhan 2003). Species extinction and destruction of native habitat are associated with the disappearance of indigenous languages and with the erosion of cultural biodiversity (Maffi 2001). Indigenous peoples can be considered "ecosystem people"; their territories are regions of origin of biodiversity as well as "cultural" phytogenetic reserves, which are unique in the world, such as corn in the Mesoamerican cultures of Mexico (Boege 2004), among many other examples.

The concept of Biocultural Diversity expresses the complexity of the scientific endeavor, since it goes beyond the reductionist view that tends to set apart the natural and social sciences knowledge. Bioculture involves a new philosophical vision of life and Earth. This complex concept has to consider the profound processes of cultural hybridization that indigenous peoples are subject to in their modern dynamics. These are the central aspects that must be considered if we want to advance towards an ethical legitimacy (Agraz and Matsumoto 2010).

The field of "sociology of conservation", with contributions from both rural and environmental sociology, tries to understand how natural resources and the environment create the conditions for social organization, and how social welfare is linked to patterns of use of the natural resources, while at the same time considering people's values and attitudes about environmental problems. It focuses on conservation work associated with communities that practice sustainable use and livelihoods (Torrealba and Carbonell 2008). Sociology of conservation studies may start with a specific focus on locations or resources to arrive at a "macro" understanding of the processes of political and economic organization and examine them within a global perspective.

## *5.2 Ecosystem and Biodiversity Degradation*

When a natural habitat is destroyed it is unable to keep most of the native species. Plants and animals linked to it will be destroyed or forced to emigrate, and as a result biodiversity is reduced. Habitat destruction by humans through agriculture expansion, mining, forest logging and urban sprawl are currently the most important causes of species extinction. Other causes of habitat destruction or degradation include habitat fragmentation, geological events, effects of climatic change and the presence of invasive species (Pimm and Raven 2000). Conversion of forests to agriculture is the main cause of deforestation in the tropics (Sanderson et al. 2002; Geist and Lambin 2002).

Degradation, fragmentation and pollution are aspects of habitat destruction resulting in the collapse of ecosystems. Desertification and deforestation are specific types of habitat destruction. Actions to minimize the destruction of ecosystems should consider those irreplaceable services provided by natural habitats, and they should be aimed at protecting remaining intact areas, educating communities about the importance of biodiversity and natural habitat, developing ways to increase agricultural production without increasing the cultivated area and preserving corridors to reduce damage of fragmented habitat (Geist and Lambin 2002).

The majority of future scenarios predict that during the present century the levels of extinction and habitat loss will increasse, with consequent decreases in the provision of environmental services that are important for human well-being (Vitousek et al. 1997; CBD 2010). If ecosystem degradation reaches certain thresholds or points of no return, there is great risk of drastic losses of biodiversity, with the consequent deterioration of a wide range of ecosystem services. These changes will likely affect the most vulnerable communities first and with higher intensity, but in the long run all societies and communities will suffer the consequences.

### *5.3 Strategies to Conserve Biodiversity*

Most forests, especially primary forests, when in their natural state, are relatively resilient and resistant to diverse types of changes. Therefore it is important to try to keep the specific and genetic composition of the biodiversity of these ecosystems in order to preserve the natural mechanisms that provide their capacity for recovery or resilience (Thompson 2012).

Future human activities need to focus on the conservation of endangered species that are of commercial and cultural importance and functional ecological groups that play specific and fundamental ecosystem roles such as pollination, control of numbers of herbivores by predators of higher trophic levels, nutrient cycling and soil formation and protection. It will be increasingly necessary to restore terrestrial, marine and continental shelf ecosystems to reestablish ecosystem function and the provision of valuable services.

Considering the large number of endangered species, funding aimed at safeguarding biodiversity is insufficient and therefore it is essential to define conservation priorities of "biodiversity hotspots" (Myers et al. 2000). Globally, 34 sites have been identified for these categories, which are characterized by the greatest biodiversity, and have large concentrations of endemic species, many of them currently endangered. These hotspots are experiencing large losses of habitat, in some cases up to 70% of their habitat (Cincotta and Engelman 2000).

Most of the biodiversity hotspots are located in tropical and subtropical regions. Latin America contains several biodiversity hotspots (Giraudo and Povedano 2004), including the Atlantic Forest comprising Brazil, Paraguay and Argentina, which has been reduced to 8% of its original forest cover. In the Province of Misiones, Argentina, the Interior Atlantic Forest (Atlantic Forest of Alto Parana) retains 40% of its original forest cover. Approximately 800,000 ha are forests of varied density and structure and 600,000 ha are rural degraded secondary forests in agricultural land areas (Ministerio de Ecología 2010).

The true benefits of biodiversity and the costs of losing it should be reflected in the economic and market systems of the human populations that they sustain. Perverse subsidies and lack of economic valuation of the enormous benefits that ecosystems provide have contributed in great part to biodiversity loss. However, through regulations and other measures, markets can and must create incentives that protect and strengthen natural infrastructure instead of overusing it. The restructuring of economies and financial systems after the global recession is a good opportunity to conserve the biodiversity of species and ecosystems that are vulnerable, have cultural value, or protect key ecosystem services (CBD 2010).

Ecosystem restoration can bring financial benefits to the involved communities (Montagnini and Finney 2011). However, the levels of restored biodiversity and services rarely reach pre-disturbance levels. This confirms the assertion that if possible, it is convenient and even more economically sound to avoid degradation and to conserve rather than restore the damaged ecosystem.

Mechanisms of PES (Payments for Environmental Services) can be used to favor the sustainable management, use and marketing of NTFP (non-timber forest products). This can favor the diversification of income sources, so that farmers do not depend solely on conventional crops. In addition, promoting a variety of products can also serve to prevent the environmental degradation associated with monoculture systems (Logan-Hines et al. 2015, Jarrett et al. 2017, Chap. 12, this volume). The support through subsidies, PES programs, certification of NTFP, as well as the creation of a value chain for these products can support the maintenance of local livelihoods and the conservation of natural resources (Montagnini and Jordan 2005; Montagnini and Finney 2011; Logan-Hines et al. 2015; Montagnini and Metzel 2017, Chap. 2, this volume).

## 6 Integration of EIK and ESK in Marketing of Indigenous Non-Timber Forest Products from Agroforestry Systems

In this section we show examples of how through collaboration between scientists, international organizations and communities mechanisms are devised to add value to non-timber forest products and facilitate their entry and access into larger markets, benefitting the indigenous communities through an integration of EIK and ESK. Technical and scientific knowledge can be instrumental in ascertaining the medicinal, nutritional, or other use value of specific products. Likewise, personnel from research institutions, private companies, foundations or non-government organizations can inform local communities about the different steps in the value chain to reach key markets for their products. This can involve mechanisms to add value to the products before they reach markets so that the producers obtain better financial returns. Collaborators from other sectors can also inform communities about new or best practices for processing, packaging, branding and advertising their products.

Indigenous agroforestry systems can be brought into alignment with integrative landscape management strategies. Increasingly these strategies seek to incorporate supply chains based on the sustainable management of forests and agroforestry systems that generate income from a variety of native species (Jarrett et al. 2017, Chap. 12, this volume). There are several examples where indigenous communities have been able to reach local and/or international markets for their agroforestry products.

In this section we describe successful cases where indigenous non-timber agroforestry products have been incorporated to the local economy, with the assistance of technical and scientific personnel, thus integrating indigenous and scientific knowledge in a purposeful and useful fashion. This section provides examples of how businesses and communities have worked together to maintain traditional agroforestry practices and organic cultivation techniques while increasing the product quality and market growth of indigenous non-timber forest products.

### 6.1 *Guayusa (*Ilex guayusa* Loes.) from Napo, Ecuador*

Napo, Ecuador, is a region in the Upper Amazon that has been characterized in recent decades by immigration, urbanization and the consolidation of indigenous land holdings through communal land tenure. These processes have been both accompanied and facilitated by increased state involvement in natural resource governance, infrastructure development and the expansion of government services to rural communities. Rapid expansion of road networks has increased the ability of smallholders in the region to continue expanding the agricultural frontier, resulting in a "post-frontier" moment where landscape management has become increasingly important in order to avoid extensive resource degradation and loss of ecosystem services. At the same time, urbanization and greater market integration has led local communities to become more reliant on the cash economy, generating a pressing need for market-oriented livelihood opportunities that are compatible with existing agroforestry systems. In Napo, Runa, a social enterprise, has been able to create new value chains for agroforestry products and to work with state agencies and indigenous communities to support biodiversity conservation in buffer zones between settled areas and natural reserves (Jarrett et al. 2017, Chap. 12, this volume).

One of Runa's most successful agroforestry products, the guayusa, *Ilex guayusa* Loes., is native to the Northwestern Amazon. Traditionally, this small tree has been used and cultivated by indigenous communities to prepare a stimulating drink which is consumed very early in the morning. Due to its high levels of caffeine and antioxidants, the guayusa leaves are used as a natural stimulant. Today, the guayusa is present in the kichwa amazonian culture of Northeastern Ecuador and in Northern Peru. The Runa Company currently sells guayusa products in over 7000 stores in the United States, Canada and Ecuador. Through their research program, Runa focuses on the domestication process of the guayusa for its growth in agroforestry based on the traditional "chakra" system. In addition, the creation of a guayusa value chain supports the sustenance of the local livelihoods and the conservation of natural resources (Logan-Hines et al. 2015).

Since 2010, Runa has bought, processed and marketed leaves from approximately 2500 indigenous farmers in the Ecuadorian Amazon. Starting in 2010, Runa Foundation and their partner, the Runatarpuna Exportadora, S.A. enterprise, started to produce *Ilex guayusa* in community nurseries. Between 2010 and 2012, about 150,000 guayusa plants were produced by approximately 750 farmer families in Napo Province. From the start of the marketing process the economic benefits have been an important factor to maintain interest among farmers in participating in Runa initiatives. Before they started working with Runa, the average income of farmers was about USD $50/month. With Runa, some farmers have earned up to USD $300 in one day through selling the leaves of mature trees (Logan-Hines et al. 2015).

It has been estimated that sales of guayusa leaves have increased annual producer incomes by 5–10% (Jarrett et al. 2017, Chap. 12, this volume). Runa calculates that farmers could harvest 0.5–1 kg per guayusa plant in the first year. The model developed by Runa attempts to avoid farmer dependence on guayusa as a monoculture crop, and instead promote its growth in agroforestry systems planned and managed based on the traditional growing systems for guayusa in the farmers' chakras. These multistrata agroforestry systems include native fruit and timber trees, food crops and guayusa to diversify production and provide subsistence products in addition to commercial crops. Runa's participatory research program has developed a guayusa domestication handbook that includes tree planting, agroforestry design and management, harvest operations and marketing procedures (Logan-Hines et al. 2015).

## *6.2 Organic Yerba Mate from Argentina, Paraguay and Brazil*

Yerba mate (*Ilex paraguariensis* Saint Hilaire, Aquifoliaceae) is native to a relatively large region encompassing eastern Paraguay, northeastern Argentina, and southern Brazil. When the Spanish colonists arrived in the fifteenth century, they observed the Guarani indigenous people consuming yerba mate as an infusion made with dry and ground leaves. The Spanish adopted its use relatively quickly. The Jesuit priests who established their religious missions in Misiones, Argentina observed that the Guarani people who drank mate stayed awake longer and could work harder than those who did not. Domestication of the species started during the eighteenth century, and the first successful plantations were established in the early 1900s in San Ignacio, Misiones (Montagnini et al. 2011).

Trade in yerba mate (YM) is currently a lucrative business in Argentina, Paraguay, and Brazil. YM leaves are locally consumed as a tea with a market expanding to the USA, Europe and Asia, as it contains nearly twice the antioxidant levels of green tea and is energizing, making it an alternative to coffee (Montagnini et al. 2011; Eibl et al. 2015; Eibl et al. 2017, Chap. 11, this volume). Organic YM producers can get up to 20% price surplus and most YM cooperatives have organic YM as one of their products. Typically grown in monocultures, its management can cause erosion and soil exhaustion. However, YM grows naturally in subtropical forest and is shade tolerant, making it appropriate for agroforestry systems (AFS). Many farmers have their own nurseries to produce seedlings to use with YM and to sell for additional income. The extra work involved in using the organic practices while planting and tending to native species is compensated by higher YM prices.

Guayakí, one of the most successful organic YM producers and exporters, buys YM leaves from indigenous producers in Paraguay, as well as from farmers in Brazil and Argentina. The company manufactures a variety of YM products including YM tea bags, loose YM and YM drinks. Their organic YM is certified by O.I.A. (Organización Internacional Agropecuaria, International Agriculture Organization), accredited by the USDA. The participating farmers conduct an annual census of native species in their parcels. Guayakí has a nursery to produce native species to plant with YM, and some farmers have their own nurseries. To compensate for the extra work involved in using organic practices, Guayakí pays its farmers ~2–3 times the "normal" price for their leaves (Montagini et al. 2011).

### *6.3 Wild and Cultivated Cacao from Bolivia*

Wild cocoa is a product that cannot be sold directly, but requires some processing at the collector level, either through fermenting and drying the seed or through processing the dried seed into cocoa paste. In their report on marketing chains for non-timber forest products, Rushton et al. (2004) describe the value chain for wild and cultivated cacao in two communities, San Silvestre and Carmen Emero, in the Amazon of Northern Bolivia. At the community level there are two possible products derived from cocoa collection: dried seed and cocoa paste. Three supply chains were identified in the two communities: (1) Dried seed sold to formal chocolate processors who sell chocolate on the national market and export organic chocolate; (2) Dried seed sold to an informal market in La Paz; and (3) Cocoa paste that is consumed locally, sent to nearby relatives or sold to traders in towns.

In the communities studied, 38% of the families interviewed (14 out of 37) reported growing cocoa as well as collecting it from wild sources. The proportion of family income derived from cocoa was 7–14%. Product prices relate to the supply of cocoa, the distance from a main trading center, and the availability of transportation by boat or road. Cocoa is both an important income-generating product and part of the local diet, and therefore families have local and external markets for their product. Just over half of the families interviewed reported that they sold their cocoa products to traders and the rest of the families reported that they sold to local consumers.

In France, a panel of international experts recently evaluated cocoa products and selected the top 50 to be transformed into chocolate; including three from native Bolivian cocoa. One of the grains classified in this select group comes from the Carmen Emero community, which has been strengthening their production processes and improving their cocoa quality (aroma, flavor and texture) since 2002. Through this program, the Helvetas Swiss Intercooperation Institution and the Wildlife Conservation Society have provided technical assistance and support to strengthen the value chain for quality cocoa in the tropical landscapes north of La Paz (Página Siete 2015).

### *6.4 Successful Commercialization of AFS Products*

The successful commercialization of an agroforestry product depends critically on the existence of an accessible market; potential demand; the absence of substitutes; access by producers, processors and traders to market information; technical management capacity; organization; high value/unit weight; and trader characteristics (age, experience, education, etc.). Market information is important in terms of breaking into new markets and maintaining market share. Technical capacity and organization are particularly important for products that require processing (Montagnini and Metzel 2017, Chap. 2, this volume).

The three case studies presented in this section – Guayusa in Ecuador; Organic Yerba Mate in Argentina, Paraguay and Brazil; and Cacao in Bolivia – show examples of how through collaboration between scientists, international organizations and communities mechanisms are devised to add value to non-timber forest products and facilitate their entry and access into larger markets. Influential individuals can have a high impact on product value, marketing and transportation costs, and processing decisions. For example, the local traders and processors of cocoa seeds play a key role in adding value to the product and reducing the transaction costs of regional traders.

Successful value chains require capable entrepreneurs to search, create and maintain markets. Technical and scientific knowledge are instrumental in assessing and improving product design, in researching key steps in the value chain and in providing assistance on community organizational aspects. Community collaboration with scientists and microenterprises can contribute to the growth of the non-timber forest products sector, but this growth also brings challenges in maintaining the ecological integrity and sustainability of these cultivation systems as production is scaled up.

## 7 Legislation Related to Ecosystem Restoration in Argentina

Ecological restoration is "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (SER 2004). Some of the current strategies for the restoration of degraded areas are linked to conceptions of indigenous communities about nature and human beings, focused on functionality of interactions between organisms in the processes of natural succession (Reis et al. 2010). In Argentina, current national and state legislation links indigenous communities with conservation and restoration strategies, recognizing their ancestral rights to the land they inhabit. The Constitutional Reform of 1994 established the human rights to the environment which should be "healthy and balanced", for "the satisfaction of the needs of future generations". This statement highlights the incorporation of the sustainable development concept. Similarly, the Constitution also incorporated a mandate to repair environmental damage, including restoration and rehabilitation (Law No. 25,675).

In addition, National Law No. 26,331, "Law on Minimum Standards for Environmental Protection of Native Forests", states the following objectives: (a) To promote conservation through the Management of Native Forests and regulation of the expansion of the agricultural frontier and any other changes in land use; (b) To implement the necessary measures to regulate and control the decrease in area of existing native forests, tending to achieve a lasting area in time; (c) To improve and maintain ecological and cultural processes in native forests that benefit society; (d) To use precautionary and preventive principles, maintaining native forests whose environmental benefits, or environmental damage that their absence would generate, cannot be demonstrated with the techniques available today; (e) To promote enrichment, conservation, restoration, improvement and sustainable management of native forests.

It is urgent to take actions geared towards conservation of natural resources and restoration of the productive functions of degraded areas. Likewise, it is imperative that indigenous communities and their indigenous knowledge are respected. Based on local experiences and scientific publications on the subject the scientific community should make a historic contribution to natural resources restoration by integrating EIK and ESK in the process.

## 8 Case Study of EIK and ESK Integration in the Multiple Use Guaraní Reserve (MUGR)

### *8.1 The Guarani People in Misiones, Argentina*

The Mbya people who in the nineteenth century literature appeared as Caingua or Kaygua (those belonging to the jungle), belong to the Guarani ethnic group. They inhabit lands which were inaccessible to settlers after the expulsion of the Jesuits from Misiones province in 1767. The Mbya people are characterized by their wide mobility, although currently their territories are more restricted. Their settlements are located in regions of Paraguay, Argentina, and Brazil. For them, the concept of territory goes beyond the physical boundaries of villages and trails, and is associated with a notion of the world. Their territory includes shared sectors, however in their villages they preserve their natural resources and keep the privacy of their community. For them the land is not only a production resource, but it is also the scene of religious life and social relationships that give meaning to their existence. Agriculture is the structural activity of community life; it involves joint projects, reciprocal exchange, rituals and renewal cycles (Http: /pueblosoriginarios.com/sur/chaco/mbya.html) (Accessed 05/30/2015).

The Tupi-Guarani people originated by the Madeira river, a southern tributary of the Amazon River, about 5000 years ago (Migliazza 1982). Apparently, the ancient migrations of the Tupi-Guarani looking for the "land without evil" and its consequent diversification and dispersion of families and linguistic subfamilies, could coincide with a period of reduction and fragmentation of their original habitat, the tropical jungle, caused by a drought (Schmitz 1991).

The earliest records of the Guarani presence in Misiones, Argentina date back some 1200 years B.P. (Poujade 1995), but their arrival, in what is now known as the Upper Parana Atlantic Forest, stretches back more than 2000 years, as farmers practicing shifting cultivation (Schmitz 1991; Noelli 2004). Today the southern Guarani people make up a population of more than 98,000 individuals (Azevedo et al. 2009), one of the largest indigenous populations in the lowlands of South America (Assis and Garlet 2004). In Argentina, the Guarani population is just over 6500 individuals, of which about 1000 belong to the Ava Chiripa and the remaining to the Mbya group (Azevedo et al. 2009). Both groups are widely distributed in the province of Misiones.

Among the Guarani, the gathering of natural resources consists of hunting wild animals, agriculture and harvesting of different plant products (Noelli 1993; Felipim 2001). The Guarani indigenous peoples are the custodians of Ecological Indigenous Knowledge -EIK- transmitted by word of mouth.

## *8.2 Methodology: Selection of the Study Population (Scientific and Indigenous Community) and Data Collection and Analysis*

Two types of communities were interviewed: the scientific community (34 respondents) and the local indigenous community (6 respondents). The indigenous community consisted of local people settled in the Yabotí Biosphere Reserve. Two Guaraní Mbya villages located on the Multiple Use Guaraní Reserve (MUGR) in the province of Misiones, which is part of the Yaboti Biosphere Reserve were selected. The chosen villages were the *Ita Piru* (dry stone) community and the *y'akaporã* or caramelito community (Fig. 10.1).

Semi-structured interviews and open interviews were used for the local community, and online interviews were used for the scientific community. The data were recorded using Microsoft Excel spreadsheets (2013), and processed using STATA 12.1 software.

For the scientific community, a mixed survey was designed (via email and in person), while indigenous community interviews were based on semi-structured questions and adjusted as the project progressed. Focused interviews were conducted with members of the communities under study, open surveys were carried out with "Opygua" religious leaders, traditional leaders, the "Cacique", and local experts on specific topics, identifying the different niches of ecological indigenous knowledge.

## *8.3 Results*

### 8.3.1 Indigenous Community

There were 19 members of both communities who participated in the interview process (Ita Piru: 3 men, 3 women and 5 children; Caramelito: 3 men, 1 woman and 4 children). However, only the men of both communities answered verbally the questions.


**Fig. 10.1** A Guarani indigenous community inhabiting the Multiple Use Guarani Reserve
(**a**) Development of community surveys in ita piru (Photo: L. López)
(**b**) Elder using pipe (Photo: J. Araujo)
(**c**) religious temple or Opy (Photo: L. López)
(**d**) Children playing (Photo: J. Araujo)
(**e**) Settlement village y'aka porã (Photo: L. López)

- The Caciques of both communities (two respondents) mentioned that there are difficulties in maintaining traditional knowledge, attributed to the lack of interest by young people in receiving the knowledge from older members of their communities, and the lack of spiritual leaders.
- All the respondents stated that the lack of continuity of human relationships and regular contact with the scientific community undermines confidence in the continuity of long-term projects.
- There are serious difficulties in accepting the close coexistence with communities of Western culture. This is attributed to the harmful effects that Western cultures produce to the environment (social, natural and spiritual), including contamination of biotic and abiotic resources and a supply of consumer goods that decreases the interest of young people in learning traditional knowledge.

### 8.3.2 Scientific Community

- 64% (22 people) of the survey participants reported that they have worked with indigenous communities and/or members of indigenous communities directly or indirectly, while the remaining (12 people) participants reported never having worked with indigenous communities. Most of the surveyed were located in the province of Misiones (19), with the remaining participants in the provinces of Salta and Jujuy, and some have reported work experience in Brazil.
- Among work and/or projects carried out in conjunction with the indigenous community, they mentioned three experiences related to working with orchids: assistance in designing interpretative forest trails, a native orchid exhibit; provision of orchid seedlings that had been multiplied using in-vitro propagation techniques; and workshops on orchid propagation (nursery). In addition, they mentioned environmental education; training and support in the development of community tourism; and work in a rural high school.
- The main difficulties highlighted in work directly and/or indirectly with indigenous communities were related to communication: lack of understanding of the community language, the discontinuity of activities and funding of the projects, lack of institutional networking and the lack of relevant knowledge about the communities involved.
- As for achievements in conjunction with indigenous communities and their members, scientists considered that they had good relationships, cooperation and acceptance. Eleven survey participants out of the 29 surveyed consider ESK very important, 17 consider ESK important, and one partially important. One out of 20 surveyed believe that EIK is essential, one of main importance, 8 very important and 10 important. These results indicate that there is a high stated consideration of the importance of EIK on behalf of the scientific community, but do not indicate the extent to which EIK is currently incorporated into formal learning or scientific activities in conjunction with indigenous communities.

- The vast majority, represented by 82% (28 respondents) believe that it is possible to see ESK integrated with EIK in the implementation of a program for natural resource management. As tools to favor integration for natural resource management, they mentioned participatory workshops, implemented with openness and humility to understand indigenous culture; negotiation; appropriate participatory methodologies; exchanging experiences and continuous dialogue; and grassroots collaboration.

## 9 Conclusions

Strategies for sustainable development in the Management of Natural Resources (MNR) have to resort to a wide range of knowledge, covering "ecological scientific knowledge" (ESK), as well as the "ecological indigenous knowledge" (EIK). Unlike scientific knowledge, indigenous knowledge is comprehensive, functional and adaptive to changes in the social and natural environment, and has been passed over thousands of generations. This is a challenge to the management of natural resources which is currently based on disaggregated and partial expertise. An important challenge for the integration of EIK and ESK in the MNR, therefore, is to find ways to encourage dialogue and cooperation among diverse groups of stakeholders with different forms of knowledge, rather than to impose a single vision through a hegemonic discourse that mutes all other forms of expression.

The analysis of the results of the present case study highlights the challenges, as evidenced by both communities, in the integration of EIK and ESK projects. The analysis of results from the scientific community reveals: (a) an acknowledgment of errors and/or difficulties in the process of approaching indigenous communities, (b) an interest in integrating both knowledges and (c) proposals for mechanisms to consider in implementing EIK and ESK integrated projects in the management of natural resources. It is recommended, for example, that in the process of conducting scientific research there should be a consultation stage and capture of experiences and lessons learned by indigenous knowledge. Scientific knowledge should not serve to validate and supplement cultural errors or deviations that the EIK may have suffered.

Central aspects in the analysis of integration strategies between EIK and ESK emerge from the results of surveys conducted with indigenous communities. On one hand, it appears that EIK must regenerate through the natural context where it has been gestated through millennia. On the other hand, survey participants expressed the need to implement measures to prevent and remediate the erosive processes that undermine the integrity of the cultural scene where EIK could be applied, and to preserve the integrity of the natural environment which produces this type of cultural setting. Preventive measures included ensuring the legal possession of large forest areas by indigenous peoples in order to stop or slow the advance of the agricultural frontier in natural spaces where EIK is recreated. Remedial suggestions included adopting autochthonous **strategies**, such as the use of oxen to till the land.

The dialogue with stakeholders who are bearers of traditional knowledge, at least at the local level, is very complex. Projects integrating EIK-ESK have limited institutional base and disjointed science and technology. On the other hand, the technologies applied are foreign to the indigenous communities and do not include local cognitive perceptions regarding the management of natural resources. To address rapid environmental change, we not only need to use all the sources of information and knowledge available, but also embrace a variety of ways to think, learn, adapt and transform. Integrating EIK and ESK to successfully implement environmental projects is one way to expand the variety of tools and information sources available for conservation.

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# Chapter 11
# Organic Yerba Mate, *Ilex paraguariensis*, in Association with Native Species: A Sustainable Production Alternative

**Beatriz I. Eibl, Florencia Montagnini, Miguel A. López, Lucas N. López, Roberto Montechiesi, and Eduardo Esterche**

## 1 Introduction

The "yerba mate" tree, *Ilex paraguariensis* A. St.-Hil., Aquifoliaceae, is a native species found in the intermediate canopy of the interior Atlantic forest of Argentina, Paraguay, and Brazil. Montechiesi (2007) reports that before the arrival of the Spaniards in Asunción (Paraguay) in 1554, yerba mate leaves were already consumed as an infusion by native Guaraní communities. The same author states that it was consumed for its properties as a stimulant, tonic and diuretic, breaking the "yerba" leaves in a gourd, adding hot water, and drinking it using a hollow cane or "tacuara". The domestication of the species began during the eighteenth century in the Jesuit "Reductions" (name given to Guaraní indigenous populations living under the authority of the priests); nevertheless, yerba mate was mainly harvested from natural forests at the time (Burtnik 2006). The species was classified in 1822 from material collected in Curitiba, Parana, Brazil by the botanist Augusto de Saint

B. I. Eibl (✉) · M. A. López · L. N. López
Facultad de Ciencias Forestales, Universidad Nacional de Misiones,
Eldorado, Misiones, Argentina
e-mail: beibl@facfor.unam.edu.ar

F. Montagnini
School of Forestry and Environmental Studies, Yale University, New Haven, CT, USA
e-mail: florencia.montagnini@yale.edu

R. Montechiesi
Cámara de Molineros de Yerba Mate de la Zona Productora, Posadas, Misiones, Argentina
e-mail: cmymzp@arnet.com.ar

E. Esterche
Escuela Agrotécnica Eldorado, Universidad Nacional de Misiones,
Eldorado, Misiones, Argentina
e-mail: estercheeduardo@yahoo.com



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Hilaire (López et al. 2002). The first “yerba mate” plantations (“yerbales”) were established in 1926 in San Ignacio, Argentina in the Province of Misiones (Burtnik 2006). According to Gallero (2013) the first yerba mate business venture was started in the same city as early as 1902.

In Argentina, yerba mate is grown by small or medium to large farmers, as a family business, a farmers’ cooperative, or a large-scale enterprise, both for local consumption and for export. The total area in *I. paraguariensis* plantations in the provinces of Misiones and Corrientes (Argentina) is 203,800 hectares (ha) with an annual production of 650 million kilograms (kg) of green leaf – primary raw material –equivalent to 250 million kilograms of yerba mate (INYM 2016).

There are 17,000 yerba mate producers in Misiones, 85% of whom have on average 10 ha of land. Montechiesi (2007) reports that 50% of these lands have low productivity mainly due to soil erosion, soil compaction, nutrient losses, and inadequate management practices. One way to recover the productivity of “yerbales” is by incorporating trees in the production system (Reutemann 2009; Baggio et al. 2011; Day et al. 2011). When soils are compacted, the application of fertilizer can be inefficient, as the soils’ biological activity, structure and porosity have been diminished, and they must be restored in order to recover productivity. These recommendations were first promoted in 1946 by Mr. Alberto Roth, who was a Swiss farmer and pioneer in the ecological management of yerba mate in Misiones. In fact, Roth suggested to always keep the soil covered with perennial weeds and grasses in order to prevent erosion, and to promote the use of leguminous species, the application of organic fertilizers, and the incorporation of trees in yerba mate plantations (Gallero 2013). Moreover, Lytwin (2011) recommended the use of weeds, grasses, or small shrubs between rows of yerba mate during winter and summer. Lytwin also suggested the inclusion of forest species and animals such as cattle into yerba mate plantations to increase productivity and to improve the restoration process of degraded soils.

In the Province of Misiones, agroforestry systems (AFS) are the basis for recovering productivity on yerba mate plantations; AFS are geared towards the organic production of yerba leaves based on conserving natural resources: soil, water, and biodiversity (Guayakí Latin America 2016). The sustainable management of natural resources aims to maintain or increase fertility, biotic activity, and biological diversity, as well as to decrease pests and diseases.

Organic agriculture enhances the application of traditional, indigenous, and customary farming knowledge, and can produce tastier and healthier food (Humane Society International 2010). In addition, organic products can have an added value which increases the price of products sold by the farmer. For example, in Costa Rica organic coffee produced under the shade of canopy trees can access higher prices through “Bird Friendly” Certification which is awarded by the Smithsonian Migratory Bird Center (Eco-Lógica 2013). In yerba mate AFS, the decrease in the harvest of yerba leaves resulting from the presence of trees (Eibl et al. 2000) can be offset by a better price for the organic product, timber production, and other environmental benefits provided by the system.

Furthermore, organic production in AFS contributes to ecosystem conservation and increased biodiversity. Studies conducted by Cockle et al. (2005) in yerbales under the canopy of native trees in Paraguay indicate that 66% of the birds were living in the treetops and trunks of the associated trees, with bird abundance similar to that found in the adjacent native forest. Patches of primary forest located within productive areas are crucial to promoting bird diversity (Cockle et al. 2010).

The selection criteria for tree species and their plantation densities in yerba mate AFS should be based on the preferences of the producers, as well as on the available information on the trees and their adaptations to new ecosystems (Dhakal et al. 2005; Montagnini et al. 2011). In Misiones, some native species of interest to the producer include: *Araucaria angustifolia, Aspidosperma polyneuron,* and *Handroanthus heptaphyllus.* The status of these species is classified as vulnerable, and they are categorized as "Natural Monuments" (Ley Provincial XVI n° 19 and 91). The incorporation of native species into AFS requires the availability of propagation material, which can also lead to the conservation of the resource (Niella et al. 2016).

The production of wood in an AFS adds other goods to the yerbales, thus improving productivity, increasing farmers' income, and increasing the economic value of the land (Porter 1991; Romero 1994). Although only the wood is valued for having market price, similar studies should consider the economic valuation of environmental services such as protection of water, biodiversity, carbon sequestration, landscape improvement, and others. This chapter assesses the adaptability and growth performance of native tree species for their use in AFS with yerba mate. In addition, this research aims to estimate the financial profitability of AFS of yerba mate with native trees having valuable wood.

## 2 The Cultivation of Yerba Mate in Association with Native Trees

*Ilex paraguariensis* is an evergreen tree that grows naturally in the canopy of the eastern subtropical forest; it is shade tolerant and prefers cool, humid sites (López et al. 2002). These characteristics indicate that it can be planted in shaded areas and also in open areas if it is initially sheltered from direct sunlight by applying protection elements oriented to the Northwest (as yerba mate grows in the Southern hemisphere). Yerba mate has high plasticity and a high survival rate in productive systems, therefore it is one of the native species with larger plantation areas in Misiones.

In small farms in southern Brazil, *Cordia trichotoma*, *Peltophorum dubium*, *Cabralea canjerana*, *Parapiptadenia rigida*, *Cordia americana* and *Handroanthus heptaphyllus* have been identified as the best performing tree species for yerba mate production under shade (Baggio et al. 2011). In their evaluations of yerba mate AFS (with a harvest cutting cycle of 30–40 years and a density of 50–100 native trees species per ha) Baggio et al. (2011) took into consideration the quality of yerba mate leaf as well as timber production and the environmental services provided by the system.

*Araucaria angustifolia* and *Cordia trichotoma* are native trees species that are recommended to improve the productivity of yerbales due to their good stem form and high wood quality (Cozzo 1982). Among exotic tree species, Cozzo recommended *Pawlonia tomentosa* planted with a density of 40–80 trees per ha. Reutemann (2013) suggested incorporating up to 400 trees per ha in mixed yerbales plantations, including *Enterolobium contortisiliquum* for its contribution of nitrogen to the soil, and timber species such as *Araucaria angustifolia*, *Parapiptadenia rigida*, *Peltophorum dubium*, *Bastardiopsis densiflora*, and *Cordia trichotoma*. González (2013) suggested the use of *Araucaria angustifolia* as well as the exotic species *Grevillea robusta* and *Toona ciliata,* all planted at distances of 15 m × 15 m within yerbales. González observed several benefits from this mixture of trees such as reduction of wind impact and hail damage to yerba mate leaves, as well as the microclimatic benefits generated by the shade, and the improvement of soil conditions and nutrient recycling.

There are numerous brands of yerba produced, packaged, and marketed in the Province of Misiones that have organic certification (i.e. OIA,[1] ARGENCERT,[2] Rainforest Alliance[3]). To achieve this certification, among other requisites, native trees must be included in the production system to increase biodiversity and provide a shaded environment for the yerba mate plants.

An organic yerba mate system is expected to have between 80 and 120 trees per ha in the canopy layer. The trees are planted in different positions either in the same line of the yerba mate or between the rows. In old yerbales, native tree species are usually planted on sites where yerba mate plants are missing. In addition, it is expected that seedlings arising from natural regeneration are cared for and managed within the system. Natural regeneration, which generates different canopy layers, will increase over time in terms of the number of individuals and species. Cleaning activities are carried out with "machetes" or by rolling down weeds (i.e. Rollers and Roll crimpers) two to three times per year before the yerba mate harvesting period. Forest buffer areas around streams, slopes, and biological corridors for fauna and flora are often part of the landscape in yerba mate plantation regions.

Native trees should be planted in a hole at least 80 cm in depth. The roots must reach the water table, so that the young plants are not dependent on rainwater during the first stage of adaptation. For this purpose, high quality plants are required (healthy plants with 20 to 40 cm height, produced in pots or containers) and the

[1] O.I.A. (Organización Internacional Agropecuaria, International Agriculture Organization, www.oia.com.ar), from Argentina, provides accreditation services nationally and internationally.

[2] ARGENCERT (www.argencert.com.ar), from Argentina, engages in the inspection and certification of a broad variety of fresh and processed organic products. It operates as subsidiary of Ecocert S.A.

[3] Rainforest Alliance (Rainforest-alliance.org), offers comprehensive certification services in agriculture, forestry, tourism, and carbon; provides technical and sourcing assistance and training.

planting period must be attended correctly. It is recommended to plant during the second half of August through October (in the Southern hemisphere) as there is less risk of frost, high temperatures and/or drought. Similar recommendations have been given by Baggio et al. (2008) for AFS with yerba mate in southern Brazil.

# 3 Methods

## *3.1 Description of the Experimental Sites*

The data and information gathered for this study were collected at two experimental sites located in the Province of Misiones, Northeastern Argentina. The climate of the region is subtropical humid and lacks a dry season, with an average annual rainfall of 2020 mm evenly distributed throughout the year, and an average annual temperature of 22 °C (Silva et al. 2008). Cold periods in winter are short but temperatures below 0 °C can be recorded with a minimum of −7 °C, and early (April) and late frosts (September) are common. Summers are characterized by warm weather conditions with temperatures reaching up to 40 °C. It is common for droughts to occur at any time during the year.

The data presented in this study are in part results of projects carried out by the National University of Misiones in the Department of Eldorado (Misiones) on the performance of native species associated with yerba mate. These experiments were established for research purposes and are currently used as demonstration areas. The experimental sites are the following:

**Experimental Site 1** Located on Avenida Fundadora in the city of Eldorado (Misiones), it consists of single species plantations of yerba mate with a density of 1.5 m × 3 m, and mixed plantation of yerba 1.5 m × 6 m interspersed with native forest species planted at 3 m × 6 m. The tree species included: *Enterolobium contortisiliquum*, *Balfourodendron riedelianum* and *Handrohanthus heptaphyllus* (Eibl et al. 2000). Six variables were measured: growth rate in diameter and height of the three native forest species (Barth et al. 2008); yerba mate leaves productivity per plant (Eibl et al. 2000); soil changes under the different soil covers and yerba mate leaf quality (Day et al. 2011); and carbon sequestration by timber species (López et al. 2012).

**Experimental Site 2** Located in the Eldorado Agrotechnical School on a 5 ha piece of land planted with yerba mate in different densities: 3 m × 1.25 m, 3 m × 1.5 m, and 3 m × 1.8 m. It encompasses two plots:

**Plot A** Established in 1985, consisting of yerba mate plantations with remnant trees, i.e. native trees that grew from natural regeneration: *Cordia trichotoma, Machaerium* sp., *Myrocarpus frondosus, Enterolobium contortisiliquum, Cedrela fissilis, Bastardiopsis densiflora,* and *Holocalyx balansae.*

**Plot B** Established in 1988, consisting of a yerba mate plantation and native trees species that were planted for timber and restoration purposes. The species combinations were based on recommendations made by Mr. Alberto Roth during a visit that Mr. Eduardo Esterche made to the rural community of Santo Pipó in 1978 (Montagnini et al. 2011). A set of leguminous timber trees was suggested for planting, considering their potential for restoration: *Pterogyne nitens, Enterolobium contortisiliquum,* and *Anadenanthera colubrina.* Trees were measured annually for diameter at breast height, total crown height, and stem height.

Both experimental sites are connected with primary native forest located in the margins of the yerba mate plantations. These areas provide multiples benefits. In fact, the National Government enacted National Law 26331 (2007) promotes the conservation and restoration of this type of forest remnant.

Data were also gathered from previous studies on organic yerba production sites in the Province of Misiones: Andresito, San Ignacio, Santo Pipó, Campo Ramón, Eldorado, Montecarlo, San Vicente, Oberá, Guaraní, and Dos de Mayo (Montagnini et al. 2011). In these previous studies, several native tree species were found associated with yerba mate. The species, which were not planted but had grown from natural regeneration were: *Acrocomia aculeata, Albizia hasslerii, Annona* sp.*, Apuleia leiocarpa, Araucaria angustifolia, Arecastrum romanzoffianum, Aspidosperma polyneuron, Ateleia glazioveana, Balfourodendron riedelianum, Bastardiopsis densiflora, Cabralea canjerana, Cecropia pachystachya, Cedrela fissilis, Cordia trichotoma, Cordia americana, Enterolobium contortisiliquum, Euterpe edulis, Holocalyx balansae, Jacaranda semiserrata, J. micrantha, Lonchocarpus muehlbergianus, Machaerium* sp.*, Myrocarpus frondosus, Nectandra lanceolata, Nectandra megapotamica, Ocotea puberula, Parapiptadenia rigida, Peltophorum dubium, Solanum granulosum-leprosum, Trema micrantha,* and *Handroanthus heptaphyllus.* Several of these species have shown good growth performance and adaptability in other studies in Misiones (Eibl et al. 2000; Montagnini et al. 2006; Barth et al. 2008; Crechi et al. 2010).

The incorporation of native tree species in yerba mate plantations provides other resources such as flowers, fruits, and seeds. Information on flowering and fruit bearing by the tree species, and their optimal harvest period time, is available (Eibl et al. 1997; Eibl et al. 2012). This information is considered useful for yerba mate producers who also need flowers for beekeeping, fruits for their own consumption, and seeds for nurseries, as well as for favoring wildlife.

### *3.2 Economic Analysis*

An economic analysis was made for AFS yerba mate associated with planted native timber species. Once the cost structure is defined, economic indicators at the initial stage of planting can be determined. Preliminary data collection on species survival and growth in diameter and height allowed for early economic estimates (Hosokawa 1986) based on the costs incurred for establishment of a total of 100 trees per ha. Based on costs data from local market values, the "future value" of the plot was estimated using different interest rates (Justo 1978). This analysis follows the "Historical Cost" methodology (i.e. valuation at cost), which means that an assessment is made at year 10 of all costs incurred, calculated at the time of valuation using an interest rate of 2%, 4%, and 6%. These interest rates are appropriate for the activity described (Hosokawa1986; Hosokawa and López 1995).

During the first year, the activities that were carried out included weeding the area with "machete", field marking, digging holes, planting 100 trees per ha, staking, and maintenance. Expenditures included purchase of seedlings, stakes, and hiring a manual excavator. The remuneration of the family labor in terms of wages was included in the cost structure, with an estimated value based on the Agrarian Labor Regime Decree 301/2013, Regulation of National Law 26727. From year 1 to year10 maintenance of the planted area included cleaning the area with machete twice a year, as well as the payment of city tax and property tax.

Monetary income corresponds to the "non-refundable financial aid" that the farmer can get in year 2, as established by National Law 25080 "investments for cultivated forests" (extended by National Law 26432), also known as Non-refundable Economic Assistance (AENR for the acronym in Spanish). The value of the AENR for the Upper Parana Atlantic Forest, Province of Misiones is US$877 per ha.

The economic assessment was made for standing timber, depending on size and future use of the trees (Justo 1978). Results from growth models for native species obtained from experimental areas monitored annually (Barth et al. 2008) allowed for an estimate of the potential logging cycles for timber and firewood (Eibl et al. 2015). The exchange rate from the Central Bank of Argentina of US dollar ($US) to Argentine pesos ($AR) for the purpose of this study was 1 US$ = 8 $AR.

## 4 Results and Discussion

### *4.1 Adaptability and Growth of Species Associated with Yerba Mate in Agroforestry Systems*

Based on the background information mentioned above (Eibl and Montagnini 1998; López et al. 2002; Baggio et al. 2008; Montagnini et al. 2011), a list of potential species was developed to use in combination with *I. paraguariensis* in AFS (Table 11.1).

**Table 11.1** Growth features and environmental requirements of native species of multiple uses, suitable for combination with *Ilex paraguariensis*, presented in order depending on their qualities/preferences, starting with those with monopodial growth followed by those with sympodial growth

| Species, family | Trunk/stem, crown, foliage and growth[a] | Environmental requirements at the time of planting and during the early years[b] |
|---|---|---|
| *Cordia trichotoma* Vell. Arrab. ex Steud, Boraginaceae | Upper and intermediate tree canopy. Monopodial. Medium crown sizes. Deciduous foliage. Intermediate growth rate. | Heliophyte. Tolerates low fertility sites. Tolerant to direct sunlight. |
| *Balfourodendron riedelianum* (Engl.)Engl., Rutaceae | Upper and intermediate tree canopy. Monopodial. Small crown sizes. Semi-deciduous foliage. Low growth rate. | Semi-heliophyte. It requires medium fertility sites. Sensitive to direct sunlight. |
| *Bastardiopsis densiflora* (Hook &Arn.) Hassl., Malvaceae | Intermediate tree canopy. Monopodial. Medium crown sizes. Semi-deciduous foliage. High growth rate. | Heliophyte. It requires medium fertility sites. Tolerant to direct sunlight. |
| *Nectandra lanceolata* Nees & Mart., Lauraceae | Intermediate tree canopy. Monopodial. Medium crown sizes. Evergreen. High growth rate. | Semi-heliophyte, tolerates low fertility sites. Sensitive to direct sunlight. |
| *Araucaria angustifolia* (Bertol.) Kuntze, Araucariaceae | Upper tree canopy. Monopodial. Large crown sizes. Evergreen. High growth rate. | Heliophyte. It requires deep soils of medium fertility. Resistant to light frost. Low tolerance to drought. Shade tolerance. |
| *Aspidosperma polyneuron* Mull.Arg., Apocinaceae | Upper tree canopy. Monopodial. Large crown sizes. Evergreen. Low growth rate. | Semi-heliophyte. It requires deep soils with intermediate fertility. Shade tolerance. At first stage is sensitive to direct sunlight. |
| *Euterpe edulis* Mart., Arecaceae | Palm from the intermediate canopy. Monopodial. Small crown sizes. Evergreen. Intermediate growth rate. | Semi-heliophyte. It requires humid sites. Tolerant to low intense frost. Low tolerance to drought. Sensitive to direct sunlight. |
| *Eugenia involucrata* DC., Mirtaceae | Low tree canopy (understory). Monopodial or sympodial[c]. Small crown sizes. Evergreen. Intermediate and slow growth rate. | Semi-heliophyte. Shade tolerance. Sensitive to direct sunlight. |
| *Jacaranda micrantha* Cham., Bignoniaceae | Intermediate tree canopy. Monopodial or sympodial[c]. Medium crown sizes. Deciduous foliage. Intermediate growth rate. | Heliophyte. It adapts to low fertility sites. Tolerant to direct sunlight. |
| *Syagrus romanzoffiana* (Cham.) Glassman, Arecaceae | Palm from the intermediate canopy. Monopodial. Small crown sizes. Evergreen. Low growth rate. | Heliophyte. It adapts to low fertility sites. Tolerant to direct sunlight. |

(continued)

**Table 11.1** (continued)

| Species, family | Trunk/stem, crown, foliage and growth[a] | Environmental requirements at the time of planting and during the early years[b] |
|---|---|---|
| *Cedrela fissillis* Vell., Meliaceae | Upper and intermediate tree canopy. Monopodial or sympodial[c]. Medium crown sizes. Deciduous foliage. High growth rate. | Heliophyte. It adapts to low fertility sites. Tolerant to direct sunlight. |
| *Schefflera morototoni* (Aubl)Maguire Steyerm&Frodin, Araliaceae | Intermediate tree canopy. Monopodial. Medium crown sizes. Evergreen. High growth rate. | Heliophyte. It adapts to low fertility sites. At first stage is sensitive to direct sunlight. |
| *Aralia warmingiana* (Marchal) J. Wen, Araliaceae | Intermediate tree canopy. Monopodial. Medium crown sizes. Deciduous foliage. High growth rate. | Semi-heliophyte. It requires deep soils with intermediate fertility. At first stage is sensitive to direct sunlight. |
| *Anadenanthera colubrina* (Vell.) Brenan, Fabaceae | Upper and intermediate tree canopy. Monopodial and sympodial[c]. Medium crown sizes. Semi-deciduous foliage. High growth rate. | Heliophyte. It adapts to low fertility sites. Tolerant to direct sunlight. |
| *Peltophorum dubium* (Spreng.)Taub., Fabaceae | Upper tree canopy. Monopodial or sympodial[c]. Large crown sizes. Deciduous foliage. High growth rate. | Heliophyte. It adapts to low fertility sites. Tolerant to direct sunlight. |
| *Handroanthus heptaphyllus* (Vell.) Mattos Phil., Bignoniaceae | Upper tree canopy. Sympodial. Large crown sizes. Deciduous foliage. Intermediate growth rate. | Heliophyte. It adapts to low fertility sites. Tolerant to direct sunlight. |
| *Handroanthus albus* (Cham.) Mattos A. St. Hil., Bignoniaceae | Intermediate tree canopy. Sympodial. Medium crown sizes. Deciduous foliage. Intermediate growth rate. | Heliophyte. It adapts to low fertility sites and flood areas. Tolerant to direct sunlight. |
| *Handroanthus pulcherrimus* (Sandwith) S. Grose, Bignoniaceae | Intermediate tree canopy. Sympodial. Medium crown sizes. Deciduous foliage. Intermediate growth rate. | Heliophyte. It adapts to low fertility sites. Tolerant to direct sunlight. |
| *Myrocarpus frondosus* Allemao, Fabaceae | Upper and intermediate tree canopy. Monopodial or sympodial[c]. Small crown sizes. Semi-deciduous foliage. Low growth rate. | Semi-heliophyte. It requires deep soils with intermediate fertility. At first stage is sensitive to direct sunlight. Shade tolerance. |
| *Cabralea canjerana* (Vell.) Mart., Meliaceae | Intermediate tree canopy. Monopodial or sympodial[c]. Medium crown sizes. Semi-deciduous foliage. Intermediate growth rate. | Semi-heliophyte. It requires deep soils with intermediate fertility. At first stage is sensitive to direct sunlight. Shade tolerance |

(continued)

**Table 11.1** (continued)

| Species, family | Trunk/stem, crown, foliage and growth[a] | Environmental requirements at the time of planting and during the early years[b] |
|---|---|---|
| *Plinia rivularis* (Cambess.) Rotman, Mirtaceae | Low tree canopy (understory). Sympodial. Small crown sizes. Evergreen. Low growth rate. | Semi-heliophyte. It requires deep soils with intermediate fertility. At first stage is sensitive to direct sunlight. Shade tolerance. |
| *Pterogyne nitens* Tul., Fabaceae | Intermediate tree canopy. Sympodial. Large crown sizes. Deciduous foliage. Intermediate growth rate. | Heliophyte. It adapts to low fertility sites. Tolerant to direct sunlight. |
| *Enterolobium contortisiliquum* (Vell.) Morong., Fabaceae | Upper tree canopy. Sympodial. Large crown sizes. Deciduous foliage. High growth rate. | Heliophyte. It adapts to low fertility sites. Tolerant to direct sunlight. |

[a,b]Data gathered from experimental sites from plantations and natural regeneration
[c]Some species may present either sympodial or monopodial growth after planting in the open conditions in the field, this may require different management techniques (pruning), and could be subject of genetic improvement

Trees and palms with single trunk – i.e. monopodial –are preferable for combination with yerba mate, for instance: *Cordia trichotoma, Balfourodendron riedelianum, Bastardiopsis densiflora, Araucaria angustifolia, Nectandra lanceolata, Aspidosperma polyneuron, Euterpe edulis, Jacaranda micrantha, Syagrus romanzoffiana, Schefflera morototoni,* and *Aralia warmingiana*. It is also preferable to use trees with small or medium sized crowns that allow light to filter through their foliage (Baggio et al. 2008), for example: *Balfourodendron riedelianum, Eugenia involucrata, Jacaranda micrantha, Euterpe edulis, Syagrus romanzoffiana, Aralia warmingiana* and *Anadenanthera colubrina*. The litterfall from the trees associated in AFS should enhance the cycling of nutrients (Fernández et al. 1997; Ilany et al. 2010). In addition, it is expected that the root system of the trees to be planted in yerbales does not compete with the roots of yerba mate. Finally, in all cases the species are expected to exhibit good growth and to have a good market value (Fig. 11.1).

However, there are several sympodial species with good growth features that undergo natural pruning due to light constraints thus shaping their crown in an inverted form. In these cases it is recommended that they are planted at low densities. In this group there are several species with high timber value: *Cedrela fissilis, Peltophorum dubium, Pterogyne nitens, Handroanthus* sp., and *Myrocarpus frondosus*. The species that grow best in the shade such as *Euterpe edulis*, *Myrocarpus frondosus*, *Cabralea canjerana*, *Aspidosperma polyneuron*, *Eugenia involucrata*, and *Schefflera morototoni* are recommended to be included at later stages, requiring small gaps for better growth.

**Fig. 11.1** Canopy layers allowing adequate solar radiation through foliage for an agroforestry system with yerba mate (Photo: B. Eibl)

### 4.1.1 Experimental Site 1

At this site, *Handroanthus heptaphyllus* of good timber and landscape value stagnated in diameter and height after a rapid initial growth (Table 11.2). This phenomenon has also been observed by Baggio et al. (2011). Heartwood formation can be linked to this particular feature. This species can also be planted for carbon sequestration (Santos et al. 2011; López et al. 2012). *Balfourodendron riedelianum*, with slow growth, small crown sizes, and natural pruning, is an adequate species to plant with *I. paraguariensis* (Table 11.2 and Fig. 11.2). In this site *Enterolobium contortisiliquum* showed a high mortality rate, possibly due to pruning activities. At 20 years after establishment, important regeneration of useful species such as *Cabralea canjerana*, *Nectandra lanceolata, Peltophorum dubium,* and *Jacaranda micrantha* could be observed in this experimental site, apparently growing from seeds that had been dispersed from the native forest reserve adjacent to the site (Fig. 11.3).

### 4.1.2 Experimental Site 2

At this experimental site, in Plot A, two species had adequate growth (Table 11.2): *Cordia trichotoma* (Fig. 11.4) and *Bastardiopsis densiflora*. Several remnant trees were found in the same site: individuals of *Machaerium sp.*, *Myrocarpus frondosus* and *Syagrus romanzoffiana*, with a total of 40 trees per ha. There were also many individuals stemming from natural regeneration: *Balfourodendron riedelianum*, *Bastardiopsis densiflora, Cabralea canjerana, Cecropia pachystachya, Cedrela*

**Table 11.2** Growth of timber species in plantations with *Ilex paraguariensis* at two sites in Eldorado (Misiones)

| Experimental site | | Species and age | Total average height (m) | Trunk/stem average height (m) | Average DBH (cm) |
|---|---|---|---|---|---|
| **Experimental site 1**: Avenida Fundador. Eldorado, Misiones. | | *Handroanthus heptaphyllus* – 20 years. | 12.4 | 4 | 17.8 |
| | | *Balfourodendron riedelianum* – 22 years. | 11.9 | 6.2 | 12.2 |
| | | *Enterolobium contortisiliquum* – 22 years. | 14 | 3.8 | 27.8 |
| **Experimental site 2**: Agrotechnical School. Eldorado, Misiones. | **A** | *Cordia trichotoma* – Estimated between 30 and 40 years. | 24 | 16 | 56 |
| | | *Bastardiopsis densiflora* – Estimated between 20 and 30 years. | 20 | 8 | 44 |
| | **B** | *Pterogyne nitens* – 25 years. | 14 | 3 | 57 |
| | | *Enterolobium contortisiliquum* – 25 years. | 12 | 4 | 52 |
| | | *Anadenanthera colubrina* – 25 years. | 12 | 6 | 32 |

**Fig. 11.2** Monopodial growth, natural pruning and small crown size in *Balfourodendron riedelianum* trees associated with yerba mate (Photo: B. Eibl)

**Fig. 11.3** Natural regeneration of *Cabralea canjerana* under plantations of native species associated with yerba mate (Photo: B. Eibl)

**Fig. 11.4** Adult tree of *Cordia trichotoma* in experimental site 2 (Photo: B. Eibl)

**Fig. 11.5** *Enterolobium contortisiliquum* V-Shaped crown due to competition (Photo: B. Eibl)

*fissilis, Cordia trichotoma, Cordia americana, Machaerium* sp., and *Nectandra lanceolata*, generating uneven stands (i.e. crowns of different ages).

In Plot B, *Enterolobium contortisiliquum* and *Anadenanthera colubrina* trees had an "inverted crown shape" (V-Shaped crown), as they underwent natural pruning through competition between the crowns in their early stages of growth. At 22 years of age, the *E. contortisiliquum* individuals that remained healthy had probably benefitted from the absence of pruning activities (Table 11.2 and Fig. 11.5).

*Enterolobium contortisiliquum* has a broad crown and outcropping roots. These characteristics are generally not recommended for agroforestry systems. However, many authors recommend this species in low density plantations because of its potential for soil restoration due to its nitrogen fixation capacity, the supply of nutrients through litter and the decrease in risk of soil erosion (Day et al. 2011; Montagnini et al. 2011). When planted in association with other species of similar size, natural pruning occurs through competition and the species develops a crown that does not interfere with yerba mate production.

## 4.2 *Other Benefits and Products from Species Associated with Yerba Mate in Agroforestry Systems*

In many yerbales associated with other species it is common to find large hollows in dead trees that remain in the area, leading to the presence of birds that nest in holes and feed on insects and rodents (Cockle et al. 2010) (Fig. 11.6). The presence of birds in yerbales is enhanced when there are adjacent forest remnants (Cockle et al. 2005).

In organic yerba mate systems in the region of Turvo, Brazil, fewer pest problems and diseases have been related with greater biodiversity and more complex layers of vegetation associated with yerba mate (Santos et al. 2011). Yerba mate leaves look healthier and brighter in those plants found under the shade of the trees and near the forest edge (Day et al. 2011). In addition, the incorporation of native species in association with *I. paraguariensis* cultivation provides alternative products such as flowers, fruits, and seeds.

Some of the tree species grown in association with yerba mate that are known for their positive impacts on landscape features with their colorful flowers include *Jacaranda micrantha, Peltophorum dubium,* and *Handroanthus sp.* Other species such as *Bastardiopsis densiflora, Nectandra lanceolata, Eugenia involucrata,*

**Fig. 11.6** Hollow boles in standing dead trees, in yerbales with native trees in Eldorado, Misiones (Photo: B. Eibl)

**Fig. 11.7** Large crown sizes of *Bastardiopsis densiflora* with flowers of interest for beekeeping (Photo: B. Eibl)

*Euterpe edulis,* and *Myrocarpus frondosus* have beekeeping production purposes (Figs. 11.7 and 11.8). All species provide flowers, fruits, and seeds at different times of the year which can be used for household consumption and favor the presence of birds and mammals (Fig. 11.8). These attributes favor natural regeneration and the products are also useful as propagating material for nurseries (Eibl et al. 2012, 2015).

### *4.3 Marketable Products from Recommended Species Used for Association with* **Ilex paraguariensis**

The total cost of establishment, including labor, field marking, cost of plants, manual excavation costs, planting, staking, weeding the area with machetes, municipal taxes, and property tax was US$470. The total cost of weeding activities performed twice a year from year 1 to year 10 was US$90. The only income in the first ten years came from the "non-refundable financial aid" with a total of US$877.


**Fig. 11.8** *Eugenia involucrata,* (**a**): adult tree, (**b**): flower, (**c**): fruit (Photos: B. Eibl)

Using interest rates of 2%, 4%, and 6%, the estimated income values at year 10 were 5.11 US$/tree (2%), 5.14 US$/tree (4%), and 5.31US$/tree (6%). When the farmer sells each tree (average value without differentiating by species) at year 10 for US$5.11/tree, it means that the capital invested is remunerated at 2% annually. If the farmer sells for US$5.31/tree, it means that capital is reinvested annually at 6%. If the farmer gets the price valued at year 10, it means that all the money invested was recovered –i.e. remunerating the capital invested at the interest rate that was used. It may seem that US$5.11 – US$5.31/tree is a low value after 10 years; however this could be interpreted as "it is not so expensive to produce native species" since the capital invested – i.e. costs incurred– has already been remunerated, according to the current interest rate. Finally, considering on average 100 trees per ha, the income per ha is considered attractive for famers in the region.

Although only wood currently has a market value, in addition, an economic valuation of environmental services corresponding to carbon fixation (Vaccaro et al. 2003), and the functions of enhancing biodiversity and landscape value, considering the multiple use of species, should be conducted to obtain an estimate of the total value of yerba mate AFS (Hosokawa and López 1995; Hosokawa and Eibl 1996, Law 26,331 Minimum Budget for Environmental Protection of Native Forests, Argentina).

## 5 Conclusions

Mixed plantations make better use of available energy due to a more complex stratification; they also generate product diversification and create adequate conditions favoring natural regeneration of other species. The best species combination is obtained by associating valuable species selected for their growth, and for crown and foliage characteristics that contribute to site restoration. These arrangements should consider the size and the light requirements of each of the species which would also determine the recommended number of individuals in the upper canopy. Monopodial growth, small crown, natural pruning, and foliage that allows the adequate passage of light, combined with characteristics of timber value are the attributes required to generate the benefits of production of yerba mate leaves under shade.

The benefits of incorporating native tree species in yerba mate plantations mentioned by farmers during our interviews included shade provided to the yerba mate plants, nutrient supply, the potential for physical and chemical soil restoration, increased infiltration of rainwater, benefits to wildlife, landscape improvement, and timber production. Slow-growing trees with high quality timber such as *Myrocarpus frondosus, Aspidosperma polyneuron, Araucaria angustifolia, Handroanthus heptaphyllus, Handroanthus albus,* and *Handroanthus pulcherrimus* could also be considered for carbon fixation purpose in the long term. Farmers pointed out the importance of preserving these species.

In agroforestry systems, native trees can improve soil fertility and promote sustainability by avoiding the need to apply fertilizers. Leguminous species such as *Enterolobium contortisiliquum* and *Anadenanthera colubrina* should be planted for their nitrogen contribution with the additional advantage of having large crowns with foliage that provides shade. *Cedrela fissilis,* with its good growth (although frequently attacked by shoot borers), is also valued for its timber and should be incorporated at low densities. Also contributing to restoration purposes are species such as *Solanum granulosum leprosum* (fumo bravo), *Baccharis* sp. (chirca), *Trema micrantha* (palo pólvora), *Cecropia adenopus* (ambay) and *Syagrus romanzofiana* (pindó). Although these species have no timber value, they provide nutrients to the soil, flowers for bees, and fruit for birds throughout the year – all of which are valuable landscape attributes.

In all cases, the yerba mate plantations located near forest remnants showed less damage from drought, frost, and insects attack, and the leaves of yerba mate were greener and healthier. Conservation of large hollow trees in primary and secondary forests, and in agricultural landscapes, contributes to biodiversity.

There is a marked trend for certified organic production in the Province of Misiones. The possibility of cultivation of yerba mate in AFS is an advantage in this sense; therefore, knowledge on the matter is necessary in order to obtain better prices for the yerba mate and generate income with the associated trees at the same time. Agroforestry systems of organic yerba mate with native species not only provide higher income, but contribute important social functions due to their diversified production as well. Their increased landscape diversity favors the local fauna. In addition, the yerba mate plants and the associated trees fix carbon dioxide from the atmosphere.

The economic valuation of native species at 10 years, using different interest rates (2%, 4%, and 6%) represents income values of US$5.11/tree (2%), US$5.14/tree (4%), and US$5.31/tree (6%). Considering an average of 100 trees per ha, these values indicate that the activity is financially promising for the region. The biomass of trees can have different purposes, from timber to woody biomass for energy. The economic values may be more attractive depending on the species.

Given the need for a productive restructuring due to the low productivity of yerbales, it is appropriate to assess the benefits associated with the adoption of good agricultural practices and organic certification of yerba mate plantations. These are alternatives to accessing more demanding markets and achieving higher prices for products.

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# Chapter 12
# Adapting Indigenous Agroforestry Systems for Integrative Landscape Management and Sustainable Supply Chain Development in Napo, Ecuador

**Christopher Jarrett, Ian Cummins, and Eliot Logan-Hines**

## 1 Introduction

The Amazon is typically thought of as a region with little human inhabitation and only minimal traces of human activities. Much of the public and some scholars imagine the region before European colonization, for instance, to have been mostly pristine rainforests and small mobile tribes of hunter-gatherers. Since the 1990s, however, scholars across multiple disciplines have begun to challenge this so-called 'Myth of the Pristine Environment' (Denevan 1973; Erickson 2008; Clement and Junquiera 2010). Instead, a more complex portrait has emerged of the Amazon as home to a diversity of landscapes, many of which have been heavily managed and in some cases even wholly created by humans. The idea of small-scale bands of hunter-gatherers as the only kind of social organization present in the region has also come under greater scrutiny, as evidence has emerged in some parts of Amazonia of large sedentary civilizations complete with cities, elaborate food storage, water management, and other complex technology (Erickson 2008; Heckenberger et al. 2008; Clement et al. 2015).

C. Jarrett (✉)
Department of Anthropology, One UTSA Circle, The University of Texas at San Antonio, San Antonio, TX, USA
e-mail: christopher.jarrett@utsa.edu

I. Cummins
Runa Foundation, Archidona, Napo, Ecuador
e-mail: ian@runafoundation.org

E. Logan-Hines
Runa Foundation, Quito, Ecuador
e-mail: eliot@runa.org



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Recent rethinking of Amazonian social and natural histories has drawn attention to sustainable land use strategies that might provide alternatives to either strict preservation or intensive development in the region. In this chapter we discuss a common, longstanding land use strategy among indigenous Amazonian peoples—agroforestry—in the Upper Napo region of the Ecuadorian Amazon, and explore how indigenous agroforestry practices can contribute to the integrative management of Amazonian landscapes and be adapted for the development of sustainable supply chains. We begin by briefly summarizing recent scholarship on Amazonian environmental history, both in terms of debates over pre-colonial Amazonia and with regards to more recent dynamics, thus situating agroforestry in a broader conversation about the role of human activities in the region and efforts to harmonize such activities with biodiversity conservation. Then, we describe the agroforestry system managed by indigenous peoples in the Upper Napo region, referred to in the Amazonian Kichwa language as the 'chakra', and analyze efforts to develop supply chains for agroforestry and other forest products and to combine agroforestry with other landscape management practices. We discuss how commercialization of Amazonian species can increase smallholder incomes while also promoting structurally and biologically diverse agricultural systems. We also analyze some of the challenges, both technical and political, associated with adapting indigenous production strategies for commercial purposes. Then, we discuss agroforestry as a specific component of a concerted landscape management strategy within the context of indigenous land tenure. Finally, we conclude with reflections on how to align community needs, markets, and landscape management to improve local livelihoods and biodiversity conservation.

## 2 Amazonian Landscapes from the Pre-colonial Period to Today: Implications of Environmental History for the Role of Contemporary Agroforestry

Amazonian environmental history has been the epicenter of intense debate in recent years over the role of humans in global environmental processes. Scholarly debate has focused on the nature, scope, and intensity of pre-Columbian anthropogenic land use, and the extent to which Amazonian landscapes can be considered 'pristine' wilderness. While estimates of pre-Columbian Amazonian populations vary significantly, there were likely at least six million people living in the region when Europeans arrived (Denevan 2014). Recent archaeological research has shown that pre-Columbian Amazonian civilizations engaged in a range of activities that historical ecologist Clark Erickson (2006) refers to as 'domestication of landscape,' including controlled burning, mound building, ring ditch and raised field construction, soil enrichment through the creation of 'Amazonian Dark Earth,' fisheries management, and agroforestry, among other practices (see also Erickson 2008). Yet, scholars critical of research depicting a radically different Amazonia than conventionally conceived question the scope of landscape domestication and point out that many of the most dramatic examples of such transformations have been primarily documented in the central and southern portions of Amazonia (McMichael et al. 2012) and in particular areas within these regions, such as close to rivers and in areas with dry seasons (Bush et al. 2015).

Nevertheless, the scholarly debate over Amazonian environmental history has very real implications for how we think about contemporary development and conservation challenges and the role of indigenous peoples and their practices in addressing these challenges. Recognizing that indigenous Amazonians have a long history of managing landscapes throughout the region requires us to consider 'cultural and historical continuity with many indigenous peoples today' (Clement et al. 2015), and thus to examine how longstanding indigenous practices might provide examples of more environmentally and socio-economically sustainable land-use strategies for the region. This is particularly significant given the reality of widespread environmental degradation and socio-cultural conflicts brought about by dominant approaches to land use throughout the region, such as air and water pollution and dispossession of indigenous peoples due to mining and oil development (Hurtig and San Sebastián 2004; Sawyer 2004), deforestation for African oil palm, soy, and other monoculture plantations as well as cattle ranching (Henrich 1997; Freire 2007; Erazo 2013), and habitat destruction from dam construction (Athayde 2014). Attention to indigenous practices that might prove more sustainable than more intensive land uses also opens up space for a greater role for indigenous peoples in biodiversity conservation, in contrast to 'fortress conservation' strategies that would seek to exclude humans from protected areas (Brockington 2002; Brockington and Igoe 2006; West et al. 2006).

Agroforestry is one longstanding and geographically widespread indigenous Amazonian strategy of landscape domestication that has proven particularly resilient and arguably has significant potential as a land use strategy well suited to contemporary realities (Peters 2000; Miller and Nair 2006; Erickson 2008). Yet, it had largely been overlooked as a viable land use strategy until recent decades, and even as policymakers are beginning to give greater consideration to agroforestry, there remains a lack of policies to support it (Denevan 1973; Pichón 1997). There are various reasons why agroforestry has re-emerged as a promising alternative in Amazonia, and in the Ecuadorian Amazon in particular. Recent emphasis in ecology on the biodiversity-enhancing possibilities of small-scale disturbances and heterogeneous landscape mosaics has led to increased interest in interventions such as buffer zones, and agroforestry has come to be seen as one of the more effective strategies for such interventions (Bhagwat et al. 2008; Erickson 2008; Chazdon et al. 2009). Similarly, interest in mitigating climate change has led to greater emphasis in increasing tree cover in agricultural production areas (Lelle and Gold 1994; Torres et al. 2015). Likewise, as conservationists seek to develop approaches to land uses that support indigenous peoples' livelihoods, they have found that agroforestry and the non-timber forest product (NTFP) trade, when structured in a way that is sensitive to indigenous priorities and concerns, are often particularly appealing to indigenous peoples (Zanotti 2009).

In the Ecuadorian Amazon in particular, policymakers have begun to pay more attention to agroforestry for a variety of reasons. First, Ecuador's most recent national constitution declares as 'matters of public interest' 'environmental conservation, the protection of ecosystems, biodiversity and the integrity of the country's genetic assets, the prevention of environmental damage, and the recovery of degraded natural spaces' (Ecuador 2008: Title 2, Chapter 2, Section 2). It also focuses on 'buen vivir,' or 'living well,' a vision of wellbeing that takes into account economic, political, cultural, socio-personal, and environmental factors, and seeks to build 'popular and solidarity economies' by supporting economic activities at multiple scales, including smallholder agriculture (Ecuador 2008: Title 2, Section 2; Title 6, Chapter 4, Section 1). Second, following waves of colonization, which largely followed oil roads and were driven heavily by agrarian reform legislation in 1964 and 1973, many indigenous Amazonians have seen diminished control over their once large territories and have come to adopt more sedentary residence patterns in order to access expanded educational and health services (Erazo 2013). Furthermore, there is little evidence that indigenous peoples in the region, even those who live in more remote areas and rely more on subsistence agriculture, are likely to return to shifting agriculture throughout a large territory (Sirén 2007). In this context, agroforestry represents a relatively low-input agricultural production model for communities that no longer rely primarily on shifting cultivation. Third, the expansion of road networks and government programs to incorporate indigenous peoples into national society has linked indigenous communities increasingly to the cash economy. Scholars and planners recognize that most indigenous Amazonians today seek to participate in the cash economy (Henrich 1997), even if to varying degrees and for different reasons. For instance, while desire for improvements in material conditions and access to consumer goods might motivate indigenous peoples to participate in market activity (Godoy et al. 2005), the most desirable commercialization projects allow people to maintain their subsistence practices and provide ample opportunities for community participation (Zanotti 2009). In sum, government interest in promoting biodiversity conservation, holistic wellbeing, and diverse economies, combined with reductions in territories and greater market integration among indigenous Amazonians have all contributed to renewed attention to agroforestry.

## 3 Agroforestry and Landscape Management Among the Amazonian Kichwa People of the Upper Napo

The Amazonian Kichwa are a distinct group of indigenous people living from the Andean foothills to the Amazonian lowlands, primarily in the Ecuadorian provinces of Napo, Orellana, Sucumbíos, and Pastaza. They are commonly divided into the Napo Kichwa, or "Runa" (people), and the Pastaza Kichwa/Runa, and they number roughly 55,000 (FUNPROEIB-Andes 2009). Most Kichwa households engage in a

**Table 12.1** Common land use types among the Amazonian Kichwa

| Land use | Management type | Uses | Unit size |
|---|---|---|---|
| Communal reserves | Communal | NTFP collection, hunting, ecosystem services, payment from Socio Bosque Program | 500–10,000 ha |
| Production forest | Household | NTFPs, SFM, hunting | 10–50 ha |
| Agroforestry systems | Household | Subsistence agriculture, timber plantations, cash crops | 0.5–2.5 ha |
| Fallows, early seral stage vegetation | Household | Production of fast growing timber (*Piptocoma discolor)*, hunting | 0.5–2.5 ha |
| Protected areas | Government | Use and entry is restricted by the Ministry of Environment | >15,000 ha |
| Silvopastoral systems | Household | Cattle grazing | 5–20 ha |

variety of livelihood activities, including cash and staple crop production, animal raising, fish farming, timber harvesting, cattle ranching, hunting and fishing, small businesses, and wage labor, among others. Some of these activities are more market-oriented, while others are more oriented toward household consumption. A diversified livelihood strategy is particularly important within the economic context of the Ecuadorian Amazon, where permanent jobs are scarce and frequently tied to boom-bust commodity cycles and political election cycles. Furthermore, combining a range of market-oriented livelihood strategies helps to offset the risks associated with often-volatile commodity prices, while maintaining activities oriented toward household consumption similarly reduces reliance on market participation for meeting basic needs.

The diversity of Kichwa livelihoods portfolios is mirrored by a variety of land uses. The Amazonian Kichwa manage extensive landholdings, which are primarily held under three distinct land tenure arrangements, including (1) private land titles, (2) community titles, or (3) global land titles encompassing a large area and number of communities (Bremner and Lu 2006).[1] In Napo, Kichwa communities are typically centered around a soccer field and school, and most households are located near the community center, which is ringed by a mosaic landscape composed of agroforestry, silvo-pastoral systems, fallows, forest reserves, and production forest (See Table 12.1 and Fig. 12.1). It is worth noting that even under communal land tenure arrangements, these areas are invariably managed within the community as essentially private property with well-understood boundaries and use rights.

All of these land-use types provide benefits to farmers and represent a spectrum of land-use intensities, labor allocation, and time horizons. The mosaic landscape,

[1] Global land titles are the dominant form of land tenure for non-Kichwa indigenous groups who tend to manage land under a single ethnicity based title. In Napo, the only significant area managed under a global land title is the Pueblo Kichwa de Rukullakta, which encompasses over 43,000 ha and 17 different communities.


**Fig. 12.1** Aerial image of ringed land uses around Kichwa community of Mushullakta, Napo Province, Ecuador (Photo: OpenForests (OpenForests (openforests.com) is a consulting company and expert network that support the implementation of social, ecologically diverse and profitable forestry projects))

**Fig. 12.2** Chakra agroforestry system practiced by the Amazonian Kichwa in Ecuador (Photo: I. Cummins)

for example, provides hunting grounds for a variety of small game species including paca (*Cuniculus paca*), agouti (*Dasyprocta fuliginosa*), armadillo (*Dasypus novemcintus*), opossum (*Didelphus marsupiales*) and occasionally collared peccary (*Pecari tajacu*) (Cummins et al. 2015). In less densely populated communities, forestland can make up the majority of this landscape. Forests existing within land allocated to individual families are managed at the household level. Under this type of arrangement, families with use rights are allowed to manage game, timber, NTFPs, and other resources without formal supervision by community authorities. Thus, forestlands are an important source of occasional income, especially from the sale of sawn timber. Some households also maintain significant landholdings as pastoral and silvo-pastoral systems.

The agroforestry system practiced by the Amazonian Kichwa is known locally as the 'chakra' (See Fig. 12.2). It has a long history of use and, like in other parts of Amazonia, has proven remarkably resilient despite efforts in different eras to push indigenous people to adopt radically different production systems, such as cattle ranching or monoculture (Perreault 2005). Individual chakras typically range from about 0.25 to 1.5 ha in size (Perreault 2005), and households frequently maintain multiple chakras located throughout the region (Erazo 2013). Lack of labor and mechanization tend to be the primary limitations to further expansion of cultivation areas, although some, especially younger households also have relatively small landholdings that limit their production. Kichwa people often employ a gender-based division of labor, with men typically responsible for felling trees and clearing

**Table 12.2** Multi-strata agroforestry systems

| Functional group | Strata | Common species | Average height |
|---|---|---|---|
| Palms | Canopy/canopy emergent | *Mauritia flexuosa, Bactris gasipaes, Iriartea deltoidea, Oenocarpus bataua,* | 15–35 m |
| Hardwood timber | Canopy/canopy emergent | *Cedrela odorata, Myroxylon balsamum, Cedrelinga catenaeformis, Cordia alliodora, Cabralea canjerana, Swietenia macrophylla* | 20–35 m |
| Fruit trees | Sub-canopy | *Inga spp., Theobroma bicolor, Grias neuberthii, Cecropia peltata, Pouteria caimito, Mouriri spp.* | 8–15 m |
| Shade tolerant tree crops | Middle layer | *Theobroma cacao, Ilex guayusa, Coffea canephora, Ocotea quixos, Musa spp.* | 1–3 m |
| Annual and semiannual crops | Ground[a] | *Arachis hypogeae, Manihot esculenta, Solanum quitoense, Zea mays* | 0–1.5 m |
| Herbaceous vegetation | Understory | *Ruellia tuberosa, Mentha spicata, Verbena littoralis, Ocimum micrantum, Uncaria tomentosa* | <50 cm |

[a]These species tend to be light demanding and often are grown in small patches in partial or full sun. They are frequently found within mosaic formations adjacent to multi-strata chakras

plots, and women responsible for activities such as manioc (*Manihot esculenta*) cultivation (Uzendoski 2004). However, most family members assist with chakra work, and families often take advantage of school vacations to do the most labor-intensive chakra work.

Chakras vary greatly in composition. Some are relatively simple agroforestry systems mostly dedicated to the production of one or two main crops. Others are highly diverse and structurally complex systems that mimic natural forests ecosystems (See Table 12.2). The chakra system is designed primarily to meet subsistence needs and invariably features both manioc and plantains (*Musa spp.),* which provide the foundation for the Kichwa diet, as well as a diversity of starches, fruits, legumes, hardwood species, and medicinal plants. Nevertheless, Kichwa people have long incorporated different cash crops into their chakras, and outsiders have shown interest in making chakra species commercially valuable for centuries. In the sixteenth century, Dominican friar Gaspar de Carvajal wrote of the Amazon as a 'very fruitful land,' and Spanish colonists long sought to find a way to make local products profitable (Toribio Medina 2010). Similarly, in the nineteenth century, English explorer-botanist Richard Spruce remarked in an 1857 letter to the British Ecuador Land Company on the promise of commercializing coffee, cacao, pineapples, cinnamon, and hardwood trees (Schultes 1978).

In recent decades, cash crops such as coffee *(Coffea spp.)*, cacao (*Theobroma cacao*), naranjilla (*Solanum quitoense*),[2] and more recently guayusa (*Ilex guayusa*)

[2]Naranjilla is primarily consumed domestically and is processed into fruit pulp for juice and other products.

have been increasingly integrated into chakra systems. The adoption of cash crop production has been most common among communities where road networks provide relatively easy and consistent market access. Increasing urbanization and associated involvement in permanent, rather than shifting, cultivation have also contributed to the incorporation of cash crops in chakra systems (Porro et al. 2012). Both coffee and more recently cacao have been seen as a way to sustainably raise rural incomes, yet the results of their integration into chakra systems have been mixed. Robusta coffee (*Coffea canephora*) was widely planted in Napo Province during the 1980s by Kichwa and *mestizo* farmers alike, due to high commodity prices. However, the crash in global coffee prices in 1992 devastated local farmers and led to its abandonment as a primary cash crop. Cacao production rapidly took its place and has been widely planted within Kichwa agroforestry systems. Much like coffee, however, cacao is a globally traded commodity and is subject to similar levels of price volatility. Furthermore, yields from cacao within agroforestry systems have been limited by a lack of agricultural inputs and poor management practices (Zebisch 2016). Climatic conditions in the Ecuadorian Amazon are highly conducive to the spread of fungal blights. Witches broom (*Moniliophthora perniciosa)* and Monilia (*Moniliophthora roreri*) are widespread within cacao plantations, and in some areas they have significantly reduced production (U. Zebisch, personal communication, April 2016). The commercialization of guayusa and other agroforestry/chakra products, then, is not necessarily a new idea, but the process by which it has occurred in recent years is worth analyzing for what it tells us about the potential for adapting indigenous agroforestry to sustainable supply chain development.

## 4 Guayusa: A Case Study

Guayusa (*Ilex guayusa* Loes.) is a member of the Aquifoliaceae family native to the Ecuadorian Amazon, with known records of its existence from southern Colombia to northern Bolivia (Dueñas et al. 2016; See Fig. 12.3). It is a relative of another important commercially valuable species, yerba mate (*Ilex paraguarensis*), which is also primarily consumed as an infusion of the leaves. Guayusa trees grow from 250 to 1500/2600 meters above sea level, and when not pruned can grow to a height of 25 meters with a diameter at breast height of 50–80 centimeters, although they have adventitious sprouts which make them particularly suitable for pruning (Garciá Barriga 1992). Although guayusa does have greenish red fruits, they are infrequently found, and propagation is primarily done asexually by using cuttings of mature trees that are at least 4 years old (Shemluck 1979; Garciá Barriga 1992).

Guayusa has long been a key species in the Napo Kichwa's homegardens and chakras, and in one study of ethnobotanical garden design in a Kichwa community, guayusa was the 'most used and harvested plant' (Innerhofer and Bernhardt 2011:434). The Napo Kichwa, as well as some other indigenous groups, boil guayusa leaves in water, sometimes mixing with other medicinal plants, and use the brew

**Fig. 12.3** Guayusa (*Ilex guayusa)* tree (Photo: E. Logan-Hines)

primarily as a stimulant, but also for a range of other purposes, including as a fertility aid and an anti-hemorraghic agent during childbirth, and to prevent snake and insect bites (Dueñas et al. 2016). Guayusa also plays an important role in Kichwa culture, as the early-morning hours when it is consumed are traditionally when people will make tools and implements for hunting, fishing, and gardening; tell stories; interpret dreams; give advice to young people; and engage in a variety of other cultural practices (Jarrett et al. 2013; Dueñas et al. 2016). It is also a key symbol of indigenous identity often used in beauty pageants and other public performances of Kichwa culture (Perreault 2005; Wroblewski 2014).

There have been previous attempts to commercialize guayusa in the past, most notably by the Jesuits, who grew it near their missions for local consumption and possibly within commercial plantations in Colombia (Schultes 1979) and sold it as a cure for venereal disease in Quito, before their expulsion from Ecuador in 1766 (Patiño 1968; Schultes 1972). In the nineteenth century, Richard Spruce also suggested that guayusa from Ecuador 'might successfully compete in the English market against the inferior sorts of Tea,' noting, 'it has much of the aromatic flavor without the bitterness of Chinese tea,' although it appears his proposition was never taken up (Schultes 1978:137–8).

More recently, guayusa has been made available for sale in Ecuador in local and regional markets. In Napo and elsewhere in the Ecuadorian Amazon region, it is frequently sold in restaurants as a cold beverage. In the highlands it is consumed hot and is usually prepared with alcoholic spirits. In 2009 guayusa began to be commercialized on a large scale, when an organization called RUNA started exporting it to the United States and selling it as a boxed tea infusion. RUNA was founded by three college graduates from the United States who received initial funding from a series of business plan competitions in the U.S. and Ecuador. RUNA was constructed as a social enterprise with a hybrid for-profit/non-profit structure. This structure has allowed RUNA to leverage funding from different sources to invest in the creation of a value chain based on agroforestry production.

The for-profit side of the enterprise is composed of a U.S.-based company (Runa LLC), which has a partial ownership stake in its Ecuadorian counterpart Runatarpuna Exportadora S.A. Runa LLC imports processed guayusa leaves from Runatarpuna. Depending on the final product, the leaves are then packaged, or bottled by a contracted third-party. Runa LLC operates in a highly competitive U.S. beverage industry and has invested significant resources in branding, marketing, and strategic product distribution. These investments have been key to driving demand for guayusa in the United States. Runatarpuna Exportadora S.A. owns and manages a guayusa processing facility in Napo, Ecuador, which is capable of processing one million pounds of fresh guayusa leaf annually. They manage buying operations over a complex, geographically dispersed supply chain through a network of field technicians. Runatarpuna works directly with their non-profit counterpart, Fundación Runa, to maintain both Fair Trade and Organic certification as well as to conduct research and development for a variety of new products. Fundación Runa has been instrumental in developing and financing the smallholder-based production model by accessing funding sources not typically available to for-profit institutions.

RUNA has built a market for guayusa in the U.S. as a boxed tea, bottled iced tea, and energy drink; more recently the boxed tea and bottled iced tea products have also been marketed in Ecuador. In recent years, a number of other guayusa companies have also emerged, such as Waykana, which primarily sells within Ecuador but also exports some to the United States. RUNA and others are also currently in the process of trying to gain access to European and Asian markets. As of now, RUNA remains the largest guayusa enterprise, and the rest of our discussion will focus primarily on their experience.

## *4.1 Potential of Guayusa Commercialization to Integrate Agroforestry with Sustainable Supply Chains*

The creation of the guayusa value chain is an example of how the cultivation of an Amazonian agroforestry product can be expanded from household consumption scale production to export commodity scale, without significantly changing the agricultural systems and social structures in which it is produced. In order to support the production of guayusa within high biodiversity chakra systems, RUNA has adopted a smallholder based production model, which sources fresh guayusa leaf from over 2500 indigenous farmers in Napo, Orellana, and Pastaza Provinces (Fig. 12.4).

The adoption of a smallholder-based production model has been crucial in allowing for commercial guayusa production to be integrated into the chakra agroforestry model rather than replacing it with plantation agriculture. Smallholders typically

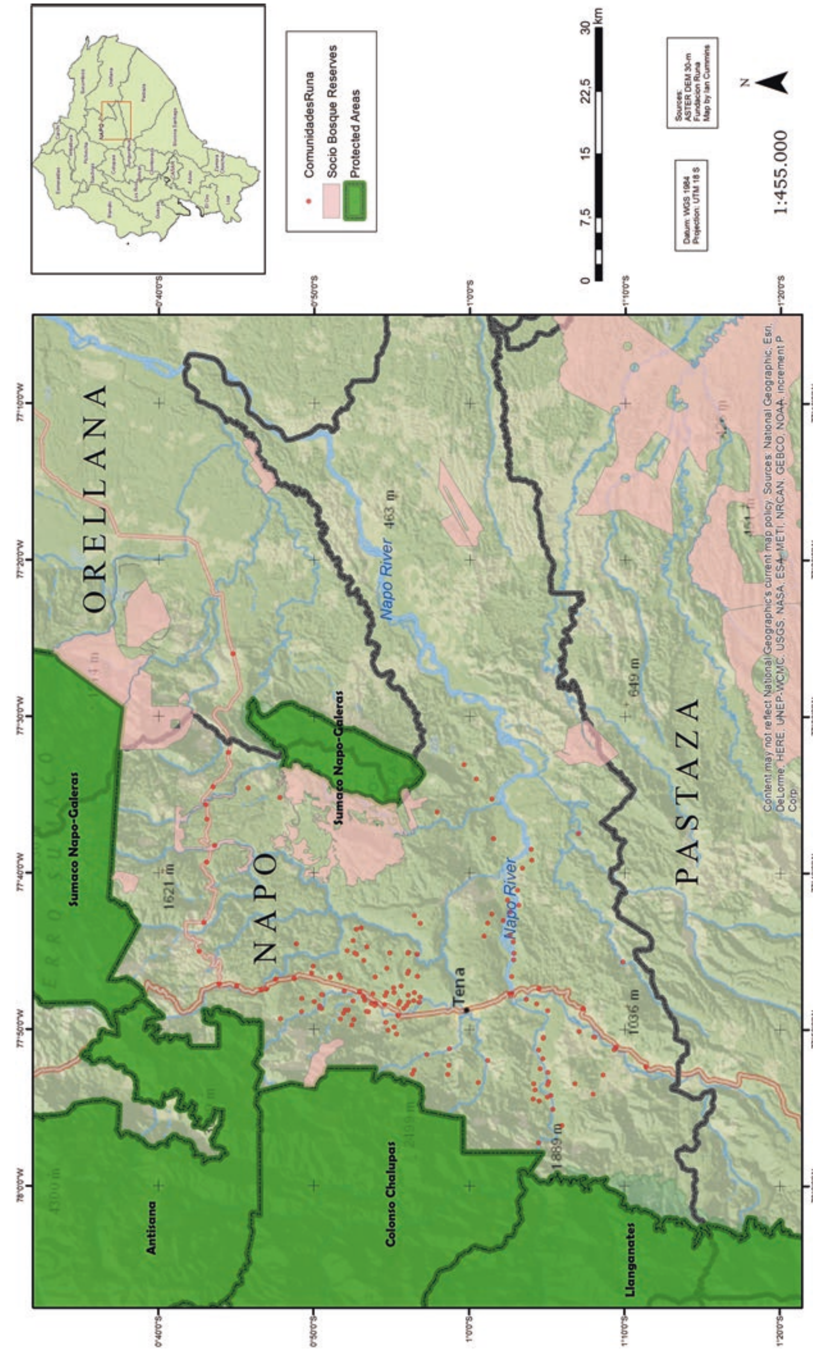


**Fig. 12.4** Map of guayusa producing communities in Napo Province, Ecuador (Map: I. Cummins)

interplant relatively modest quantities of guayusa (50–1000 plants, generally in areas of 2 ha or less) with other species frequently found in agroforestry systems. Because the guayusa model is based on purchasing directly from smallholders, it does not require the mobilization of large-scale agricultural wage labor. Guayusa farmers are thus able to maintain control over the allocation of their own labor and use of inputs.

Guayusa commercialization has generated important, albeit modest, contributions to Kichwa livelihoods. While it is difficult to calculate the exact contribution of guayusa production and other agroforestry activities to livelihoods due to seasonal fluctuations in income (Freire 2007) and heterogeneous livelihoods strategies, one study by Runa Foundation[3] suggests sales of guayusa leaves have increased annual producer incomes by between 5% and 10% (Collen et al. 2013). Moreover, since RUNA operates according to Fair Trade certification standards, which require the guarantee of a minimum price, the guayusa market has been established with greater price stability than other commodities typically grown by Amazonian smallholders, even if producers often hope that the price (RUNA purchases fresh leaves for $0.35/lb) will increase (Huchet-Bourdon 2011). Another benefit to producers stemming from RUNA's Fair Trade certification is that guayusa producer associations have been able to access community development funds through a 'Social Premium Fund' (SPF), which comes from an additional payment of 15% of the purchased value of unprocessed guayusa leaves.

Furthermore, guayusa commercialization has provided an economic incentive for producers to expand agroforestry activities, sometimes leading them to opt against more environmentally damaging land uses such as cattle ranching or monoculture cultivation of naranjilla, the former of which often requires deforestation and the latter of which conventionally requires application of pesticides. RUNA's work with organic certification has contributed to many producers' shifts away from naranjilla, since in order to comply with organic standards they are not allowed to grow guayusa near naranjilla and must wait a minimum of 3 years after having planted naranjilla before planting guayusa on a particular plot of land. The restriction on naranjilla production is due to the fact that in the region it is nearly always cultivated in monocultures, which require fumigation, so a fortunate bi-product of organic certification for guayusa is that it has promoted polycultures more generally. Indeed, all guayusa producers involved in commercial sales continue to grow guayusa in polycultures in their chakras, and there is no substantial evidence of widespread shifts to monoculture production. Producers typically grow guayusa in association with a variety of fruit trees, hardwood species, medicinal plants, and other species used for subsistence. They also sometimes grow cacao and coffee for sale in rows between guayusa trees.

In order to explore what might occur if guayusa production were to shift to monoculture, from 2013 to 2015, RUNA carried out a participatory research project with Kichwa producers to compare guayusa planted in a polyculture chakra, with a

[3] Runa Foundation (Runafoundation.org) is a public, non-profit organization whose mission is to "create new value for tropical forests that benefit the people and the local ecosystem".

density of 4 × 4 meters (625 plants/ha) with three small plantations of a guayusa monocrop planted at 0.5 × 1 meter (20,000/ha) in rows at 1 ha each. The major finding was that after 2.5 years, the monocrop plantation was nearly destroyed by a fungus that contaminated all of the 3 ha of the experiment. In the polyculture chakra, even those plants as close as five meters to the monocrop plots were not affected. This is consistent with findings in theories of density-dependence and the ecological role of biodiversity in agro-ecosystems and reinforces the theory that agroforestry leads to greater ecosystem resilience by ensuring adequate nutrients and creating natural barriers to the spread of pests (Altieri 1999; Ouyang et al. 2014). Therefore, the case of guayusa commercialization has shown that it is possible to integrate indigenous agroforestry with supply chain development while maintaining, and even strengthening biodiversity conservation.

## 5 Extending the Guayusa Model to Other Agroforestry and Forest Products

If chakra agroforestry systems are to play a more significant role in income generation for indigenous smallholders, it will be necessary to find markets for a wider variety of chakra species. For a number of reasons, guayusa sales have primarily served as a supplementary, rather than primary, source of income for the large majority of producers. First, most producers grow relatively small quantities of guayusa. Second, there is only one large-scale purchaser (RUNA). Third, consumer demand (which has been primarily concentrated in the U.S. market) has not grown as quickly as supply. RUNA has identified a number of new products that may have commercial value, including heirloom Amazonian peanuts (*Arachis hypogaea*), Amazonian cinnamon (*Ocotea quixos)* and a variety of palm species, such as ungurahua (*Oenocarpus batua*), morete (*Mauritia flexuosa*), and peach palm (*Bactris gasipaes*) (See Table 12.3). While many of these species are currently sold locally, they have not been integrated into value-added products and produce only occasional and/or seasonal incomes. In this respect, Ecuador is considerably less developed than other Amazonian countries such as Peru and Brazil insofar as these governments have done substantially more to create value added products from Amazonian species (Broekhoven 1996; Manzi and Coomes 2009; Steward 2013).

There are a number of challenges to creating international and regional value chains based around smallholder production of agroforestry and other forest products. Most smallholders lack the infrastructure necessary to gather, store, process, and transport these goods to markets. Smallholders are, by nature, dispersed over a landscape and so the aggregation of perishable agricultural products can prove particularly costly. Many species are either not grown on the scale necessary to consistently fill purchase orders or are available over large areas. The problem of consistent supply is exacerbated by the fact that producers are highly responsive to changes in

**Table 12.3** Agroforestry species with commercial potential

| Species name | Trade name | Uses | Barriers to market |
|---|---|---|---|
| *Mauritia flexuosa* | Morete, Buriti | Fruit, timber, palm grubs | Difficult to harvest, highly perishable, underdeveloped national market |
| *Bactris gasipaes* | Peach Palm, Chonta | Fruit, timber, palm grubs | Slow maturity phase, perishability of fruit |
| *Ilex guayusa* | Guayusa | Leaves boiled and used as stimulant | High levels of competition from tea, yerba maté |
| *Ocotea quixos* | Ishpingo, Amazonian Cinnamon | Leaves, fruit capsules and bark used as flavoring | Low quantities available, competition from Asian cinnamon varieties |
| *Oenocarpus batua* | Ungurahua | Oil extracted from fruit | Low yields and high costs |
| *Theobroma bicolor* | Cacao Blanco | Seeds can be processed similarly to cacao or fried and eaten | Low densities, lack of product knowledge outside of Amazon |
| *Croton lechleri* | Dragon's blood | Latex used medicinally for healing wounds | Extract already used in HIV drugs and patented, may be used to treat wounds |
| *Cedrelinga cateniformis* | Chuncho | Fast growing timber species, highly sought after in local markets | None |
| *Cedrela odorata* | Spanish cedar | Fast growing timber species commonly found in agroforestry areas | Cannot be legally harvested. |
| *Bixa orellana* | Achiote, annato | Seeds used for colorant | Already widely commercialized |
| *Genipa americana* | Wituk | Fruit used for organic colorant | Low availability, very slow maturity of plantings |
| *Cordia alliodora* | Laurel | Fast growing timber species, highly sought after in local markets | None |

price and to other economic opportunities and so may quickly abandon production, or sell products to third parties if other options present themselves. There are also significant obstacles related to the investment of foreign capital in product development. Firstly, most production takes place on communally titled indigenous land, and many companies are reluctant to invest in land under this type of land tenure due to the perceived difficulty of working with indigenous governing organizations. Secondly, the relatively long time horizon between planting and harvesting of most NTFPs presents additional challenges, since poor households often struggle to invest in productive activities with longer time horizons. Fruit-bearing palms such as shigua (*Oenocarpus batua*) and morete (*Mauritia flexuosa*), for example, take about a decade to mature. Wituk (*Genipa americana)* has potential for use as a natural colorant, but it requires 15 years to fruit. Amazonian cinnamon, or ishpingo

(*Ocotea quixos*), produces fruit a decade after planting. Most timber species do not reach commercial sizes until two decades after planting.[4]

Due to these reasons (decentralized production, lack of infrastructure, inconsistent supply, investor reluctance, and long time horizons), there is a definite need to subsidize the commercialization of agroforestry and non-timber forest products, especially for species that take a long time to generate income for producers. A key factor in RUNA's ability to build a supply chain and market for guayusa has been funding from a number of government agencies (e.g. the United States Agency for International Development-USAID and the Ecuadorian Ministry of Industries and Productivity), multilateral donors (e.g. the Latin American Development Bank-CAF and the Inter-American Institute for Cooperation in Agriculture-IICA), and private foundations (e.g. the Mac Arthur Foundation). This model may prove difficult to replicate for other Amazonian products, particularly without a hybrid structure like that of RUNA, which facilitates access to private investment as well as funding only available for non-profit organizations.

The creation of a supply chain for guayusa suggests other possible challenges in relation to the technical processes of production and quality control. When RUNA began, most people had only grown a few guayusa trees in their homegardens. RUNA thus experienced a variety of difficulties in its early stages with planted cuttings not maturing correctly or dying before reaching maturity, and they have constantly engaged in research efforts to determine the best place on the tree to extract the cutting, the ideal size of cuttings, the ideal amount of shade for different stages of maturity, and other technical factors that affect growth. Quality control and ensuring uniformity of leaves is also another challenge, as mosses and lichens can affect taste, and there is a need to prevent extraneous material (e.g. insects, household items), which might end up in harvest sacks, from entering the supply chain. RUNA has a team of quality control specialists who manage this work. The team also actively researches leaf humidity and drying speed and their potential effects on the taste of guayusa-based beverages. RUNA has synthesized this research into a best practices manual focused on the propagation, management and harvest of guayusa (Fundación Runa 2013).

A final difficulty related to expanding guayusa production has been compliance with government regulations that continue to treat guayusa as if it were a wild non-timber forest species. Since guayusa is classified as a 'wild' forest species, the Ministry of Environment (MAE) requires that each individual producer register and zone their entire land with the MAE in order to legally sell guayusa and other NTFPs. Producers must submit a land-use zoning map of their property, show proof of tenure, and register their landholdings through an online platform known as the Forest Administrative System (Sistema Administrativo Forestal, SAF). This, in turn, allows farmers to obtain a harvest permit (*guía de movilización* in Spanish), which

[4] One exception to this is pigüe (*Piptocoma discolor*): a fast growing primary succession species which is frequently found in dense stands on abandoned pasture and fallows (Erazo et al. 2014). This species reaches merchantable volumes in 3–5 years and is milled locally for the production of boxes and pallets, primarily for shipping naranjilla.

is valid for a 24-hour period. This process presents financial and technical challenges to many farmers, and the cost of obtaining a harvest permit may outweigh the value of the goods harvested. Until recently, the MAE had not been strictly enforcing this regulation, and so the question of how guayusa is categorized (as a wild versus a cultivated species, the latter of which would imply regulatory oversight by the Ministry of Agriculture, rather than the MAE) did not have any real material implications for the development of the supply chain. However, in December 2015, the MAE stopped and held a RUNA truck full of harvested guayusa leaves for 5 weeks, halting all guayusa purchases from local farmers and causing RUNA to lose a substantial amount of raw material, since the leaves were damaged from having been left in sacks for so long. If the current MAE regulation continues, and enforcement efforts become more common, this could potentially incentivize large-scale monocrop production of guayusa by pushing indigenous producers who maintain biodiverse agroforestry systems out of the supply chain, since the only feasible way to comply would be to apply for permits for a fewer number of larger tracts of land.

## 6 Leveraging Sustainable Supply Chain Management to Enact Integrated Landscape Management Within Buffer Zones

In the heterogeneous landscape mosaics surrounding Kichwa communities, commercial agroforestry and NTFP harvesting have the potential to work in productive synthesis with other land uses that contribute to integrative landscape management. Moreover, since much of Kichwa territory is near protected areas controlled by the Ecuadorian government, finding ways to provide livelihood opportunities while maintaining biodiversity can also contribute to the management of buffer zones. Buffer zones are generally conceptualized as multi-use areas adjacent to protected areas (PAs), which are primarily controlled by local communities or individuals[5] and where certain low-impact activities prohibited in PAs may occur (Aumeeruddy and Sansonnens 1994). While the Ecuadorian government has no formal legal definition of buffer zones, it has enacted a number of policies and programs, which taken together, can be used to create a site-specific strategy for broadly managing areas abutting PAs. Conservationists increasingly acknowledge the importance of buffer zones in maintaining biodiversity across landscape mosaics (Chazdon et al. 2009). In Napo, for instance, community-managed buffer zones provide habitat for a number of locally threatened large mammal species (See Figs. 12.5 and 12.6).

[5] The Ecuadorian government still maintains significant control over community resource management by regulating and/or controlling legal access to markets for a variety of natural resources. Sub-surface resources including petroleum and mineral resources are the sole property of the state. The government also requires harvest permits to commercialize all forest products and NTFPs regardless of origin. The selling of wild game is banned under almost all circumstances.


**Fig. 12.5** Jaguar (Community forest, Santa Rita, Napo Province) (Photo: Ian Cummins)


**Fig. 12.6** White-lipped peccary (Community forest, Santa Rita, Napo Province) (Photo: Ian Cummins)

There is also growing consensus among scholars and policy makers that successful buffer zone management must focus on allowing local communities to sustainably manage resources while simultaneously engaging in livelihood activities (Aumeeruddy and Sansonnens 1994; Heinen and Mehta 2000; West et al. 2006).

Promoting agroforestry and NTFP harvesting is one key component of integrative landscape management within buffer zones, especially in tropical landscapes such as Napo where PAs abut densely populated areas. Complex, biodiverse agroforestry systems have been shown to support high levels of bird and insect biodiversity as well as forage and habitat for small and medium-sized animals (Tscharntke et al. 2011; De Beenhouwer et al. 2013). Providing more livelihood opportunities from agroforestry production and promoting maximum biodiversity within agroforestry plots can also help to reduce resource extraction from natural forest systems, an added conservation benefit. Nevertheless, in order to strengthen integrative landscape management in buffer zones, it is important to find ways to combine agroforestry and NTFP harvesting with other land use strategies. Sustainable timber production and community forest reserves are two possible options for such a synthesis.

## *6.1 Sustainable Timber Production*

Timber sales are an important source of income for many rural Kichwa households and are often used to pay large expenses (Mejia and Pacheco 2013). Much of the timber harvesting in the Ecuadorian Amazon is done on land under communal title but managed as household units. Household management units are typically less than 50 ha in size and have been subjected to repeated harvest cycles, which frequently target specific high value species for local markets and then move to less valuable species as these become depleted.

One way to reduce harvest pressures on existing forests and thus contribute to integrative landscape management in buffer zones is to establish new timber plantations on fallows and pastures. Toward this end, RUNA is working with and helping to finance a few Amazonian Kichwa communities that are creating small (1–3 ha) plantations containing two fast-growing timber species (*Cedrelinga cateniformis* and *Cordia alliodora*) with strong local demand. To integrate these plantations with agroforestry systems, the timber species are being planted alongside short-rotation crops such as maize, manioc, and naranjilla, as well as shade-tolerant crops such as coffee and guayusa (See Figs. 12.7 and 12.8).

While the Ecuadorian Ministry of Agriculture (MAG) provides funding through its Forestry Incentives program for new forestry plantation establishment, since funds from the program are not disbursed until 1 year after planting, Kichwa communities have not been able to take advantage of this financing. In order to close this financing gap, RUNA is providing bridge funding to guayusa producer associations. This funding has been used to cover seedling acquisition costs, buy fertilizer, and cover some of the labor inputs for site preparation and plantation establishment.

**Fig. 12.7** Planting *Cedrelinga cateniformis* in an agroforestry system in Mushullakta, Napo Province, Ecuador (Photo: Ian Cummins)

**Fig. 12.8** An 8-year-old *Cedrelinga cateniformis* in an agroforestry system in Santa Rita, Napo Province, Ecuador (Photo: Runa Foundation)

This strategy reduces risk to farmers and covers the financing gap during the plantation establishment phase. Once the funds are disbursed by MAG, RUNA will channel them to producer associations to finance expanded reforestation and forest management activities.

Many producers have opted to interplant hardwood plantations with short-cycle crops such as maize, naranjilla, and manioc or have planted alongside shade tolerant groups such as coffee and guayusa. This planting method is analogous to the *taungya* agroforestry system practice, which was developed for forestry plantations in Southeast Asia. The *taungya* system allocates temporary usage rights to shifting agriculturalists to cultivate short-cycle crops during the early stages of plantation establishment (Weersum 1982). One crucial difference is that the communities with which RUNA is working will be able to plant crops within the plantations while also owning both the land and the resulting forestry plantations. Furthermore, production of the plantation relies on household rather than wage labor, as has been the case for taungya systems in Asia. In both scenarios, interspersing the plantation alongside fast yielding crops provides the additional benefit of short-term income for smallholders and promotes the active management of the forestry plantations through weeding, insect control and fertilization. Both species are fast growing with *Cedrelinga cateniformis* reaching harvestable diameters after 16–20 years with yields of up to 250 $m^3$/ha (Baluarte Vasquez and Alvarez Gonzalez 2015). RUNA is also working with communities to organize forest management cooperatives that will manage forest resources at a community scale, negotiate higher prices with timber buyers, and finance compliance with Ecuadorian forest laws, reforestation activities, and value added processing.

### *6.2 Community Forest Reserves*

Many Kichwa communities with large land holdings and/or inaccessible tracts of forestland also maintain communal forest reserves. These areas have traditionally been used for hunting, NTFP collection, and shifting agriculture. Since 2009, many communities have elected to place communal forest reserves into the Ecuadorian Ministry of Environment's Socio Bosque (Forest Partner) program. The Socio Bosque Program (SBP) aims to reduce deforestation and greenhouse gas emissions, while alleviating poverty by paying an annual monetary incentive for each hectare of native forest enrolled under the program. In the case of communally owned land, SBP pays the affiliated community biannually to forego activities such as agricultural expansion, timber extraction, and hunting over the course of a 20-year contract (Krause and Loft 2013). In many areas the SBP has played a key role in buffer zone management strategies by expanding the effective area of conservation around PAs and providing a significant source of income to buffer zone communities (See Fig. 12.9). These payments are based on the area put into the program, with total annual payments in Napo ranging from roughly $10,000–$65,000 per year (Ministerio del Ambiente del Ecuador 2011).

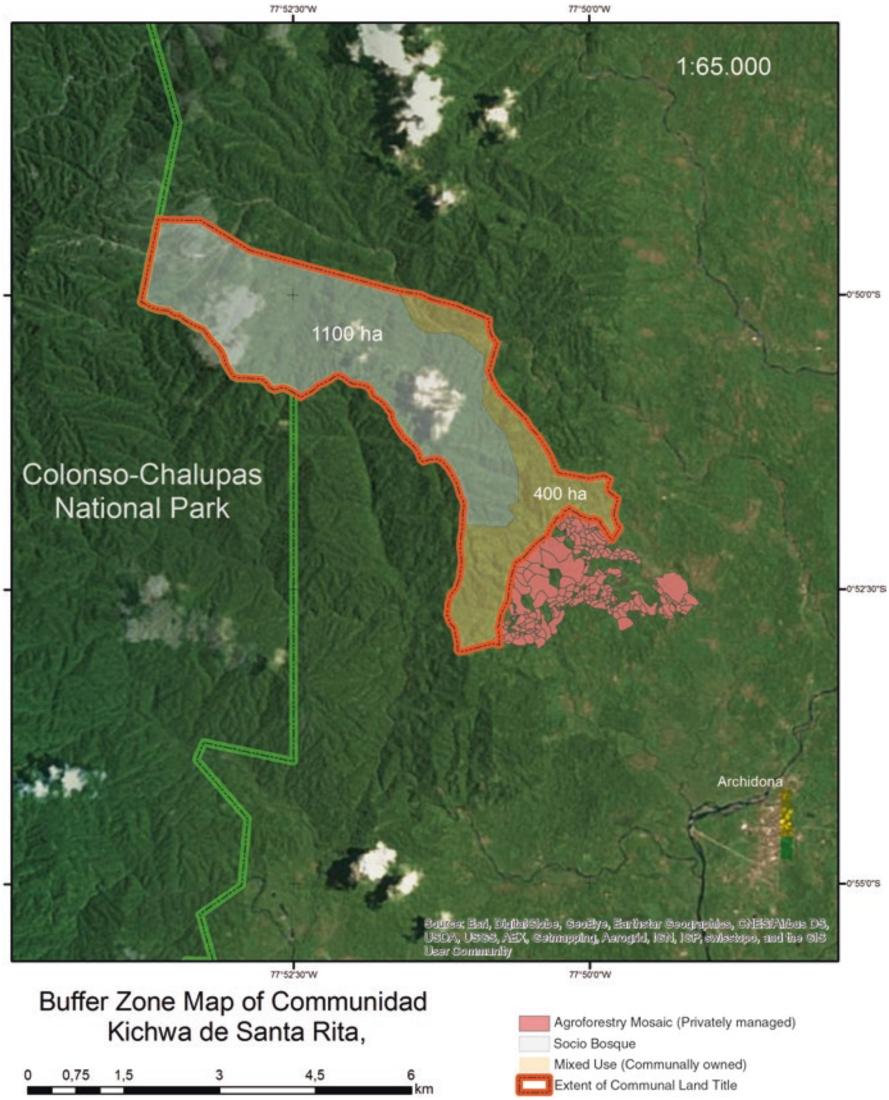


**Fig. 12.9** Example of integrated land use planning around Colonso-Chalupas National Park, including Socio Bosque reserve (Map: I. Cummins)

RUNA is working with community organizations that participate in SBP to leverage SBP funds with the Fair Trade Social Premium Fund to finance investment in agroforestry and conservation initiatives, thus integrating community forest reserves with other landscape management strategies. While there have been some successes in directing the flow of the Social Premium fund towards these types of initiatives, it has proven difficult to leverage SBP funds for these efforts. This is mainly due to the fact that the guayusa producer associations that manage the Social Premium Fund do not always encompass the same communities as the community organizations participating in SBP, and the leaders who manage these two funds are often different individuals. Furthermore, while the Social Premium Fund is meant to be used for the collective benefit of guayusa producers within each association, SBP funds are typically allocated by communities to leaders' salaries, administrative and travel costs, and management of the reserve (e.g. hiring community members to demarcate boundaries, conduct monthly patrols, and maintain community infrastructure). Ideally, with the continued support of the SBP, communities will have even more opportunities in the future to further integrate their community forest reserves with agroforestry and NTFP harvesting, as well as with other land use strategies that can work together to enhance buffer zone management.

## 7 Conclusions

Indigenous agroforestry, in combination with other land use strategies, has great potential in Amazonia to sustain livelihoods and contribute to broader biodiversity and landscape conservation. New markets for Amazonian plants can generate important revenue streams for local communities and create incentives for sustainable management. Historically, the creation of new markets comes with risks. Common agroforestry crops such as coffee and cacao have had volatile markets with large prices fluctuations. Markets for new plant products like guayusa, with Fair Trade-certified supply chains, benefit local communities by providing a stable price, but they still exist in a highly competitive market where consumer fads can quickly die. In order to mitigate these risks, the public and private sector need to work together to align incentives that support sustainable management and local people's needs.

Indigenous groups throughout the Ecuadorian Amazon have largely been effective in securing title to land and in maintaining traditional agricultural techniques. This in turn has been decisive in halting the advance of large estate crops at the expense of forest as observed on the Ecuadorian Coast. At the same time, it does not appear that income from agroforestry systems are or can be enough to meet household needs on their own, largely because there are currently only a few economically valuable chakra species. The inadequacy of income from agroforestry is especially apparent in most of Napo, where most households are fairly well integrated into market economies and do not possess sufficient landholdings to meet basic needs through subsistence activities alone. In this context, chakras can be seen as a supplementary source of both income and food security.

The case of guayusa commercialization and related efforts to adapt agroforestry for integrative landscape management and sustainable supply chains has a variety of policy implications. Firstly, it should be recognized that while chakra agroforestry systems have a variety of benefits, they may not be the most profitable agricultural system. Thus, there is a need to subsidize production in these systems, whether in the form of low interest loans, organic amendments, or preferential market access for goods produced in these systems. In some countries, such as Britain, governments subsidize the maintenance of culturally valuable landscapes. Ecuador might consider a similar strategy with the chakra system in its Amazonian region, a system that in addition to being central to indigenous peoples' livelihoods is also often preferred for its aesthetic value. Secondly, government and non-governmental support (financial, legal, and technical) for local actors to play a more significant role in value-adding processes such as drying and packaging, might also help to build local capacity and increase participation in sustainable supply chain management. Thirdly, sustainable production of commercial timber species and compensation for maintenance of communal forests provide two promising options for synthesizing agroforestry with other land use strategies, and further support for bringing together these various strategies will help to strengthen integrative landscape management, especially in protected area buffer zones.

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# Chapter 13
# Fuel Alternatives for Developing Countries

Kjell E. Berg

## 1 Introduction

Extreme pressure on forests from the use of wood and charcoal for space heating and cooking in developing countries has had a major impact on the viability and production capacity of landscapes for food, fuel and other uses. The extraction of wood for fuel can impact forest structure, function and biodiversity. For example, results of recent studies indicate that the forest may become degraded due to wood extraction, with negative consequences for the people who depend on the forest and for conservation (Sassen et al. 2015). In many areas fuelwood extraction results in a net loss of available wood and charcoal fuels. Extensive damage to groundcover results in soil erosion and loss of soil carbon, nutrients and minerals. Many other environmental services such as air and water filtration and conservation are also lost. Research into local ecological and cultural contexts and perceptions concerning costs and benefits can help devise more sustainable management options, including alternative sources of fuel (Sassen et al. 2015).

It is estimated that the number of people that rely on fuelwood resources total approximately 2.6 billion (FAO 2015). FAO data indicates that in 2011 wood removals worldwide totaled 3 billion cubic meters of which 49% was used for fuelwood (FAO 2015). The developing countries consumed and burned nearly half (1.47 billion cubic meters) of the wood removals (FAO 2015). The percentages of roundwood used as fuelwood in 2014 were approximately 50% globally: Africa 90%, Asia and the Pacific 65%, Latin America and the Caribbean 55%, Europe 20% and North America 8% (FAO 2016).

As of 2011, about 1.26 billion people do not have access to electricity and 2.64 billion people rely on traditional biomass (fuelwood, charcoal, dung and

K. E. Berg (✉)
Formcell AB/BiorenSystems, Hampden, MA, USA
e-mail: kjelleberg@biorensystems.com; kjelleberg@hotmail.com



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agricultural residues) for cooking, mainly in rural areas in developing countries (IEA 2013). Under a baseline scenario, IEA (2013) foresees that the number of people without clean cooking facilities could remain unchanged until 2030. Household cooking consumes more energy than any other end-use services in low-income developing countries (IEA 2006; Daioglou et al. 2012 in Malla and Timilsina 2014).

The widespread practice of cooking with solid fuels, such as traditional biomass and coal, can have severe implications for human health. Existing studies, such as those of Bruce et al. (2000) and WHO (2006), have reported that air pollutants, emitted from solid fuels often burned indoors on inefficient cook stoves, are one of the biggest challenges to human health in developing countries. Lim et al. (2012) in Malla and Timilsina (2014), for example, estimated that in 2010, about 3.5 million premature deaths were caused by household air pollution (HAP) resulting primarily from cooking with solid fuels. They also estimated that there were 500,000 deaths from outdoor air pollution caused by household solid fuels used for cooking in developing Asia and Sub-Saharan Africa (SSA) in the same year.

The heavy use of inefficient, primitive devices for heating and cooking creates major health problems from smoke inhalation, resulting in millions of people suffering from many respiratory ailments. It is reported that the numbers of people afflicted total in the millions (WHO 2000). According to the World Health Organization (WHO), smoke-induced diseases are responsible for the death of 4.3 million people every year, a greater number than caused by malaria or tuberculosis, making it one of the most lethal environmental health risks worldwide (Martin et al. 2011; WHO 2014; Langbein 2017). It is of great urgency that equipment be improved to reduce fuelwood use and to enhance local environmental conditions.

Current fuelwood consumption for cooking is about 1.35 billion cubic meters annually and is expected to remain about the same for at least the next 20 years (Cushion et al. 2010). About three-quarters of the 2.4 billion tons of annual global $CO_2$ emissions from fuelwood come from its use for cooking. Thus, encouraging households to use cookstoves that burn less wood is one way to reduce emissions. However, more efficient cookstoves must be affordable if users are to adopt them, and cookstove projects must be a cost-competitive source of emission reductions. With valid concerns for emissions, reduced wood burning would also provide numerous environmental benefits, such as decreased carbon dioxide emissions, and reduction of nutrient loss from soils. Although logistics is an important factor in making alternative fuels and equipment available, a desirable goal would be to encourage funding to improve conditions for implementation.

Among the 17 Sustainable Development Goals (SDGs) that were adopted in 2015 as part of a new sustainable development agenda to be achieved over the next 15 years, SDG number 7 refers to energy: Ensure access to affordable, reliable, sustainable, and modern energy for all (Montagnini and Metzel 2017, Chap. 2, this volume). This chapter presents the problems and possible alternatives to current methods for heating and cooking in developing countries. Fuelwood options using the most suitable tree species are reviewed from the vast research performed at many universities and institutions dedicated to forestry and agroforestry worldwide. Biofuel production is also discussed from recent research and implementation as it holds great promise to contribute to Sustainable Development Goal (SDG) number seven.

## 2 Environmental Impacts of Wood Removal for Energy Production

The loss of forest area has been very significant in most parts of the world but has been most severe in South America and Africa where average per capita forest area declined from 0.8 ha to 0.6 ha per person from 1990 to 2015. The net loss of forest was 129 million ha, about the size of South Africa, during the same period (FAO 2015). However it should be noted that at least for humid forests, deforestation is caused mainly by land clearing and although wood from deforested areas is used as energy source, this is not the main driver.

Forest degradation is of great concern as vital functions of the forests are lost. The filtration of air and water supports local ecological health. It has been shown that tropical forests, especially those growing in lowland locations with more than 2000 mm annual rainfall, tend to accumulate a much larger proportion of nutrients in biomass (living vegetation plus litter) than in the soil (Montagnini and Jordan 2005). This is especially the case for calcium and potassium which can wash away in drainage waters. Nutrient accumulation in biomass is thus considered to be an important nutrient conserving mechanism in forests growing on relatively nutrient poor soils. Therefore, removal of wood from the rainforest destroys an important mechanism for conserving the integrity of those landscapes, even if the slash remains on site. Logging seriously affects nutrient stocks and nutrient conserving mechanisms and can threaten the ability of a tropical site to regenerate the forest (Montagnini and Jordan 2005).

In the Caribbean, Haiti is an example where forest cutting for energy and agriculture has resulted in environmental degradation and poverty. A few centuries ago, almost all of the country was forested, but today less than 2% of the forest cover is left. As a consequence, from 1950 to 1990, the amount of arable land fell by more than 40% due to soil erosion and other factors, in a country where less than 30% of land is arable. Much of the remaining trees are being felled to produce charcoal or burned to clear new land to cultivate. Wood is the main source of energy and house building material. Today the burning of charcoal and wood accounts for 75% of Haiti's total energy consumption, requiring the cutting of around 30 million trees per year (Murray and Bannister 2004; Tarter et al. 2015).

So as not to reach such extreme conditions as in the case of Haiti, it is of vital importance not to clearcut forests in order to minimize erosion and loss of nutrient and mineral containing soils and subsoils where regrowth is impeded as a result. Tree removal for energy production also results in losses in the forest function to recycle nutrients. Disturbing the mineral, nutrient and carbon rich soils results in massive escape of those elements from the forest floor. Removal of forest litter will also interrupt the replenishment of vital nutrients and minerals, further degrading the soil.

Healthy regrowth conditions must be maintained in order to promote ecosystem sustainability. This may include the application of ashes from wood burning as well as waste products from sanitary facilities to degraded soils. Composting of organic materials should be done and maintained in order to minimize the risk for spreading disease and bacteria in the local ecosystem.

## 2.1 Other Implications of Increased Reliance on Forest Biomass for Energy Production

The following is an example of an egregious abuse of natural resources to satisfy the needs of the European Union (EU) regulations on meeting its Renewable Energy Goals. The adverse environmental effects on the forests of the Southeastern United States are obvious and demonstrates that the impacts of fuelwood consumption are not restricted to developing countries.

It is estimated that by 2025 a total of 10–12 million tons of wood pellets will be sent overseas annually (UK and other EU countries) to fuel biomass energy plants, replacing coal as an energy source, from South East US forests (Lowenthal-Savy 2015) (a second document estimates a tonnage of up to 70 million but this is probably excessive) (NRDC 2015). Eleven million tons of wood pellets production, if all of it came from clearcut forest, would result in approximately 36,000 hectares being clearcut per year, in an area of the USA which is home to numerous endangered species of plants and animals (NRDC 2015).

Some areas in the Southeastern US appear to be clear cut of all vegetation which may include stump harvesting. In riparian areas, the trees function to purify and filter water. The harvesting is done in many riparian areas where the trees buffer effect to keep nutrients from entering streams and water bodies is lost, and the important role of trees to stabilize water flows is removed. The movement of important nutrients and carbon from the Southeastern US to Europe may have long lasting negative effects on the Southeastern states and surrounding land and water resources.

The wet raw wood being priced at between $5.00 and $10.00 per ton will translate to an average of approximately $20.00 to $40.00 per metric ton of pure carbon (compare to anthracite coal at $60.00 to $90.00 per ton). The source of water for the Florida upper aquifers lies within mainly Georgia, South Carolina, Alabama, and of course Florida itself, therefore there is obvious concern for the impact of heavy logging and forest slaughter in these states. Florida as well as other coastal states with long shorelines on saline ocean water must intensely guard against the lowering of fresh groundwater levels to avoid salt water intrusion.

## 3 The Role of Agroforestry in Energy Production

The largest component of fuel used in rural areas comprises wood and locally produced charcoal (Onyekwelu 2011), although in many areas of the world, manure and crop residues are also important. As a system that integrates land uses (forest and open-field agriculture), agroforestry can – with the appropriate combinations of trees, crops, and livestock – offer a range of goods, benefits, and services simultaneously, providing nutritious food, renewable energy, and clean water, while conserving biodiversity (van Noordwijk et al. 2015).

Agroforestry systems (AFS), such as homegardens, provide households with food and fuelwood as well as with high value products that generate cash. The characteristics and properties of the most productive multiple purpose trees (MPTs) used in AFS will vary depending on the goods and services it produces. For example, MPTs used for timber/fuelwood purposes should have high wood density and high caloric value (Montagnini and Metzel 2017, Chap. 2, this volume).

When people need fuelwood for cooking in jurisdictions with lax harvest restrictions, trees and shrubs are cut early for that purpose, impeding the development of tree planting projects and programs. However, AFS can also provide a way of fulfilling energy needs through coppicing tree and shrub species, and through this harvest, reduce the deforestation pressure on local forests (Olsson 2010).

AFS can also provide important environmental services such as carbon sequestration and storage. The carbon sequestration potential of AFS and silvopastoral systems is high and needs to be protected. For example, multistrata AFS can capture up to 18 Mg $ha^{-1}$ $year^{-1}$ (Nair 2012 in Toensmeier 2017, Chap. 18, this volume). The carbon stored in soils worldwide is significant, estimated to be 1500 Gt (1Gt = $10^9$ tons) (IPCC 2014). Multistrata AFS can store up to 300 Mg/ha as soil organic carbon (SOC) in tropical regions depending on conditions (Nair 2012).

Agroforestry systems are one of the strategies that contribute to the implementation of climate-smart agricultural landscapes. According to a report by the World Bank (2012), the carbon benefits that can be obtained through climate-smart agriculture can be summarized as follows:

> *The triple imperatives of increasing productivity, reducing emissions, and enhancing resilience to climate change call for alternative approaches to practicing agriculture. Climate-smart agriculture (CSA) seeks to increase productivity in an environmentally and socially sustainable way, strengthen farmers' resilience to climate change, and reduce agriculture's contribution to climate change by reducing GHG (Greenhouse Gases) emissions and increasing soil carbon storage. One of the key elements of CSA is sustainable land management (SLM) involving the implementation of land-use systems and management practices that enable humans to maximize the economic and social benefits from land while maintaining or enhancing the ecosystem services from land resources* (World Bank 2012).

## 4 Cooking and Heating Devices and Fuels

The availability of alternative fuels and appropriate equipment to rural populations in developing countries and regions, is usually limited to their proximity to urban areas where these devices are more readily available. Lack of infrastructure, transportation, suppliers and economic means are constraints and obstacles to taking advantage of the more efficient and safer options for cooking and heating that prevail in many parts of the world.

### *4.1 Stoves*

Cooking devices currently being used as stoves range from three point stone arrangements to enable placement of a grate to hold pots and pans, to more efficient stoves that provide for some control over the burning process. Most devices do not provide for venting the gases and are thus very dangerous and have an adverse effect on the health of the users. There are models that utilize gas, kerosene or oil which can be regulated and totally shut off after use and are much preferable over uncontrolled wood burning.

In view of the total world economy, relatively modest amounts of funding could provide improved safety, health and sustainability for hundreds of millions of people throughout the world. For example, according to the IEA (International Energy Agency, www.IEA.org), halving the number of households using traditional biomass for cooking by 2015 - a recommendation of the United Nations Millennium project – involves 1.3 billion people switching to other fuels. Alternative fuels and technologies are already available at reasonable cost. The IEA, for example, has estimated that providing LPG (Liquefied Petroleum Gas) stoves and cylinders would cost $1.5 billion per year to 2015 (IEA 2006). While these figures appear to be extremely low, the point is that even when fuel costs and emissions are considered, the household energy choices of developing countries need not be limited by economic, climate change or energy security concerns (IEA 2006).

To provide a safe installation with proper venting and other safeguards, the costs would increase and the availability would be reduced accordingly. There are many types of stoves and fuel options available in the more developed countries that would be more fuel-efficient and provide greater safety, convenience and efficacy (see Sect. 7 on improved cookstoves).

For the locally acquired fuelwood, which predominates in most developing countries, there are many options of stoves which burn less fuel, are easier to ignite and contain the heat more efficiently. To minimize health risks it is necessary to vent these stoves to an outdoor space (Langbein 2017). Portable cooking devices would lend themselves to use in the outdoors if desired.

## 4.2 Fuels for Stoves and Heating Devices

In this section the most commonly used fuels for stoves and heating devices are presented, along with their advantages, disadvantages and limitations for developing regions. Fuelwood options and different types of biofuel alternatives are presented in separate sections (Sects. 5 and 6, respectively).

Pellet fuels, or pellets, are biofuels made from compressed organic matter or biomass. Biomass sources for pellets include industrial waste and co-products, food waste, agricultural residues, energy crops, lumber and roundwood. Wood pellets are the most common type of pellet fuel and they are made from compacted sawdust and related waste from sawmills, tree tops, branches and stems. Pellet fuel is likely not a viable option in most locations. The cost of pellet stoves and the need for electricity to operate an auger and fan would limit its use to areas with electricity. Proximity to the pellet supplier and transportation would also be a limiting factor.

Coal and charcoal may be an option where the forest and lands are severely degraded and near collapse. This option could be applied with a total ban on tree felling in order to restore the land from a depleted condition. The charcoal option can be found in most areas but carries a higher cost and with more limited availability. Peat is a great source of energy and after drying contains similar calorific value to dry wood, but is limited in availability due to transportation and handling costs. Peat could be an option where locally available.

Biofuels/oils from locally grown plants could provide energy for cooking and heating and would lend themselves to intermittent use as they can be regulated and shut off with a simple turn of a valve. Solid biofuels such as animal waste, dung and agricultural residues are low in energy content as well as in Energy Conversion Efficiency (Table 13.1). They may be readily available but would find better use as fertilizer in the gardens and fields (see Sect. 6 on Biofuels for more details).

Biogas (60% Methane) would also provide control for intermittent use but would likely have to be stationary with robust plumbing to minimize the risk for explosions and lethal gas flowing into the living space. The equipment cost would also be high compared to the wood burning option. The biogas could be separated from anaerobic digestion of organic materials such as animal, human and garden waste in locally operated digesters. However, methane could be very safe: there are models that are low-cost (such as that illustrated in Fig. 13.1) and the possibility of poisoning and explosions is extremely low for small and medium-scale operations (see Sect. 7).

Kerosene and diesel are an option for areas with landscapes and forests in severe distress but would be very limited by transportation and economic factors. The ability to regulate the on/off condition of the heating device would save fuel and reduce GHG emissions compared to wood burning which has difficulties in regulating and throttling.

Propane would be an efficient source of fuel for cooking but would require costly, sophisticated equipment for heating. The expense would limit the number of households which could acquire this option.

**Table 13.1** Typical efficiencies of different fuel sources at the final consumption stage of cooking

| Fuel source | Energy content (MJ/kg) | Typical conversion efficiency[a] (%) | Useful energy at final consumption stage of cooking (MJ/kg) | Approximate quantity of fuel necessary to provide 5 GJ of useful energy for cooking (kg) |
|---|---|---|---|---|
| Liquefied petroleum gas | 45.5 | 60 | 27.3 | 180 |
| Natural gas ($MJ/m^3$) | 38 | 60 | | 219 ($m^3$) |
| Kerosene (pressure) | 43.0 | 55 | 23.6 | 210 |
| Kerosene (wick) | 43.0 | 35 | 15.1 | 330 |
| Biogas (60% methane) | 22.8 ($MJ/m^3$) | 60 | | 365 ($m^3$) |
| Charcoal (efficient stoves) | 30.0 | 30 | 9.0 | 550 |
| Charcoal (traditional stoves) | 30.0 | 20 | 6.0 | 830 |
| Bituminous coal | 22.5 | 25 | 5.6 | 880 |
| Fuelwood efficient stoves, 15% moisture | 16.0 | 25 | 4.0 | 1250 |
| Fuelwood traditional stoves, 15% moisture | 16.0 | 15 | 2.4 | 2000 |
| Crop residue (straw, leaves, grass, 5% moisture) | 13.5 | 12 | 1.6 | 3000 |
| Dung, 15% moisture | 14.5 | 12 | 1.7 | 2900 |

Modified from Sullivan and Barnes (2006)
[a]The typical conversion efficiency for charcoal, fuelwood and kerosene is based on their respective stove types

Solar Photo Voltaic Cells may be an option for remote areas where minimal power is required for lighting, powering a cellphone or other low energy uses, however, cost would be a major limiting factor. It could also power a pellet stove with a couple of standard PV panels and a matching battery storage system. The cost of Solar Panels has been greatly reduced since their introduction and could be a very efficient option for many developing regions, especially as it applies to cooking and other low-energy use.

Wind Turbine Power may not be a viable alternative as equipment and infrastructure costs may be prohibitive. Turbines would also pose a danger to birds and would pose health risks to people living near or working within the turbine magnetic fields.

**Fig. 13.1** Organic farms with production of biofuels from animal manure assisted by technical personnel of CATIE in the Turrialba region of Costa Rica. Photos: F. Montagnini
(**a**) Goats are fed *Erythrina* leaves in stables and their manure is collected to be used for methane production. (**b**) Other farmers have pigs and cows that are fed bananas and other feedstock produced in the farm, and their manure is also collected to be used for methane production. (**c**) Manure kept under a synthetic membrane for accumulation and recovery of methane gas. (**d**) Connecting pipes from accumulated methane to the house. (**e**) Farmer lighting up a cook stove with methane produced in the farm

## 5 Fuelwood Options

More than 80% of rural people in the developing world still depend on fuelwood for cooking as well as warmth (Angelsen et al. 2014; FAO 2015). In most developing countries, fuelwood is often harvested from trees that are growing on the farm or outside the forest. Approximately two-thirds of fuelwood in developing regions comes from trees on the farm (Smeets and Faaij 2007; Somarriba et al. 2017, Chap. 15, this volume). The establishment of more trees in different land uses can increase the fuelwood supply and avoid the extraction of wood from forests (Ndayambaje et al. 2013).

Fuelwood, preferably grown from an AFS with nitrogen fixing species, fast growing energy plants and trees suitable for coppicing, could be a viable alternative when space and conditions allow. AFS can play a role in supplying fuelwood energy and facilitating the provision of other sources of energy, thus avoiding forest cutting for fuelwood (Marlay 2015; Montagnini 2017, Chap. 1, this volume).

Fuelwood produced in tree plantations and AFS can be a viable alternative energy source, as tree plantation productivity is often much higher than that of natural forests (CATIE 1986; Wadsworth 1997; Evans and Turnbull 2004; Wishnie et al. 2007). At least half of all the timber cut is used as fuel for cooking and heating (FAO 2016). Another major use of fuelwood is for small processing/local industries (coffee and tobacco drying, sugar mills, other).

The heavier the wood, the greater the calorific value. Heat given off is enhanced approximately 20% by resins found in conifers and by oils and gums found occasionally in hardwoods. Green wood has lower heating value than dry wood because some energy (approximately 20%) is used in evaporating the moisture (20% loss is equivalent to one year lost in a 5 year cycle for a firewood plantation) (NRC 1980).

### *5.1 Research on Fuelwood Species*

There are several trees and shrubs which lend themselves to fast growth, can be coppiced and have high calorific values. They include species of the genera *Acacia, Leucaena, Gliricidia, Albizia, Eucalyptus, Calliandra, Casuarina, Paraserianthes, Pinus*, and several others that grow well in short rotation plantations in tropical regions (NRC 1980; Onyekwelu 2011). For example, according to Onyekwelu (2011) the energy yield of *Acacia mangium* ranges between 4890.0 and 8150.0 GJ $ha^{-1}$ while the energy yield of *Eucalyptus grandis* is much lower at 312.0–520.0 GJ $ha^{-1}$. However, energy yield is not the only factor in selecting species for inclusion in energy plantings. Climate, local soil and hydrologic conditions, commercial demand, farmers' needs, species management and possibility to be used in AFS are also important considerations.

A total of 1200 tree and shrub species were recorded by NRC as having use for fuelwood, of which 700 had top ranking (NRC 1980). The list includes species for domestic or industrial use and most of them are MPTs. Several legume trees, such as *Acacia* spp. are excellent fuelwood species and are suitable for AFS. Because of their ability to grow fast (rotations of 5–10 years) exotic fuelwood species may become invasive, as it has been reported for *Acacia mangium*, *Leucaena,* and some species of pines and eucalypts in some locations. In any trials of fuelwood plantations, local species should always be given first priority (Montagnini 2005).

Early in the 1980s the Tropical Agriculture Research and Training Center (CATIE, www.catie.ac.cr) pioneered research and dissemination on fuelwood species in Central America, with The Fuelwood and Alternative Energy Sources project and subsequent follow up projects and programs. The Fuelwood and Alternative Energy Sources project was a six-year project funded primarily by the U.S. Agency for International Development's Regional Office for Central America and Panama (USAID/ROCAP) and implemented by CATIE in Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua and Panama (Donovan et al. 1986).

The goal of this fuelwood project was to improve the welfare and productivity of low-income groups and increase the supply of low-cost energy for the rural and urban poor. The purpose of the project was to develop, demonstrate and make available for transfer improved cultivation practices to increase fuelwood production and supply. In terms of both CATIE and the national institutions, the fuelwood project's major value was establishing institutional capability in the technical area and links with other appropriate institutions. The project firmly established CATIE as a regional center for information on seeds for fast-growing species, particularly those of importance regarding fuelwood.

The fuelwood project tested a total of 150 species. In many cases, however, these were very limited trials and/or demonstration units and were not definitive enough for analysis that could ultimately lead to widespread dissemination. The project recommended a total of 24 especially promising species for fuelwood (and other uses) in this region, based principally on silvicultural, rather than socioeconomic, success: *Leucaena leucocephala, Gliricidia sepium, Caesalpinia velutina, Calliandra calothyrsus, Casuarina equisetifolia, Gmelina arborea, Cassia siamea, Guazuma ulmifo1ia, Tectona grandis, Casuarina cunninghamiana, Melia azedarach, Eucalyptus grandis, Leucaena diversifolia, Mimosa scabrella, Eucalyptus tereticornis, Acacia mangium, Eucalyptus deglupta, Eucalyptus camaldulensis, Eucalyptus citriodora, Eucalyptus globulus, Eucalyptus saligna, Azadirachta indica, Grevillea robusta, Alnus acuminata*.

The project also established management trials: spacing, fertilization, plantation regeneration, natural forest regeneration, planting type (direct seeding or seedlings), plantation harvest, pest control, site preparation and natural forest harvest. In addition, Agro-Forestry Demonstration units included planting trees in Taungya (planting trees associated with crops until canopy closure, see Montes-Londoño 2017, Chap. 3, this volume), live fences, windbreaks, inter-row plantings, planting trees for crop shade, crop borders and silvopastoral systems.

The project concluded that all species considered for inclusion should be screened by using "species elimination trials." For a given species, this type of trial lasts approximately one year. Seedlings are planted in straight lines with considerable repetition. Lines may be placed across any type of soil, aspect or terrain. All information worthy of recording is plotted on a map showing the location of each line and the position of each species on a line. At the conclusion of a trial, those species found suitable for formal trials will have become obvious by their superior growth, good form and healthy appearance. By means of seed trees and seed orchards, the region strives for regional self-sufficiency in tree seeds, in great part supported by the Latin American Forest Tree Seed Bank, headquartered at CATIE in Turrialba, Costa Rica. CATIE has prepared field manuals for management of the principal promising species, with detailed instructions for each species, with any necessary adjustments according to life zones.

The fuelwood project succeeded in identifying priority areas where fast-growing species are a potentially cost-effective answer to energy problems (e.g., small industries such as coffee mills and sugar cane processing). On the second phase of the Madeleña Project (1986–1991) research was focused on 24 promising multipurpose tree species including silvicultural and socio economic studies directed to contributing to fulfill farmer's needs. The third phase (Madeleña-3, 1991–1995) was aimed at developing improved strategies for extension work and dissemination, and strengthening inter-institutional relations in the region. The next phase had as main goals to strengthen forestry socioeconomics and provide bases for improving technical assistance on management of existing plantations. Over its existence the project generated an extensive data set of information on silviculture and socioeconomic aspects related to planting and management of MPTs (Belaunde and Rivas 1993).

Most recently CATIE has been involved in research and dissemination projects to contribute to finding solutions to environmental issues, with activities focusing on research and technical assistance including projects on sustainable biomass and renewable energy (CATIE 2004). Lately, several projects have dealt with different aspects of climate change adaptation and mitigation, for example, projects geared to developing and testing tools and methodologies as well as technical and scientific information useful for the design and implementation of Clean Development Mechanisms (CDMs) in the areas of afforestation, reforestation and bioenergy (baseline, additionality, allometric and growth models, emission factors). Projects have also developed tools to calculate emissions (CATIE 2017).

## 6 Biofuels

### *6.1 Importance of Biofuels Worldwide*

Biofuels have been pursued in recent years to reduce overdependence on fossil fuels, in great part because they are believed to be environmentally friendly. Sustainable Development Goal (SDG) number seven seeks to substantially increase contribution of renewable energy to global energy supply, as well as to double the rate of improvement in efficiency of energy. Biofuels can play a role in the pursuit of SDG 7 as they are one of the most advanced alternative energy sources.

Even though biofuels have a great potential in aiding climate change mitigation, their large scale adoption is regarded as problematic because of their potential negative trade-offs in terms of land use change and emissions, especially for first and second generation biofuels (Acheamponga et al. 2017). Additional negative impacts would be the loss of carbon and nutrients, in addition to soil erosion and lost hydrological services that can be brought along by land use changes from forests to energy plantations. Finally a major concern particularly relevant for large scale commercial biofuel production is competition for lands that are suitable for food production (Onyekwelu 2011).

First generation biofuels are those obtained from conversion of feedstock such as sugar, cassava and sugar beet into ethanol, as well as those that utilize oil-seed crops such as rapeseed, sunflower, soybean and palm oil. These types of biofuels have reached the most advanced forms in their production and are commercially available, with oil palm and sugarcane accounting for over 90% of total biofuel feedstock investments in tropical countries since the year 2000 (Popp et al. 2014).

Second generation biofuel technologies utilize more flexible and energy-efficient lignocellulosic feedstock such as biomass from agricultural and forest residues. These include jatropha, straw, bagasse, and energy crops grown on marginal lands which are converted into ethanol and methanol utilizing the entire plant. In this way, energy yields per hectare of land can be much higher (Senauer 2008). The third generation biofuels are based on improvements in biomass production of algae and other feedstock which are specially engineered through advanced biotechnology (Acheamponga et al. 2017).

One of the major issues related to expanding the use of biofuels is its potential impacts on deforestation, land use and food production in the tropics. Expanding biofuel production interferes with food production, existing land uses and land tenure. One of the main reasons behind suggestion of biofuel adoption has been how it can help to reduce GHG emissions, with the assumption that carbon emissions as a result of biomass combustion are balanced out by carbon fixation during biomass growth (Song et al. 2015). However, this does not take into consideration the entire life cycle of biofuels, ignoring emissions that would take place as a result of land use changes (Gao et al. 2011; Timilsina and Shrestha 2011). The long time horizon needed to recapture carbon lost to combustion back into living matter is a pressing issue as well.

Beyond this debate, and taking into consideration specific site conditions, it is still hoped that a combination of carbon capture techniques and novel bioconversion processes provided by third generation biofuel technologies has opened an era of fuels that can be abundant, energy efficient and clean which can support the seventh SDG (Acheamponga et al. 2017).

Consequently, there is a need to reconsider current biofuel policy and a shift from heavy dependence on food crops as biofuel feedstocks as, for example, in the case of the extensive use of corn to produce ethanol. There are high yielding energy crops such as *Jatropha curcas, Azadirachta indica, Moringa oleifera* and other non-food seeds which have the ability to grow on degraded soils and can also grow in low and high rainfall locations (Onyekwelu 2011).

### *6.2 Examples of Successful Biofuel Production*

Biofuels have a potential to alleviate domestic fuel needs, especially at the small scale using raw materials in the form of agricultural residues or animal wastes (Fig. 13.1). This can generate employment opportunities at the local level while not upsetting the traditional agricultural livelihood base of such areas.

For example, the BIOMAS-CUBA project has been operating since 2009 based on the production and utilization of biodiesel and biogas, biomass gasification and the production of bio-products. The project is directed at the integrated production of food and energy in the context of "agro-energetic farms" (Suárez et al. 2014). The project promotes a local agricultural innovation model, with large involvement of producers and impact studies. The project was executed in 87 scenarios of five Cuban provinces making possible the sowing of 109 ha of *Jatropha curcas* L. associated to crops in AFS, the installation of a biodiesel production plant (105,600 liters/year), two biomass gasifiers for generating electricity, and the construction of 69 biodigesters. The second phase of the project is directed at the formulation and implementation of local strategies of integrated production of food and energy in six municipalities, and also aims to attain greater incidence in national, regional and local policies associated with food security, renewable energies and environment (Suárez et al. 2014).

At CATIE's Commercial Farm, milk production is an intensive tropical lowland production model whose main objective is to produce quality milk at low cost with minimal emissions. To achieve this objective, a milking parlor was built according to animal comfort needs and to ensure proper use of wastes from the activity, especially the manure, which is used to produce organic fertilizer (bokashi) and biofertilizer (biodigester effluent). It has a biodigester that transforms biogas into electricity for mechanical milking, solar panels to heat water and a complete infrastructure for capturing rainwater from the roofs of the facilities (https://www.catie.ac.cr/en/products-and-services/commercial-farm.html).

It should be noted that the farm animals at CATIE are fed with fodder produced in silvopastoral systems, and that part of the biodigester effluent is used as fertilizer for crops in AFS, thus showing the integration of fuelwood and agroforestry production. Likewise, the examples shown in Fig. 13.1 illustrate this type of integrated system, as the animals eat fodder harvested from silvopastoral systems and the biodigester effluent is used as fertilizer in the farm (Montagnini personal communication July 2017).

## *6.3 Jatropha as a Biofuel*

Jatropha (*Jatropha curcas* L.) is a good example of a species that has been promoted as renewable energy source as this tropical woody perennial tree or shrub may survive in harsh climate and soil conditions. Despite lack of enough information about some of the agronomic, socio-economic and technical aspects of the jatropha value chain and its implications for the sustainable livelihoods of local communities, large numbers of projects on different scales have been implemented. However, in an assessment of key economic, environmental and social issues pertaining to jatropha biofuels, based on almost 150 studies covering 26 countries, van Eijck et al. (2014) found that total jatropha production has remained small, with numbers declining since 2008. In Kenya, jatropha plantation projects were found to be uneconomical and risky due to competition for land and labor with food crops (Mogaka et al. 2014).

Jatropha plantation projects require high financial inputs, and smallholders can only achieve financial feasibility in low-input settings and when opportunity costs are low. Yield increases and value addition (e.g., through utilizing by-products) would be necessary to stimulate jatropha projects (van Eijck et al. 2014).

Most studies indicate significant GHG benefits over fossil fuels, and minimal negative social impacts have been revealed so far. If its financial feasibility is improved, jatropha can still become an option for sustainable energy production, GHG mitigation and rural development, especially through smallholder models. Successful implementation requires careful advance assessment of local circumstances, such as the political climate, gender aspects and land ownership structures (van Eijck et al. 2014).

Finally it is expected that using jatropha as a component of AFS by intercropping with annual crops (Taungya) or other species combinations may make jatropha energy projects a more viable alternative. In Belize, jatropha is intercropped with cash crops such as peppers while there are experiences of intercropping jatropha with vanilla in Madagascar, Uganda and Tanzania (Montagnini personal communication, July 2017).

## 7 Improved Cookstoves

Most devices used for cooking and heating in developing countries are generally inefficient, waste large amounts of fuel and are unsafe. Although there are many initiatives for improving equipment and methods, much greater efforts are needed to satisfy worldwide demand. It would be a very economical way to greatly reduce carbon dioxide and other emissions.

Improving access to affordable and reliable modern forms of energy services is essential in reducing poverty and promoting economic development, especially for developing countries (Malla and Timilsina 2014). In 2011, recognizing the importance of access to modern affordable energy services in developing countries, the United Nations launched the Sustainable Energy for All (SE4ALL) initiative with three objectives: (i) ensuring universal access to modern energy services, (ii) doubling the global rate of improvement in energy efficiency, and (iii) doubling the share of renewable energy in the global energy mix by 2030 (WWW.SE4ALL.ORG). This initiative has also attracted worldwide attention on issues related to clean cooking fuels. A separate global alliance, known as Global Alliance for Clean Cookstoves (GACC), has been also initiated under a global partnership of public and private sectors to foster the adoption of clean cookstoves and fuels in 100 million households by 2020 (GACC, cleancookstoves.org).

The World Bank has recently launched a number of regional clean cooking initiatives. For example the Africa Clean Cooking Energy Solutions (ACCES) initiative promotes enterprise-based, large-scale dissemination and adoption of clean cooking solutions (web.worldbank.org). The East Asia and Pacific region's Clean Stove Initiative (CSI) intends to scale up access to advanced cooking stoves for rural poor households through country-specific technical assistance and a regional knowledge-sharing and cooperation forum (www.esmap.org).

Besides these global initiatives, there are several national and regional initiatives to promote clean cooking. For example, in India, the government launched the National Biomass Cookstoves Program in 2009 to provide 160 million improved cookstoves to households currently using solid fuels (Venkataraman et al. 2010). The EcoTipping Points Project includes efforts in Mexico where approximately one quarter of the population- or 28 million- still rely on open fires for cooking and/or heating (Nuñez 2009).

Given all the environmental and public health concerns that surround the burning of firewood, how can a wood burning stove be environmentally friendly? By reducing the amount of wood used relative to traditional open fires and significantly improving both household air quality and family health. The Patsari stove is a good example. The Patsari improved burning stove was developed in Mexico as part of the EcoTipping Points Project (Nuñez 2009). The Interdisciplinary Group for Appropriate Rural Technologies (GIRA), based in the central Mexican state of Michoacán, used a participatory approach in which input was provided by actual users from indigenous Purhépecha communities, to design a simple yet effective stove which rural households are now actively embracing instead of the traditional open fires.

The Patsari stove consists of a closed, boxlike combustion chamber that cuts fuel use in half, and a chimney to channel smoke out of the home, which results in a 70% reduction in indoor air pollution. Hot plates on the top surface, over the fire, provide the cooking surface. Despite the promise of improved efficiency and cleaner air, families were initially reluctant to change the way they have cooked for thousands of years. The tipping point came rather unexpectedly, when women realized that kitchens with the Patsari stove were both cleaner and easier to keep clean. As of 2006, over 3500 hundred families and 70 small businesses had installed Patsari stoves. Microcredits and discounts to businesses have been made available to facilitate the widespread adoption of the Patsari stove.

By purchasing the pre-made parts (such as the chimney) from local providers and training local residents in the construction and promotion of Patsari stoves, the project becomes self-sustaining. Local governments and NGOs often provide the raw materials (which are obtained locally), so that customers need only pay the stove-builder's labor. Over 100 individuals have been trained as stove-builders, who in turn train families on proper operation and maintenance. Builders conduct at least three follow-up visits to check the stoves and correct any deficiencies. Health studies have since shown Patsari households to suffer from 30% less respiratory infections and 50% less eye infections, adding further incentive to switch. These health benefits could be even larger once neighboring households also adopt the Patsari stove (Nuñez 2009).

Several other types of improved cookstoves have been designed for other locations/projects. Cleancookstoves.org has an online catalog, http://catalog.cleancookstoves.org/ which includes 350 stoves, 650 test results and a list of biofuels, processed and unprocessed solid biomass, liquid/gas, electricity, solar and more.

As seen above, there are many health, economic and environmental benefits from pursuing the widespread use of improved cooking devices. To a lesser extent, improvements to heating devices, their proper placement and safe venting would also provide similar, positive benefits.

## 8 Conclusions

With the world's continuous population expansion creating pressure on natural resources and arable lands, the need for lending assistance to the poorer regions of the world has never been greater. Millions of people, lacking land tenure, are dislocated from lands under their control for generations, displaced by the hunger for raw materials of the industrialized countries. Plantation lands, in many cases, are occupied likely with the consent of governments but without consulting the native people. Disruption of old established ecosystems provokes significant loss in biodiversity of plants, animals and people.

Renewable energy directives by the EU and other countries have led to coal and other fossil fuels being replaced by biomass such as pellets, roundwood and chips, etc. This has led to an explosion in harvesting of forest products in the Southeastern US and other forested areas, likely leading to land degradation and loss of ecological services. This needs a closer look as it appears sustainability is in jeopardy.

The loss of forest lands and degradation of soils therein can have major adverse effects on food security and sustainability as vital functions of the forest are lost. Efforts to curb and modify fuelwod use would be a major factor in protecting food security and sustainability.

There are many alternatives to clearcutting the second growth and old forests to acquire wood for charcoal production. With equipment better able to regulate and throttle the consumption of wood and liquid fuels, the possibility exists to reduce fuel consumption to much lower levels worldwide wherever devices for cooking and heating are used.

Fuelwood options are many and the most suitable tree species can usually be found through consulting/checking/reviewing the vast research already performed at many universities and institutions dedicated to forestry and agroforestry. Biofuel production has been heavily researched and implemented on a smaller scale in recent years and holds great promise to contribute to Sustainable Development Goal (SDG) number seven. Many studies indicate significant GHG benefits over fossil fuels and should become more prominent with time.

An extensive share of equipment and devices currently in use for cooking and heating in the developing countries are inefficient, egregiously waste fuel and are unsafe. The developed nations, many of which collect carbon taxes for mitigation of GHG emissions, should be well positioned to allocate a significant share of those funds to upgrade inadequate cooking and heating systems. This would have a major impact on reducing GHG emissions and save millions of lives.

The world is awash in carbon with few signs of a reversal. Upgrading cookstoves and space heating equipment to more efficient versions provides a great opportunity for significantly lowering GHG emissions to the atmosphere throughout the world and improve health conditions for billions of people.

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# Chapter 14
# Specialty Crops in Temperate Agroforestry Systems: Sustainable Management, Marketing and Promotion for the Midwest Region of the U.S.A.

**Gregory Ormsby Mori, Michael Gold, and Shibu Jose**

## 1 Introduction

Agriculture is the dominant land use across the Midwest Region of the U.S.A., and the region is home to some of the most agriculturally intensive production in the world. Approximately 66.8 million hectares across the region are under some form of commodity agriculture, just over 50% of the total land surface. In Iowa, Nebraska, and neighboring states approximately 90% of the land area is in agricultural production (USDA 2015). The intensification of agriculture in the region over recent decades, characterized by increasing farm size and expansion of corn-soy monocultures, has brought tremendous advances in production, but has also raised concerns about long-term sustainability and the environmental consequences. During 2015 in Illinois, 79% of all agricultural land was planted to corn or soy (USDA 2015). These farming systems, which are highly dependent on fossil fuels, genetically modified seed, agrichemical inputs, and ever larger and more specialized machinery, contribute to negative ecological outcomes including loss of soil through erosion, pollution of surface and ground water from nutrient leakage and contamination, and loss of habitat, biodiversity, and ecosystem resiliency (Gordon and Newman 1997; Jose and Gordon 2008).

Concurrent with the trend towards larger, low-diversity farms, has been a significant removal of perennial grass-strips, on-farm trees, hedgerows, and windbreaks that served as reservoirs of biodiversity and as effective buffers against soil loss, and water and air pollution across the landscape (Pimentel 2006). Soil loss and nutrient leakage from farms affects not only local surface and ground water, but eventually ends up in the Mississippi river, contributing to the rise of a hypoxic dead zone in

G. O. Mori (✉) · M. Gold · S. Jose
University of Missouri Center for Agroforestry, Columbia, MO, USA
e-mail: ormsbyg@missouri.edu; goldm@missouri.edu; joses@missouri.edu



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the Gulf of Mexico (Alexander et al. 2008; Helmers et al. 2008; Randall and Goss 2008). To mitigate these impacts, Midwestern agriculture requires greater diversification and more widespread integration of continuous living cover with sustainable practices across the landscape.

In response to these concerns, numerous initiatives including an array of government cost share programs, have been undertaken to promote more sustainable practices, with varying degrees of impact. The Conservation Reserve Program (CRP), enacted in 1985, and administered by the Farm Services Agency, has provided financial support to farmers for taking ecologically sensitive areas out of production. The primary goal of the program is to "re-establish valuable land cover to help improve water quality, prevent soil erosion, and reduce loss of wildlife habitat." Rental and/or cost share payments are made to place the acreage in conservation and plant species that will contribute to improving environmental health and quality (USDA FSA 2016). However, because there has been no allowance for harvesting of any sort on CRP lands, once the 10–15 year contracts expire, farmers may have little incentive to keep these areas in conservation and often convert back to cultivation and row crop monocultures. The Natural Resources Conservation Service (NRCS), with a mandate to conserve soil and water resources, also administers multiple programs intended to promote sustainability and resource conservation, including practices such as cover crops, no-till, terracing, and more recently agroforestry (USDA NRCS 2016).

The 2016 national cover crop survey (USDA SARE 2016) collected data from 2020 respondents from 48 states and the District of Columbia. Planting of cover crops has risen steadily since 2010 with projected plantings in the summer of 2016 expected to continue the trend. Eighty one percent of those surveyed are using cover crops. The top three benefits identified with cover crops were increased soil health, increased soil organic matter, and reduced soil erosion. Respondents were enthusiastic about cover crops, including a new trend to graze cover crops. Tax credits, reduced crop insurance premiums, and more cover crop information top the list of favored enticements for increased use.

Agroforestry practices, by regaining some of the structural and functional characteristics that contribute to the sustainability of natural ecosystems, offer solutions to many of the environmental problems associated with modern agriculture (Gordon et al. 2009). Agroforestry systems (AFS), which at their core involve the intentional integration of trees and shrubs with crops and/or animals on the same managed land unit, can be a viable alternative for sustainable agricultural production. Transforming agricultural practices to include a wider array of perennial species presents numerous advantages, both environmental and economic, over many current land use practices. As stated, annual crop monocultures, lacking ground cover during significant parts of the year, are "leaky" (e.g. soil loss, nutrient and agrichemical contamination in runoff). Designed systems integrating trees, shrubs, and perennial grasses can sequester more carbon, promote enhanced soil health and water quality, while enhancing biodiversity, habitats for wildlife, and increased ecosystem resiliency across the landscape (Jose and Gordon 2008; Schoeneberger 2009). Diversifying systems to include multiple productive components creates additional revenue streams, contributing to both increased incomes as well as reduced financial risk (Alavalapati et al. 2004; Grado and Husak 2004; Godsey et al. 2009).

Research and promotion of AFS in the United States until recently has focused largely on the five main practices, as defined by USDA, of alley cropping, riparian buffers, windbreaks, silvopasture, and forest farming. However, a broad range of opportunities exist beyond these core practices for expanding and diversifying the number and types of perennial species integrated into productive landscapes through myriad combinations of crops, trees or shrubs, and animals (Gordon and Newman 1997; Garrett 2009; Toensmeier 2016, see also Roberts 2017). Leakey (1996), described agroforestry as a suite of practices in which the varying degrees of integration of trees into land use systems can be seen as stages in the development towards mature systems of increasing ecological integrity.

Numerous efforts, both formal and informal, are currently underway around the region to research and develop sustainable alternatives using agroforestry practices. In addition to the ongoing work of the Center for Agroforestry at the University of Missouri and the USDA National Agroforestry Center in Lincoln, Nebraska, notable examples range from the "Multifunctional Woody Polyculture for Sustainable Food Production" trials coordinated by the University of Illinois (Wilson and Lovell 2016) to the "Regenerative Agriculture" approaches modeled by New Forest Farm in Wisconsin and Versaland in Iowa (Shepard 2013; Versaland 2016). Green Lands Blue Waters (Jewett and Schroeder 2015) supports the widespread adoption of five "continuous living cover" practices (including AFS) on farms as a vehicle to achieving a robust, resilient agriculture that delivers yields, healthy soil, clean water, and a good quality of life for rural and urban citizens. The Savanna Institute (2016) is conducting participatory research with farmers and scientists across the Midwest to test and develop production AFS using perennial food and fodder crops within multifunctional polycultures mimicking the original native oak savanna biome of the region.

An important consideration in the design and promotion of AFS is the availability of appropriate species that can be successfully integrated into these systems. Whether through selection and management of native tree species and non-timber forest products (NTFPs) or the adaptation and breeding of non-native species, there is a need for reliable, high quality, productive options with which to design agroforestry systems. Specialty crop development for AFS is an approach that seeks to make more of such options available. Achieving widespread adoption of integrated AFS practices based on specialty crops will depend not only on the development of genetically improved ecotypes and/or cultivars, but also on viable, stable markets and effective promotion and support for prospective growers. Economically viable specialty crops can serve as the tree component in alley cropping and silvopasture, or be integrated into buffers or multi-functional polycultures. The additional or enhanced revenue streams realized by transforming riparian buffers or windbreaks into profit centers through the integration of marketable specialty crops should help make these practices more attractive to farmers and land-managers, leading to increased adoption and further contributing to diversification and connectivity across a fragmented landscape.

This chapter presents an overview describing the approach and ongoing efforts by the Center for Agroforestry at the University of Missouri (UMCA) to develop specialty crops for use in agroforestry systems in the Midwest region of the U.S.A., and the range of potential economic and environmental benefits that these systems can provide when properly implemented and managed.

## 2 Specialty Crop Development

The University of Missouri Center for Agroforestry (UMCA),[1] recognizing the importance and potential of specialty crops for design of robust, ecologically sustainable and economically productive AFS, has placed an emphasis on the research and development of regionally adapted and promising specialty crops. This includes genetic improvement, release, and promotion of well known (e.g. eastern black walnut – *Juglans nigra*) and unfamiliar (e.g. Chinese chestnut – *Castanea mollissima*, elderberry – *Sambucus* canadensis, pawpaw – *Asimina triloba*) native and non-native tree nut and other tree species and non-timber forest products for managed production within an agroforestry practice.

The harvest and use of Non-Timber Forest Products (NTFPs) is prevalent throughout the U.S.A. (Chamberlain et al. 2009; Davis and Persons 2014; Mudge and Gabriel 2014), including the Midwest. Upwards of 140 NTFPs are harvested in Michigan's Upper Peninsula by indigenous and non-indigenous people, for both commercial and non-commercial uses (Emery 1998). Many NTFPs harvested throughout the region, such as native nuts, fruits mushrooms or other edibles and a range of decorative, floral or medicinal plants, have potential for development as specialty crops and use in agroforestry designs. For those NTFPs whose conservation status is threatened, e.g. American ginseng (*Panax quinquefolius*), a transition to managed 'wild simulated' cultivation in agroforestry systems is a sound approach for long-term conservation.

Early in the twentieth century Smith (1950) explored the potential for producing specialty forest products on marginal cropland as part of his vision for transforming American agriculture through transition to perennial tree crops in multistory systems. MacDaniels and Lieberman (1979) advocated for research to explore the feasibility of growing tree crops on marginal land as supplemental sources of food and forage. Molnar et al. (2013) expanded upon ideas proposed by Smith (1950), supported by modern scientific understanding and advances, emphasizing the largely overlooked potential of tree crops to enhance world food and energy security and environmental sustainability. Examples from around the globe have demonstrated the potential for the domestication of specialty crops and the transition from wild harvesting. A several decade-long effort to domesticate and develop markets for under-utilized native trees across Africa such as bush mango (*Irvingia gabonensis*) and African cherry (*Prunus africana*) for managed cultivation in agroforestry practices has resulted in both significant conservation benefits as well as

[1] University of Missouri Center for Agroforestry (UMCA), 203 ABNR Bldg. University of Missouri, Columbia, MO 65211 Tel: +1 573 884 2874 Web: centerforagroforestry.org.

poverty reduction and livelihood enhancement for small holder farmers across the continent (Simons and Leakey 2014). Previous work at the University of Nebraska, beginning in 1999, evaluated the potential of 30 species of fruit and woody floral species in demonstration trials intercropped with corn, soy, and wheat. The data from these trials confirmed that a market driven approach to encourage natural resource conservation through agroforestry specialty crops can be a viable approach for the region (Josiah et al. 2004).

UMCA specialty crop development includes work on pecans (*Carya illinoinensis*), chestnuts (*Castanea mollissima*), black walnuts (*Juglans nigra*), elderberry (*Sambucus* canadensis), pawpaw (*Asimina triloba*), hybrid pine for pine straw (*Pinus taeda* and *P. taeda* × *P. rigida*), and shiitake (*Lentinula edodes*) and other forest grown mushrooms and medicinal plants.[2] The long-term goals of UMCA's specialty crop development efforts include creating viable on-farm enterprises and promoting the adoption of practices that can contribute to enhanced ecosystem services across the landscape.

UMCA's comprehensive approach to specialty crop development includes multiple foci:

1. Develop, test, and deploy improved cultivars
2. Research, test, and disseminate field production and management techniques
3. Conduct market, consumer, and value-added research
4. Increase consumer awareness and demand (creating market "pull")
5. Create financial decision support tools
6. Provide grower training and support to promote industry "grower clusters" or coops

Another important dimension of UMCA efforts includes bioactive phytochemical research to elucidate and test unique compounds found in botanicals including the potential to patent and market value-added products for pharmaceutical, cosmetic, and industrial applications. This provides another avenue to create market opportunities and increase the economic attractiveness and adoption of agroforestry. Development of viable markets for products from AFS is an important but poorly researched topic that is summarized in the following section.

## 2.1 The Importance of Marketing and Market Development for Agroforestry

Marketing of niche specialty crops may present opportunities for many farmers and landholders, especially those with landholdings that are too small to be profitable or competitive in commodity farming. However, for producers to make money from agroforestry practices, it is crucial to move beyond knowledge of which crops and

[2] Additional discussion for many of these species is also presented in Roberts 2017, Chap. 4 in this volume.

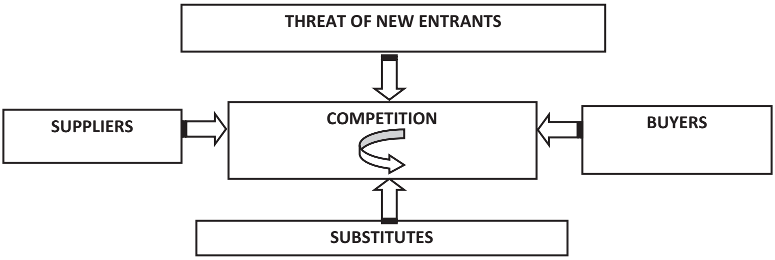


**Fig. 14.1** The Porter Five Forces Model (PFFM) (Porter 1980)

how to grow them, to understanding what products to sell and how to profitably sell them. Marketing has been described as "a set of processes for creating, communicating, and delivering value to customers in ways that benefit the organization and its stakeholders" (AMA 2016). It is a process that requires research, planning, and creativity. To achieve greater levels of agroforestry adoption, there has been a fundamental need to address these challenges and develop viable product markets. This requires moving beyond approaches that attempt to "push" new crops to potential adopters or a strategy based on the erroneous assumption that "if we grow it they will buy it" (Hammett and Chamberlain 1998). Launching and growing a specialty crop industry is more likely to achieve success when it is "pulled" along by market forces and when development efforts follow a market oriented strategy.

However, for new or emerging niche specialty crops, there is often a lack of detailed market information, therefore research into market dynamics and potential is essential. UMCA has pioneered market research focused on several agroforestry niche specialty crops (Gold et al. 2009). An important tool guiding much of this research is the Porter Five Forces Model (Porter 1980). This framework is a useful guide for analyzing competition within an industry and considers five areas of competition: competition among producers, bargaining power of suppliers, bargaining power of buyers, potential for substitutes, and threat of new entrants and interaction between these "forces," which defines an industry's structure and nature of the competition. The methodology is particularly useful for farm businesses that are looking to enter new markets, the typical case for agroforestry practices that integrate niche specialty crops (Fig. 14.1).

## 3 Edible Tree Nuts

Tree nut production in the U.S.A. has grown rapidly over the past four decades. Both in the U.S.A. and abroad (especially China) tree nut consumption has increased. China has become an important market for U.S. tree nut commodity exports. Between 1980 and 2014, U.S.A. tree nut exports increased almost sevenfold, and domestic utilization of tree nuts increased over 200%. During the same time, per capita tree nut consumption in the U.S.A. more than doubled (USDA ERS 2015a, b, 2016).

Several native tree nut species are present throughout the Midwest region including black walnut (*Juglans nigra* L.), butternut (*Juglans cinerea* L.), pecan (*Carya illinoensis* Wang.), shagbark hickory (*Carya ovata* Mill.), shell bark hickory (*Caray laciniosa* Michx.f.), and hazelnut (*Corylus americana* Marsh.). American chestnut (*Castanea dentata* (Marshall) Borkh), now nearly absent throughout its native range in the eastern U.S.A. due to the chestnut blight (*Cryphonectria parasitica*), occurred in limited areas on the very eastern edges of the Midwest region. Ozark Chinkapin (*Castanea pumila* var. *pumila*) also affected by the blight, was once common across southern Missouri and the states of the Ohio Valley. Historically, many of these species were important to the diets of Native Americans and early European settlers (Peattie 1966; Moerman 1998).

A select few of these nut trees stand out as promising specialty crops with potential for integration into AFS and are currently under development and evaluation. A range of potential products can be produced: including edible nutmeats, flour, and oils along with numerous value added products, and, in some cases, timber and biomass (Garrett et al. 1991; Josiah et al. 2004). For the past 20 years UMCA's comprehensive nut tree research program has had a major focus on northern origin pecan, eastern black walnut, and Chinese chestnut (*Castanea mollissima*), including selection and breeding, field trials, market research, financial decision tool development, and training/outreach. Looking forward, UMCA plans to begin evaluating promising selections of hybrid hazelnuts (Molnar et al. 2013). The following sections present UMCA's comprehensive approach to specialty crop development based on long-term efforts with Chinese chestnut and black walnut.

## *3.1 Chinese Chestnuts*

Edible chestnuts (*Castanea spp*.) are a relatively new crop for U.S. producers and a novel food for U.S. consumers. According to the 2012 Census of Agriculture, the United States had 919 farms growing chestnuts on more than 1151 ha (3750 acres), a 13.5% acreage increase over the 2007 Census (USDA NASS 2014). Field research in Mid-Missouri indicates that Chinese chestnuts (*Castanea mollissima*) are well adapted for Missouri and surrounding U.S. Midwest states (Hunt et al. 2012). Chestnut production in orchards and alley cropping provides profitable and sustainable alternatives for the Midwest family farm. Chestnut cultivation in the U.S. is an attractive enterprise for a number of reasons including high product demand (which in turn is based on growing consumer interest in local, healthy, and sustainably produced foods, coupled with documented consumer receptivity when exposed to chestnuts) and favorable prices (1 kg. of chestnuts sells for \$0.68–\$1.80 wholesale and \$2.25–\$3.60 retail (\$1.50–\$4/lb wholesale and \$5–\$8/lb retail) (Gold et al. 2006). Chestnuts grow well on fertile, erodible sloping lands, and can be effectively combined with annual crops or vineyard production in agritourism settings.

Relatively low initial investments are needed to establish orchards (Gold et al. 2006; Hunt et al. 2012). Chestnuts have favorable nutritional characteristics (e.g. low oil content, high vitamin C) and chestnut flour is sweet and gluten free, making it appropriate for the growing gluten free market which includes people with Celiac Disease. Current U.S. demand exceeds national production which is offset by imports. The United States imported about 4910 metric tons (10,825,000 pounds) of in-shell chestnuts valued at $12.7 million in 2010 primarily from Italy (60%) and South Korea (25%) (USDA FASS 2011).

Researchers at the University of Missouri Center for Agroforestry have been working with Chinese chestnut since the late 1990's, testing and promoting its use as the orchard overstory tree in alley cropping systems.

### 3.1.1 Cultivar Development and Testing

Due to the small size and undeveloped nature of the chestnut industry of the U.S.A., and concurrent lack of research conducted by Land Grant universities or the USDA, few of the Chinese chestnut (*C. mollissima*) cultivars that are resistant to the blight (caused by *Cryphonectria parasitica*) found in the eastern U.S.A. have been subject to multi-location testing and/or side-by-side comparisons in carefully designed, replicated, multi-year trials. To realize its full commercial potential, the establishment and growth of the U.S. chestnut industry will depend on the identification and use of clonally propagated chestnut cultivars with well-characterized nut quality and agronomic traits (Hunt et al. 2004).

Orchards comprised of chestnut cultivars offer a number of advantages to the growers over seedling based orchards. Asexually propagated cultivars provide predictable performance (e.g. tree form, pollen production, yield, nut size, harvest date, post-harvest storage life), therefore, every cultivar planted in the orchard should perform (almost) identically. Scion wood, derived from cutting fruiting "bud wood sticks" from mature grafted cultivars, is both clonal and sexually mature and as a result, asexually reproduces the parent cultivar and initiates commercial nut production earlier than trees grown from seedlings. Cultivars enable the grower to consider and opt for specific traits (e.g. taste, size, yield potential, tree shape and size, insect or disease resistance) and they can select (or change) cultivars to match the growers' needs, reflecting changes in consumer preferences or the release of improved cultivars.

To develop a new chestnut industry in Missouri and surrounding states, it is essential to conduct long-term studies that directly compare *C. mollissima* cultivars at the same location or locations over multiple years to determine their local adaptation and performance. For nut production, the most commonly planted species in the Eastern United States is *C. mollissima*, but interspecific chestnut hybrid cultivars (mixes of *C. dentata, C. crenata, C. sativa, C. mollissima* and other species) are also grown, e.g. 'Sleeping Giant' (*C. mollissima* * *C. crenata* * *C. dentata*) (Anagnostakis n.d.).

**Table 14.1** Average yield per tree (kg and lbs) and per hectare (and per acre) of Chinese chestnut cultivars at the University of Missouri Horticulture and Agroforestry Center (HARC), New Franklin, Missouri, summed over 4 years, 2008–2011, plus 2015

| | 2008–2011 | | 2015 (Age 16) | | 2008–2011 | | 2015 yield | |
|---|---|---|---|---|---|---|---|---|
| | Average yield/tree | | Average yield/tree | | Average yield | | | |
| Cultivar | *kg/tree* | **lb/tree** | *kg/tree* | **lb/tree** | *kg/ha* | **lb/Acre** | *kg/ha* | **lb/Acre** |
| Colossal | *42.1* | **92.6** | – | – | *5187* | **4631** | – | – |
| Qing | *24.0* | **52.8** | *42.9* | **94.4** | *2957* | **2640** | *5285* | **4719** |
| Eaton | *14.8* | **18.0** | *34.6* | **46.0** | *1823* | **1628** | *2575* | **2299** |
| Sleeping giant | *11.3* | **17.6** | *29.9* | **58.7** | *1392* | **1243** | *3289* | **2937** |
| Homestead | *8.2* | **14.7** | *20.9* | **44.2** | *1010* | **902** | *2476* | **2211** |
| Mossbarger | *8.0* | **13.6** | *26.7* | **70.4** | *986* | **880** | *3942* | **3520** |
| OK-Kwang | *6.7* | **52.8** | *20.1* | **76.1** | *825* | **737** | *4263* | **3806** |
| Peach | *6.2* | **32.6** | *32* | **65.8** | *764* | **682** | *3684* | **3289** |

A limited number of cultivars are available from commercial sources, however the supply of grafted trees is limited and to obtain large quantities of grafted cultivars requires custom ordering a year in advance. At the University of Missouri Horticulture and Agroforestry Center (HARC), New Franklin, Missouri, Center for Agroforestry scientists established a collection of 65 known *Castanea* cultivars from 1996 through 2005 in a germplasm repository for long-term evaluation (Hunt et al. 2004).

A second more limited, twelve cultivar replicated trial was established in 1999 in an effort to identify outstanding, locally-adapted cultivars that have traits suitable for commercial chestnut production (e.g. large size nuts and high yields). Yield data were tallied from 2008 through 2011, plus 2015, and combined to determine yield and average nut weight. All twelve replicated cultivars under test are currently bearing commercial quantities of chestnuts (e.g. in excess of 5 kg/tree). Commercial yields generally begin when cultivars are in their sixth to ninth year from graft. To achieve yields over 1125 kg/ha (1000 lb/acre) at the currently recommended spacing of 9.1 m × 9.1 m (30′ × 30′) or 125 trees/ha (~50 trees/acre), requires an average yield of 9.1 kg (20 lbs) per tree.

Cultivar trial data was not recorded for 2012–2014, however data collection resumed in 2015. Data from 2015 indicate that cultivar yields continued to increase from age 12 to age 15 as the tree canopies continued to expand in height, width and diameter. By age 15, all of the top yielding cultivars were exceeding the 18.2 kg/tree (40 lb/tree) threshold resulting in yields that exceeded 1 ton per acre, ranging from a low of 2476 kg/ha (2211 lb/acre) for the cultivar 'Homestead' to a high of 5285 kg/ha (4719 lb/acre) for 'Qing' (Table 14.1).

Chestnut nut size translates to market prices. Larger sized chestnuts (over 12 g/nut) sell for higher prices and chestnuts exceeding 15 g/nut receive the highest prices. There are several ethnic market outlets (East European, Asian) for smaller chestnuts (10 g or less) but the price per pound drops as nut size decreases. Nut weight varies within and between cultivars and also from year to year. Based on market prices, UMCA recommends cultivars that consistently produce chestnuts averaging 12 g or larger. As indicated in Table 14.1, there are a select number of cultivars (at the New Franklin location in high quality, fertile soils) that have consistently maintained both high yield and nut sizes in excess of 12 to 15 g as the cultivars have come into full production at age 16.

### 3.1.2 Chestnut Production and Management

Chinese chestnut trees perform best in well-drained, loamy to sandy loam soils. Heavy, poorly-drained soils, or soils that have a perched water table during wet seasons promote *Phytophthora* root rot, a devastating disease of chestnuts. Soils should be slightly acid (pH 5.5–6.5). Most Chinese chestnuts can tolerate −29 °C temperatures when fully dormant, but frost pockets should be avoided as planting sites, to avoid injury to swelling buds in the spring. Site selection is similar to the requirements for peaches; summit and shoulder slopes provide the best air drainage to safeguard from winter and early spring frost injury.

Chinese chestnut trees are rather drought tolerant once established, but ample water throughout the growing season promotes good tree growth and regular nut production. Maximum chestnut yields and nut size are obtained only under optimum soil water conditions, therefore irrigation is recommended. A lack of water during mid-August will result in smaller nut size, while a lack of water in September can prevent burs[3] from opening normally. Micro-irrigation techniques (drip and/or micro-sprinklers) are best suited for chestnut orchards.

Chinese chestnuts can be established by planting grafted trees, by planting seedling trees then field grafting one to 2 years later, or by planting nuts then field grafting 2–3 years later. Each of these methods has advantages and disadvantages. Prospective growers should choose the method most suited to their skills and economic situation.

At present, most (though not all) commercial chestnut growers establish cultivar-base orchards. However, not all growers elect to plant cultivars and instead plant seedling orchards with seedlings derived from the seed of proven cultivars. In untested geographic locations throughout the Midwest U.S.A., areas that may be much colder in winter than Mid-Missouri, with later spring frosts and earlier killing freezes in the fall, chestnut seedlings provide a lower risk option. On the upside, seedlings are more winter hardy and faster growing with no risk of graft failure. On the downside, seedlings take 3 or more years longer to come into production and may never produce adequate yields or nut sizes. The only way to determine the quality of seedling trees is to wait at least 15–18 years for a full evaluation.

Providing optimum weed control, proper fertility, and ample water ensures vigorous tree growth and early fruiting. As previously indicated, commercial production of grafted cultivars (1125 kg/ha, with 125 trees planted per hectare) begins between the sixth and ninth year after the grafted cultivar is planted. Based on the

[3] A bur is a seed or dry fruit or infructescence that has hooks or teeth (Editor's note).

cultivar trial data from the HARC farm, expected production from selected cultivars should reach 2250 kg/ha (2000 lb/acre) in a well-managed orchard by age 16.

To maximize nut yield, initial tree spacing can be either 6.1 × 9.15 m (~175 trees per hectare) or 9.15 × 9.15 m (~120 trees per hectare). As trees grow and limbs of adjacent trees start to touch (at 175 trees/ha ~age 12, and at 120 trees/ha ~age 15), every other tree on the diagonal should be pruned or removed to permit full sunlight to penetrate the tree crowns on all sides. Crowded trees create excessive shade on lower branches allowing flower and nut production only in the tops of the trees. Severe crowding and tree-to-tree branch overlap creates shade and causes lower branches to die out and compromises general tree vigor.

Harvest in the Midwest occurs from early September to mid-October, depending on location, cultivar and growing season. Fallen nuts must be harvested promptly to preserve quality and prevent excessive predation by deer, possums, turkey, mice, and other wildlife. Individual trees generally drop nuts over a 10 day period. Small acreage orchards can be hand harvested using a rolling wire basket. In larger plantings, highly efficient mechanical vacuum harvesters, produced by various European manufacturers (e.g. FACMA in Italy), are capable of handling large volumes.

Unlike most tree nuts that are high in oil content and low in water content, ripe chestnuts are high in carbohydrates (49%) and water (44%) making these nuts subject to molding and decay. Nuts must be picked up at least every other day to preserve nut quality. They should be promptly stored in a refrigerator (0 °C (32 °F) or slightly above) in 11.25 kg (25 lb) "onion sacks" to retard kernel molding. Ventilated bags are needed for larger quantities to allow some air movement while still reducing excessive moisture loss. To maintain optimal nut quality, the "cold chain" must be maintained from the grower to the wholesaler, retailer and consumer.

### 3.1.3 Chestnut Market Dynamics

**Chestnut Markets**

A nationwide survey of U.S. chestnut (*Castanea* spp.) producers was conducted using a variety of tools (e.g. Strength-Weakness-Opportunity-Threat (SWOT) analysis, the Porter Five Forces Model (Porter 1980), and Conjoint Analysis choice preference questions to understand the U.S. chestnut market (Gold et al. 2006). Results indicated that the U.S. chestnut industry is in its infancy. The majority of chestnut producers have been in business less than 10 years and are just beginning to produce commercially. Volume of production is low (less than 700,000 kg). U.S. chestnut producers are mainly part timers or hobbyists with small, manually harvested operations (Gold et al. 2006).

Additional information revealed through the national chestnut market survey (Gold et al. 2006) indicate that demand for quality chestnuts exceeds supply. Demand for fresh chestnuts is expected to continue to increase by 10–25% in the next 5 years. Grower retail prices range from $1.75 to $13.25/kg at farmers' markets; $3.25 to $13.25/kg at on-farm sales; and $4.4 to $15/kg at restaurants, retail grocers and health food stores. Overall, wholesale prices average $6.25 to $8.00/kg

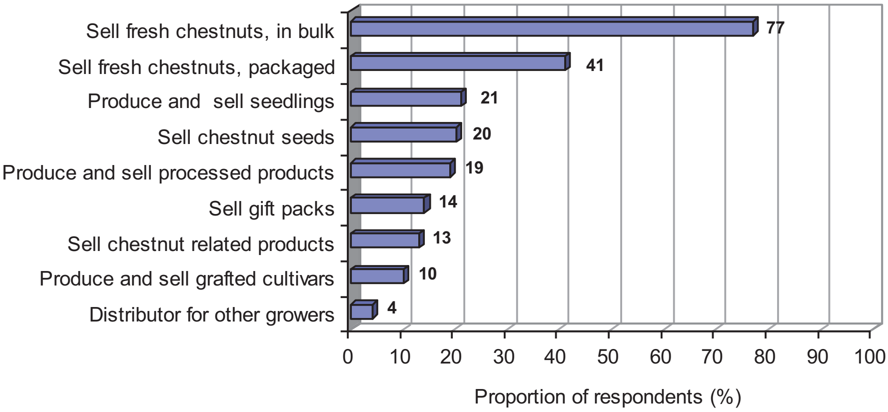


**Fig. 14.2** Range of economic activities performed by participants in the chestnut producer survey and percentage of respondents involved in each activity (N = 90). Percentages do not add to 100 because respondents had the option to select more than one choice (Gold et al. 2006)

to the grower. Producers who grow chestnuts from cultivars, grow organically, or sell under a brand name achieve the highest prices. The majority of respondents sell their chestnuts locally, 38% sell regionally and 21% sell nationally. Thirty eight percent sell chestnuts on-farm, 34% sell to farmers markets, 23% sell fresh chestnuts to restaurants and less than 20% sell to different retail locations (e.g. ethnic stores (19%), upscale grocery stores (18%), health and natural food stores (17%), and national chain grocery stores (11%)).

According to Gold et al. (2006) most respondents produce and sell fresh chestnuts in bulk (77%) or packaged (41%). Some producers act as small nurseries and produce seedlings (21%), grafted cultivars (10%) or chestnuts for seed (20%). Nineteen percent of respondents sell value-added products like chestnut flour, dried chestnut kernels, frozen chestnuts, chestnut honey, soup mix and jam, jellies or preserves while 13% sell chestnut-related products (e.g. roaster, mug, cap, knife) (Fig. 14.2).

An analysis using the Porter Five Forces Model revealed barriers to success in the chestnut business. These included a lack of information for producers, retailers and consumers, a 5- to 10-year time lag to get a return on investment, and shortage of available chestnut nursery stock of commercial cultivars. There were also concerns related to pest and disease control and market uncertainties. Lengthy quarantines for cultivars from other countries and lack of chemicals registered for use with chestnuts can also be considered barriers to success. Chestnut growers associations, universities, state and federal agencies must join their efforts to fund and support chestnut research and industry development (Gold et al. 2006).

**Consumer Research**

A longitudinal study (2003–2008) revealed that quality, locally grown, and nutrition-diet-health were consistently perceived as the most important attributes influencing chestnut purchase decisions (Aguilar et al. 2009). Another study explored preferences for different characteristics including nut size, production process and geographic origin. Results suggest consumers strongly prefer locally and U.S. grown compared to imported chestnuts with additional preferences for chestnuts that are medium sized and organically certified. Growers that provide the market with chestnuts meeting these characteristics are likely to capture price premiums (Aguilar et al. 2010).

Multiple consumer research studies have shown that familiarity with chestnuts increased based upon repeat exposure. Compared with people that attended the Missouri Chestnut Roast festival for the first time, repeat visitors demonstrated higher interest and consumption of chestnuts and a gain in knowledge regarding three key chestnut attributes: need for refrigeration, low fat content, and a source of gluten free flour. The Missouri Chestnut Roast provided a forum for interested people to ask questions and receive pertinent written information to take home and read, furthering the education process. These results demonstrate that the Missouri Chestnut Roast is having an impact on consumers' familiarity and interest concerning chestnuts and that public events of this nature are an effective tool to educate consumers and help create a viable chestnut industry in the region (Cernusca et al. 2008).

Results of a follow up survey of 2016 Missouri Chestnut Roast (MCR) participants (Cai and Gold 2016 unpublished) clearly show that the Center's longstanding "market pull" strategy, achieved in part via the annual MCR, is continuing to increase consumer's familiarity with and willingness to purchase chestnuts. Past purchase and consumption results of the 2016 MCR consumer survey indicate that there is an increase in festival participants' chestnuts purchasing behavior. A higher percentage of respondents in 2016 (60%) had previously purchased chestnuts compared to 2015 respondents (45%). Approximately 37% of the respondents in 2016 indicated they had consumed chestnuts at least 2 times a year compared to 25% in 2015. Almost 70% of the respondents indicated they had purchased chestnuts in places other than chestnut festival.

#### 3.1.4 Grower Engagement

With support from a Missouri Specialty Crop Grant (2008–2010), a "beginning grower" chestnut workshop series (four per year) was developed to provide existing and potential growers the information, skills and tools to successfully produce and market chestnuts. Sixty current and potential growers participated in the workshop series and the post-training feedback was overwhelmingly positive. A follow-up survey of all chestnut workshops participants in 2011 indicated that 35% of survey respondents created a new chestnut orchard, 20% increased the size of their chestnut orchard, and at least 22 ha (55 acres) of new or additional chestnut orchards were established as a direct result of the workshops. Based on production estimates of 2250 kg/ha (2000 lb per acre), 22 ha (55 acres) of chestnuts will result in an annual harvest of 55 tons or 110,000 pounds of chestnuts within the next decade.

This does not account for the continued addition of new chestnut orchard area since the 2011 survey.

Production and market research, grower workshops and open information sharing through the Chestnut Growers of America have all led to an increasing number of growers establishing chestnut orchards 4 ha (10 acres) in size and larger over the past decade. Based on the superior performance of tested chestnut cultivars, demand has shifted from bare-root seedlings to containerized, grafted cultivars. For example, since 2007, production and sales of RPM™ (a patented technology) containerized chestnuts has increased by more than 600% and grafted stock by more than 33% at the Forrest Keeling Nursery. This points to the strong demand by landowners for establishing chestnut orchards and also indicates that landowners are interested in getting into production quickly and are willing to increase their up-front investment costs to achieve early production.

An Excel™-based Chestnut Financial Decision Support Tool (Godsey and Cernusca 2015) was released to help chestnut growers and other decision makers make financially sound management and investment decisions. In 2014, 2015 and 2016 the membership of the national chestnut industry, the Chestnut Growers of America, was surveyed to obtain annual production and sales data along with market trends (Cernusca and Gold 2015b, 2016). Data from the 2016 CGA member survey included additional indications of positive growth in the U.S. chestnut industry. Specific 2016 survey findings revealed that 43% of growers plan to expand their chestnut acreage in the coming year and 63% of growers indicated that current demand for fresh chestnuts had increased compared to previous year, whereas only 13% indicated a decrease in demand.

## *3.2 Black Walnut*

UMCA researchers initiated black walnut research in the mid-1970's, testing and promoting its use as the primary tree component in alley cropping and silvopastoral systems. Black walnut's morphology and growth characteristics make it an ideal species for these agroforestry practices. It leafs out late in the spring and drops its foliage early in the fall. Even at its maximum leaf surface area, with compound pinnate leaves, it produces only a moderate, dappled shade and admits sufficient light to allow growth of many potential companion species (Garrett et al. 1991; Garrett and Harper 1999). A black walnut AFS has the advantage of producing income in multiple ways. Initially, there is income from the various crops planted between the tree rows. Later, as the trees grow and are thinned to enhance nut production, there is additional income from the wood of thinned trees.

Long term annual income can be realized from nut production and crop, hay or livestock production between the rows until the trees reach maturity. In some cases, with proper management, trees can be harvested for high value veneer and saw-logs. Several pioneers early on successfully established and managed black walnut AFS using unimproved seedlings available at the time. For example, at the Sho-Neff plantation in southern Missouri, corn and other field crops were harvested from the alleyways during several years following the establishment in 1976 of black walnut trees planted on a 3.05 × 12.2 meter spacing (later thinned to 6.1 m × 12.2 m). As the trees grew and shade increased, the plantation managers transitioned to haying and later grazing cattle. Most of these plantings, derived from unimproved seedlings, resulted in very low nut yields. Other characteristics, including alternate bearing tendencies and susceptibility to pests and diseases, can also reduce nut production in trees from unimproved wild seedlings. Taking this information into account, UMCA created a long-term selection and breeding program to develop improved black walnut cultivars for nut production (Reid et al. 2009; Coggeshall 2011a).

### 3.2.1 Black Walnut Cultivar Development and Testing

UMCA began an applied breeding program in 1996 (Reid et al. 2004; Coggeshall 2011a) focused on: (1) identification of the best adapted and most productive cultivars currently available (Coggeshall and Warmund 2009); (2) maximizing future crop yields in terms of both nut quality and quantity (Warmund and Coggeshall 2010) and (3) defining the genetic basis for host resistance to emerging pests and diseases, such as thousand cankers disease[4] (Utley et al. 2013). Using both clonal and seedling-origin pedigreed populations, ongoing work continues on evaluating the controlled crosses of the best available cultivars (Coggeshall and Romero-Severson 2013). In excess of 60 cultivars have been acquired and managed in grafted orchard collections. A total of 20 phenological and morphological descriptors have been recorded for each cultivar over multiple years. These data, combined with the use of microsatellite markers have served as the foundation for the development of the ongoing breeding program using traditional control pollination techniques (Coggeshall and Woeste 2010; Coggeshall 2011b).

Genotyping work completed in 2011 created two full sib mapping populations, which will facilitate the identification of genetic markers within the black walnut genome that are associated with specific phenotypic traits of interest (e.g. early flowering, kernel percent, anthracnose tolerance etc.). Advances in biotechnology capabilities have made this genetic marker discovery process much more efficient. Ultimately, it is anticipated that these genetic markers will lead to more efficient breeding efforts. The ongoing process of establishing and accurately evaluating all individuals within these full sib pedigreed populations, combined with the development of a robust "genetic map" for black walnut, will maximize breeding efficiencies for this species (Coggeshall and Romero-Severson 2013). This efficiency will primarily result from a decrease in the time period required to evaluate the desirability of an individual tree derived from the breeding program (Table 14.2).

A key target criterion for improvement has been the nut yield ratio. Nutmeat from the nuts of wild trees can average between 7–10% of total weight (nutmeat/

[4] A disease complex resulting from the combined activity of the fungus (GEOSMITHIA MORBIDA) and the walnut twig beetle (PITYOPHTHORUS JUGLANDIS).

**Table 14.2** Comparative performance of recommended Black Walnut cultivars under study by UMCA

| Cultivar name (fingerprint alias) | Bud break | Spur fruiting | Anthracnose susceptibility | Alternate bearing | % Kernel | Season length[a] | Ripening season | Yield efficiency[b] |
|---|---|---|---|---|---|---|---|---|
| Emma K | Early | Yes | Medium | High | 34 | 148 days | Mid | 0.09 |
| Football | Early | Yes | High | High | 29 | 170 days | Late | NA |
| Hay | Mid | Yes | Low | Low | NA | 135 | Late | 0.08 |
| Kwik Krop | Mid | Yes | Medium | High | 31 | 148 days | Mid | 0.03 |
| Sparks 127 | Mid | Yes | Mid | High | 32 | 118 days | Early | 0.10 |
| Sparrow | Mid | Yes | Low | Medium | 32 | 119 days | Early | 0.08 |
| Surprise | Mid | Yes | High | Low | 33 | 143 days | Late | 0.05 |
| Thomas | Late | No | Medium | Medium | 24 | 145 days | Late | 0.07 |
| Tomboy | Early | No | Low | Medium | 27 | 135 days | Early | 0.125 |

[a]Season length: the # of calendar days between first female flower being pistillate receptive and harvest (ripe)
[b]Yield efficiency: Aggregate nut production for year/$cm^2$ of stem
Source: Coggeshall and Romero-Severson (2013)

shell ratio). Nut yield in cultivars under study at UMCA is averaging around 30% kernel, with some cultivars demonstrating consistent nut yields up to 38%. Also, those cultivars exhibiting a tendency to produce nuts on short 2-year-old lateral shoots (called "spur fruiting") are more precocious and productive (Coggeshall 2011a). Development of an ideal improved cultivar that optimizes both timber and nut production has so far proved elusive.

### 3.2.2 Black Walnut Production and Management

The full potential of black walnut as an orchard crop for nut production is not yet known. So far, available data suggest that under optimal conditions and management, production in excess of 2250 kg/ha (2000 lb/acre) (hulled, dried in-shell) should be expected from the best cultivars (Reid et al. 2009). UMCA and its collaborators have also conducted extensive research and performance trials to evaluate production and management techniques including best practices for weed control, and orchard design and management, including spacing, pruning, thinning, and the effect of rootstock origin on cultivar performance.

A UMCA study begun in 2009 is assessing the feasibility, practicality, and profitability of converting mature un-grafted seedling derived black walnut stands and orchards to grafted productive orchards of improved cultivars for enhanced nut production. Weed control is critical in the establishment period for black walnut, which together with the careful selection of compatible ground cover species can profoundly impact performance (Van Sambeek and McBride 1991; Garrett and Harper 1999). Adequate and appropriately timed fertilization (late summer), as well as thinning and pruning are necessary to achieve full production potential (Thomas et al. 2009; Van Sambeek and Garrett 2005). Findings from multiple ongoing production trials and recommendations for best practices have been compiled in a comprehensive growers guide "Growing Black Walnut for Nut Production" (Reid et al. 2009). When designing alley cropping systems using black walnut, attention needs to be given to selection of appropriate companion species, due to the potential allelopathic effects of root exudates (juglone), and root pruning may be an effective management approach (Scott and Sullivan 2007). Due to the inherent difficulty of selection and breeding a genotype optimized for both improved nut qualities and timber production, future walnut growers will be selecting, designing, and managing their black walnut plantings for either timber or nuts, not both.

### 3.2.3 Black Walnut Market Dynamics

Market development for black walnuts presents unique challenges. A well-established, regional market already exists for black walnuts. Unlike English walnuts, the majority of black nuts entering the market are collected by hand from wild trees and brought to a network of buyers/hulling stations operated by Hammons Products Company of Stockton, Missouri. The company is the primary actor in the black walnut market and is the only large-scale production company in the country. Hammons operates a network of 220 hulling stations in 11 states across the Midwest and central U.S.A. Gatherers bring in green (hull on) black walnuts collected from wild stands and farmyard trees across the region, often by the pick-up truck load, and are paid between 0.07–0.33 cents/kg for the remaining fresh in-shell nuts after hulling. Annual wild harvests vary considerably (4.54 million kg in 2015 and 9.5 million kg in 2016) but historically average about 23 million pounds (10.4 million kg) per year. Hammons products extracts nutmeats at its cracking plant, grades and sorts the pieces, and markets nutmeat for use in baked goods, ice cream, covered chocolates, and other food products. Following drying, cracking, and sorting, approximately 0.7 million kg of nutmeat are sold annually. While nutmeat is the core business, black walnut shells are also an important and marketable byproduct, transformed into a range of products with industrial applications as abrasives, water filters, and oil industry drilling (Hammons Products 2016).

UMCA researchers have collaborated with Hammons Products for over 30 years to advance planting of improved cultivars with better nut yields and quality. Hammons offers a premium price for nuts with better crack-out rates and superior quality. Table 14.3 compares the yearly volumes of nuts from wild sources and from growers of improved cultivars, and highest price and crack-out (percent kernel) average for each year. Despite price premium, volumes of nuts from improved cultivars have not shown any steady increase over the last decade.

The current prices offered by Hammons for nuts from producers using improved cultivars, while superior to prices paid for wild nuts, are not high enough for producers to secure profitable financial returns on their investment in the establishment of plantations of black walnut cultivars. A black walnut marketing board has been

**Table 14.3** Yearly production and prices for Black Walnut cultivars under study by UMCA

| Year | kg of wild product (millions) | kg from improved cultivars | High price $/kg | Percent kernel | Cultivar |
|---|---|---|---|---|---|
| 2006 | 13.62 | 18,614 | $1.80 | 35.6 | Emma-K |
| 2007 | 5.45 | 5448 | $1.52 | 30.2 | Sparrow |
| 2008 | 17.2 | 3178 | $1.58 | 31.4 | Sparrow |
| 2009 | 7.71 | 10,442 | $1.80 | 32.8 | Bowser |
| 2010 | 4.54 | 4540 | $1.74 | 34.3 | Jackson |
| 2011 | 12.26 | 17,252 | $1.96 | 35.7 | Bowser |
| 2012 | 3.18 | 4994 | $1.50 | 26.1 | Thomas/ Kwik-Krop mix |
| 2013 | 14.0 | 14,528 | $2.09 | 38.2 | Emma-K |
| 2014 | 9.99 | 9534 | $2.09 | 37.2 | Emma-K |
| 2015 | 4.54 | 11,350 | $1.80 | 31.7 | Kwik-Krop |
| 2016 | 9.53 | NA | NA | NA | NA |

Source: Hammons Products (unpublished data)

established to promote Hammons Products marketing and sales. Additional research, financial resources and market arrangements are still needed to promote the development of the industry as a whole.

### 3.2.4 Grower Engagement

Despite these challenges and current domination of the market by a single company, a handful of entrepreneurs have made various attempts to establish alternative processing and marketing infrastructure for planted black walnuts of improved grafted cultivars. UMCA has worked with these individuals and numerous new and prospective growers over the years to provide support to grow the industry and expand the adoption of black walnut based agroforestry. In addition to the black walnut grower's guide (Reid et al. 2009), UMCA has conducted grower outreach and training and developed a black walnut decision support tool (UMCA 2013). UMCA has provided up-to-date information and training to a number of walnut grower organizations including the Missouri Nutgrowers Association, the Northern Nutgrowers Association, and various chapters of the Walnut Council.

Difficulty in hulling, cracking, and sorting black walnuts and equipment requirements remain barriers for individual grower entrepreneurs. Regional cooperatives of growers sharing equipment, pooling resources, and aggregating production are likely the best approach. One example is the Heartland Nuts and More Cooperative, with approximately 50 member growers from Nebraska and bordering states. Production levels remain modest due to limited acreage of mature plantings, but are slowly increasing. Growers have observed that on good sites, cultivars that are well cared for can begin producing in year five or six. Nuts have averaged a minimum of 25% kernel with nutmeats and other value added products being marketed mostly through local channels (Coggeshall 2011a).

Success as an individual operator however, is possible. A grower in Cape Girardeau, Missouri grows, harvests and sells nut products from a 28.35 ha planting of trees derived from nuts from open-pollinated, first generation crosses of several improved cultivars. Ben's Black Walnuts, of Centreville Iowa, established in 1983 (until retiring in 2013 and transferring production and equipment to Heartland Nuts and More) was fully vertically integrated. Ben's Black Walnuts harvested nuts from 18 acres (7.3 ha) of grafted trees of improved cultivars, cracked, sorted, processed and sold all of their value added nut products under a brand name through local retail outlets. The proprietor being skilled in engineering and able to fabricate, adapt or re-purpose equipment to meet their processing needs, was likely an important factor in their success (Jensen 2014).

## 4 Fruits and Berries

Many fruit species, both native and non-native, are grown or harvested across the Midwest region. Just as blueberry and cranberry were once entirely wild harvested prior to their development into widely planted commercial crops, numerous other native fruits are excellent candidates to develop for entry into commercial markets and use in AFS. Among these, buffaloberry (*Shepherdia argentea* Pursh.), elderberry (*Sambucus* canadensis L.), serviceberry (*Amelanchier alnifolia* Hook.), red mulberry (*Morus rubra*), chokeberry (*Aronia melanocarpa* Michx.), wild grape (*Vitis riparia*), hawthorn (*Crataegus* spp.), highbush cranberry (*Viburnum trilobum* Marsh.), Paw Paw (*Asimina triloba*) and American persimmon (*Diospyrus virginiana*) are the best options (Josiah et al. 2004). Most of these have been gathered historically and were eaten fresh, dried, or turned into jams, wines, sauces, and a range of other products. Some are highly versatile and can be used for multiple purposes, as ornamentals, for fruit production, habitat enhancement for wildlife in a range of practices including riparian buffers, shelterbelts, food forests, as the main or secondary row tree species in an alley cropping design, or as a component in a multi-functional woody polyculture. The chokeberry, for example, is receiving renewed attention, is the subject of ongoing research efforts around the region, and has a growers association active since 2009 (Secher 2008; Brand 2010; MAA 2016). UMCA specialty fruit crop development efforts have focused on elderberry (*Sambucus* canadensis) and renewed future work is planned with pawpaw (*Asimina triloba*).

### *4.1 Elderberry*

The American elderberry (*Sambucus* canadensis) is a medium sized, fruit bearing shrub native to North America. It is widely distributed throughout the Midwest and grows commonly across a wide range of habitats. It is an excellent candidate species for inclusion in integrated, multi-tier riparian buffers, in food forests and other polycultures, or as the perennial component in an alley-cropping system. Unlike European elderberry (*Sambucus* nigra) for which there has been significant commercial development, the American elderberry until recently has remained considerably less well known and under-utilized (Byers et al. 2014). Since the mid-1990s, researchers at the UMCA and collaborators have pursued several areas of research: cultivar development and testing, horticultural trials, agronomic and production trials, post–harvest processing, medicinal property research, market and consumer research, and grower support and training. Some of the outputs of these efforts include a market survey and analysis (Cernusca and Gold 2015a), a growers' guide (Byers et al. 2014), an international symposium on elderberry (Thomas et al. 2014), several published journal articles and an Elderberry Financial Decision Support Tool (UMCA 2013).

### 4.1.1 Cultivar Development

New elderberry growers often propagate their own cuttings from wild plants or buy untested/unproven materials from whatever sources are available. Earlier in the twentieth century, elderberry cultivars were developed at the New York Agricultural Experiment Station (e.g. 'Adams I', 'Adams II', 'York') and at Agriculture and Agri-Food Canada in Nova Scotia (e.g. 'Johns', 'Nova') (Finn et al. 2008). But these initial efforts did not lead to the establishment and growth of a significant U.S. elderberry industry. More recently, with renewed interest and recognition of elderberry's potential, several initiatives were undertaken in the Midwest region to develop cultivars better suited to the region, including a research effort in collaboration with UMCA (Thomas et al. 2014). Several improved cultivars have emerged, including two new promising named cultivars ('Wyldewood' and 'Bob Gordon') introduced by researchers from the University of Missouri that have proven to be heavy producers and well suited for production in the Midwest region (Byers and Thomas 2011).

### 4.1.2 Production and Management

Elderberry thrives on or tolerates a range of soils and conditions but performs best on moist, well-drained sunny sites. It is commonly found along streams, and roadside ditches throughout the mid-west region. Moderately fertile soils with adequate drainage and pH5.5–6.5 are recommended. As elderberry flowers in June well after risk of frost and also tolerates cold temperatures after bud break, it is not critical to select sites with good air flow. Still, selecting sites that are somewhat elevated relative to surrounding terrain, can reduce risk of frost damage and contribute to optimal growth performance. For best fruit production, elderberry will benefit from full sun. Weed control during the establishment period is highly beneficial, as is a noncompetitive ground cover. There are various options for propagation, some highly effective and easy. Sprouted cuttings from dormant hardwood stems root easily and are probably the best and most cost efficient.

Many American elderberry cultivars also perform well if pruned completely to the ground in winter using mechanized equipment, such as a sickle-bar cutter rather than pruning one plant at a time by hand. This pruning strategy forces all flowers and fruit to be produced on similarly aged and similarly sized stems, rather than on both old and new stems at various times and positions on the bush. Further, pruning to the ground usually results in the production of fewer but larger fruiting cymes, a more uniform fruit ripening, and a narrowing of the harvest window; all of these factors may lead to greater efficiencies in the orchard and processing facilities. Pruning all stems to the ground in winter may also have the added benefit of removing over-wintering insect eggs, pests, and disease inoculum from the orchard if the pruned stems are collected and destroyed (Byers et al. 2014).

Until recently, elderberries have proven to be relatively pest free. There are a number of notable pests and diseases which can potentially cause problems, such as elderberry rust disease, Japanese beetles, and elder borer. Most of these have proven manageable and organic production remains very feasible (Byers et al. 2014). During the last few years, however, with the appearance of spotted winged drosophila (*Drosophila suzukii*), organic production has become more challenging (Pinero 2013). Birds can also become a major nuisance by feeding on ripe fruit and causing significant losses. Netting to prevent access, noisemakers or other scare tactics can be effective in reducing losses. Cultivars with pendulous cymes (inverted or hanging down), such as 'Bob Gordon', appear to be less attractive to birds as is it is more difficult for them to eat, which can contribute to crop protection (Byers et al. 2014).

### 4.1.3 Market Development and Analysis

Elderberry can be used for a very wide range of products. The majority of the elderberries grown in the Midwest are harvested for processing markets and the market for sale of fresh fruit is limited. Products include juice, wine, vinegar, jams and jellies, concentrates, and tinctures for dietary supplements and nutraceuticals.[5] The berries are also used in the preparation of pies, punch, and liqueurs. Elder flowers are used to make teas and alcoholic beverages, or added to batter for pancakes or baked goods. Elderberry is also increasingly being promoted and used as a medicinal plant, primarily for its antiviral properties and for use in prophylaxis and treatment of influenza (Zakay-Rones et al. 2004; Charlebois 2007; Roschek et al. 2009; Thomas et al. 2014).

Given the wide range of products and uses, market analysis has shown there are significant opportunities for expansion and that elderberry remains highly underutilized. The number of growers and volume of production remains small, but both are

[5] A nutraceutical is a pharmaceutical-grade and standardized nutrient.

increasing. A limiting factor for expansion of the industry has been the lack of research and literature about elderberry production and marketing in the U.S.A.

A recent market survey by Cernusca et al. filled in many information gaps on important market factors such as production volumes, prices and market trends and potential. An outdated 2001 survey of fruit production across 6 Midwestern states estimated annual elderberry production at 36,000 kg and the price paid for fruit averaging $1.65 per kg (Weeder-Einspahr 2001). Respondents to the UMCA survey (Cernusca et al.) indicated that demand for elderberry fruit is high (e.g. regional wineries seeking local supply). Fresh or frozen elderberries are sold through multiple outlets for many uses. Sale prices vary widely ranging from sales to wineries at $1.20/kg (with stems), sales in farmers' markets or online to individuals at $6–12/kg (de-stemmed), and sales to nutraceutical manufacturers for $24/kg.

Until recently, growers have had difficulty finding and planting improved cultivars. These kinds of challenges have impacts up and down the supply chain. With inadequate or unreliable supply of fruit from a limited number of growers, processors and entrepreneurs are less likely to invest and expand. Until recently, existing value added producers unable to either grow more of their own fruit or source local production have purchased imported elderberry concentrate from Europe.

The elderberry industry is still in its early stages of development, but the industry is growing rapidly over the past 5 years with continued expectations of growth and expansion. The potential (or perceived) health benefits of elderberry along with the wide range of uses and products are important factors in attracting customers and driving potential growth. Being a developing industry, it is populated by small number of entrepreneurial actors and innovators who are leaders in promoting and expanding the industry along with numerous smaller participants experimenting with production at various levels. Most producers invest significant energy into customer education and promotion, building consumer awareness and demand for elderberry products. This has been a very important area of cooperation between UMCA and various actors in the industry, working to create awareness and demand for elderberry products, creating a "pull" from consumers. A range of promotion and consumer education activities have taken place including promotion at public events, sampling, and demonstrations at farmers' markets, agricultural fairs, and in supermarkets.

Many producers operate on various stages of the value chain or are fully vertically integrated. Typical producers might propagate their own plants, grow and harvest elderberry, and process and produce one or more value added products, instead of focusing only on one product or service. A significant challenge for these new growers and entrepreneurs is the lack of improved harvesting equipment (currently harvesting is labor intensive and done largely by hand) and appropriately scaled processing equipment (de-stemmers) for elderberry. Considering the investments required, those diversifying from other products or industries may benefit from leveraging existing capacity and resources (Byers et al. 2014). Another barrier is the difficulty in securing financing. This is often the case with new industries or specialty crops where information is limited, presenting challenges for new grower entry and industry expansion. The development and continual refinement of the Elderberry Financial Decision Support Tool is helpful in this regard. New and prospective growers can model what costs and revenues might look like according to certain production decisions and also produce an enterprise budget and cash flow analysis, ready to print out and include with any funding/loan application (Godsey 2012).

One important observation from the market research on elderberry, given that it is still a nascent industry with little risk of substitutes and its infrastructure is still developing, is that actual competition was found to be low or non-existent. New producers and enterprises can enter the market and establish themselves through differentiation with new products, features or innovations. Figure 14.3, below, is a graphic representation of the findings produced from the application of the Porter Five Forces Model used as an analytical tool for understanding the dynamics of the elderberry Market.

### 4.1.4 Grower Outreach and Engagement

In addition to extensive outreach and education activities over several years, UMCA researchers worked in close coordination with a few pioneering entrepreneurs who were willing to take the risks and were motivated to put in the time and effort needed to jump-start and nurture an elderberry industry. UMCA interaction with industry actors/entrepreneurs has contributed to a growing knowledge base for production, best practices and on developing appropriate equipment for harvest, post-harvest, storage and processing, that has helped foster growth of the industry.

One of these entrepreneurs, River Hills Harvest, has since taken the lead in the establishment of a growers group and marketing mechanism. The entity continues to actively seek new growers, provides support and training and guarantees purchase of production. They also host an annual growers meeting and conference that attracts both local growers and participants from around the country. The number of Elderberry growers across the country is increasing. Newly formed cooperatives and research programs are also now active in Minnesota and the Northeast (Patton 2016; Wilson 2016).

## 5 Other Potential Specialty Crops

Several other types of specialty crops can be considered for AFS, including medicinal, floral, and decorative plants as well as forest farmed mushrooms and other edibles. A number of these, which have been the focus of various research and development efforts by UMCA, are given brief treatment in the following sections.

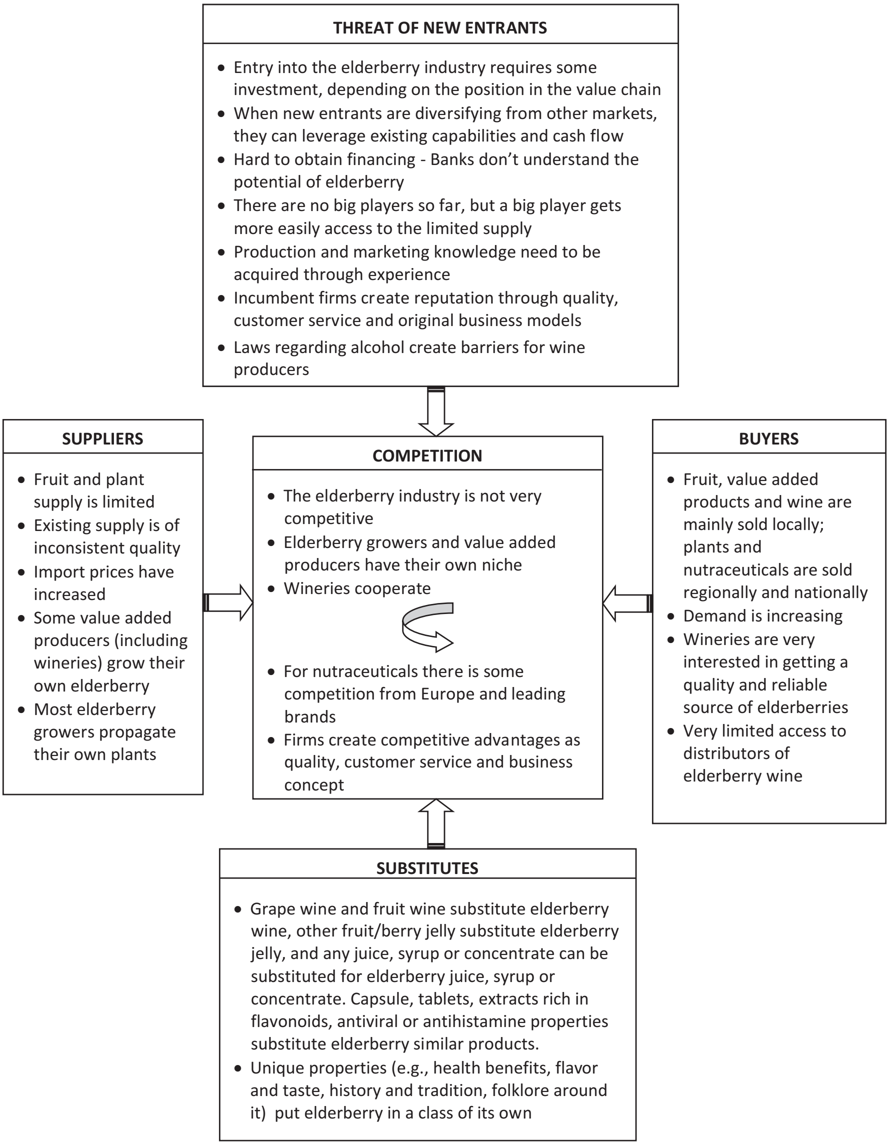


**Fig. 14.3** Representation of the influence of the Five Forces (Porter 1980) on the elderberry market as resulted from the market research study

## 5.1 *Decorative and Floral Products*

Numerous native woody decorative and floral species are good candidates for growing in conservation plantings, riparian buffers, and windbreaks, or as the main perennial species in an alley cropping practice (Josiah et al. 2004). The distinctive shape or color of species such as redosier dogwood (*Cornus sericea*), curly willow (*Salix matsudana* Koitz.) or pussy willow (*Salix caprea* L.), the flowering branches of forsythia (*Forsythia* spp.), and many fruit species make them highly attractive for use in decorative arrangements. For some of these there are established markets, both local and national for which prospective growers in the Midwest could attempt to compete (Trozzo et al. 2014). Wholesale prices for stems of 0.8–1.7 m length usually command wholesale prices in the US$0.50–$2.00 range. Field trials of pussy willow in a riparian buffer in Indiana (Miller et al. 1994) and ten woody floral species in alley cropping arrangements in Nebraska (Josiah et al. 2004) demonstrated marketable production within two growing seasons, with the most productive species providing gross incomes of nearly $15.60/m when planted on a 1.62 m in-row spacing. Actual profitability would vary widely depending on factors like row spacing, crop combinations, density, and level of management when integrating woody florals into an alley cropping, buffer or windbreak practice.

Many other types of decorative woody products are produced or harvested from wild trees around the region, some of these also have potential to be grown in conservation plantings and AFS. Throughout the northern Great Lakes region the bark of paper birch (*Betula papyrifera*) is a traditional material used to construct baskets, decorations, shelters, and canoes. Black ash (*Fraxinus nigra*) is used in basket making and is highly prized by Native American and other artisans (Diamond and Emery 2011). Boughs of balsam fir (*Abies balsamea*), northern white cedar (*Thuja occidentalis*), and other conifer tree species are used to make wreaths, an industry with an estimated value greater than $75 million for the northern great lakes region in 2010 (Handler et al. 2012). Other woody species are used for handicrafts, specialty wood products like burls or for landscaping mulches.

UMCA research has focused on potential markets for pine straw and eastern redcedar (*Juniperus virginiana*). In addition, previous research evaluated the suitability of eleven fern species for growth in agroforestry and their potential in the floral green or landscaping fern markets. Most fern species performed best under 80% shade levels, and none produced quality fronds under full sun. The native Christmas fern (*Polystichium acrostichoides*) stood out as having significant market potential and suitability for agroforestry (Kluthe 2006).

#### 5.1.1 Pine Straw

Pine straw is a natural product obtained from certain long, stiff-needled pine species, most notably the southern longleaf (*Pinus palustris*) and loblolly pine (*Pinus taeda*). Since the 1980's it has been increasingly used as a mulch in landscaping and horticulture, especially in the southeastern U.S.A., and is a sought after alternative to wood chips. Fallen needles are raked and baled for sale in a manner similar to straw. Pine straw production is well suited for integration in silvopasture and alley cropping systems. Design often consists of 3–4 tree rows with an in-row spacing of usually 3 m and alley ways of 15–27 m depending on the application. The first harvest usually occurs after about year seven. Pine straw is currently harvested from available loblolly selections in southern and central Missouri, but lack of cold tolerance of the main pine straw species limit their adoption in areas further north (Wallace and Ward 2011). In 1996, UMCA planted test plots to a pitch pine (*Pinus rigida*) × loblolly pine hybrid that has proven to be both cold hardy and producing needles of suitable length for pine straw. Ongoing work continues to assess the viability and production potential of this hybrid for the Midwest market. Commercial sale of Missouri pine straw is in its early stages but demand is strong.[6]

### 5.1.2 Eastern Redcedar

Eastern redcedar (*Juniperus virginiana*) is native to the forests of the eastern and central United States. Missouri is among the states with the highest stocking rates, which are projected to rapidly increase (Gold et al. 2005). The species tolerates extremes of drought, heat, cold, thrives on thin limestone soils, and successfully colonizes marginal land such as abused or abandoned pasture sites (Lawson 1985) as well as agricultural lands retired under conservation programs. As such, it is often regarded as an invasive or nuisance species which many land managers actively seek to eliminate, and numerous incentive and cost share programs have been created to provide support to landowners for eastern redcedar removal (USDA NRCS 2016).

At the same time, substantial markets exist for a very wide range of products from eastern redcedar – lumber, fence posts, cants[7] for use in cedar chests, wardrobes, and closets. Aromatic oils are distilled from the heartwood and woodchips and wood shavings are used for mulches and animal bedding (Gold and McKinley 2010). Its branches are used as a green floral in wreaths and boughs. It is highly rot resistant and effective as an insect repellent (Meissner and Silverman 2001). In the Midwest, eastern redcedar is useful for conservation plantings, enhancement of wildlife habitat and can be very effective in shelterbelt and windbreak plantings. It is fast growing and can produce timber and provide marketable returns much sooner than other species.

While the actual market size of eastern redcedar nationwide likely exceeds $60 million per year, it is considered an "obscure" industry with market forces largely "hidden" and not well understood by the different actors engaged in buying and selling eastern redcedar products (Gold et al. 2005; Gold and McKinley 2010). UMCA researchers initiated a comprehensive market study to better understand, document and develop the market for this economically viable species. One key problem identified was that there was very little bargaining power on the supply side. In many areas where market potential exists, the industry is undercapitalized and not taking advantage of opportunities for locally creating and selling value added products (Gold et al. 2005; Gold and McKinley 2010). Concerns over the potential invasiveness of eastern redcedar could be overcome with development of

- 6 http://mopinestraw.com, http://www.centerforagroforestry.org/profit/pine/pine.php.

7 A cant is a piece of wood usually over 5 cm thick and sawn on at least three sides.

"non-invasive" male cultivars. Many other market opportunities exist and can be further developed, from use in water filters and bio-reactors, to extraction of useful compounds. Parallel to this market research, a sustained effort was also undertaken over more than a decade to identify, isolate and commercially develop potentially useful compounds from eastern redcedar (Lin et al. 2009), most notably an anti-microbial agent effective in controlling the deadly MRSA bacteria (Hsieh et al. 2016).

### *5.2 Medicinal Plants*

Among non-timber forest product (NTFPs) harvested throughout the Midwest, medicinal plants such as black cohosh (*Actaea racemosa* L.), goldenseal (*Hydrastis canadensis* L.), and American ginseng (*Panax quinquefolius*) are perhaps the most lucrative. Numerous threats including overharvesting, loss of habitat, and the potential impacts of climate change threaten the long-term sustainability of some of these NTFPs traditions (Handler et al. 2012). Managed cultivation of native woodland medicinal plants and selection and domestication into specialty crops integrated into AFS is an approach that can yield multiple potential benefits (both environmental and socio-economic). Forest farming of wild-harvested native medicinal plants has been increasingly proposed as both a conservation strategy and as a way to strengthen markets (Vaughan et al. 2013). The intentional cultivation of some vulnerable NTFPs may reduce pressure on native populations (Burkhart 2011) while potentially reintroducing species in areas where they have been extirpated (Boothroyd-Roberts et al. 2013). Forest farming near canopy gaps or in other agroforestry practices may be more effective than growing in more dense shade for some medicinal plants (Gillespie et al. 2006) which, while shade tolerant, can also make use of full sun (Vasseur and Gagnon 1994).

Ongoing efforts throughout the Ohio River valley and the Mid-Atlantic States of the U.S.A. to transform markets and promote conservation through sustainable forest grown cultivation are focusing on:

– Development and promotion of a "Forest Grown Verification Program" for certification of sustainable practices for (PCO 2016)
– Training, technical, business development and marketing support for beginning forest farmers (Appalachian Beginner Farmer Network 2016)
– Advocacy and education with producers and suppliers throughout the value chain to promote sustainable sourcing (United Plant Savers 2016)

With the notable exception of wild harvested or wild simulated ginseng (for which there is a well-developed and highly specific Asian export market that values certain physical characteristics), for most native forest medicinal plants there is a lack of market maturity, incentives, and extension resources to support and promote managed cultivation. Growing black cohosh and ginseng are long term undertakings with significant input costs. Except for ginseng and goldenseal, the economics may not yet be sufficiently attractive for more widespread adoption of forest farming of other medicinal plants as long as wild supplies remain available and prices relatively low (Burkhart 2011).

American Ginseng, goldenseal and black cohosh are known to be cultivated by growers in forest farming practices throughout the Midwest, with particularly successful examples in the Ozarks of Missouri. Previous UMCA supported research investigated production aspects of black cohosh, confirming its suitability for cultivating in either a forest farming practice or between tightly spaced rows of trees in buffers, windbreaks or alley cropping designs (Abad et al. 2005; Thomas et al. 2006). Ongoing research at the Center for Agroforestry focuses on the impact of different forest stand management approaches (varying canopy gaps, shade levels and burn treatments) on production of several native woodland medicinal plants – goldenseal, black cohosh, stone-root, with potential for expanded markets (Johnson and Jose 2016 – unpublished). Another common medicinal plant with established markets is slippery elm (*Ulmus rubra* Muhl.*)*, a medium sized tree and habitat generalist occurring throughout the Midwest. It is widely harvested for its mucilaginous inner bark and used as healing salves for wounds, and skin inflammation or taken orally to relieve coughs and sore throats. However, it is increasingly under threat due to overharvesting and susceptibility to disease (Burkhart 2016). A few entrepreneurial pioneers in Missouri have begun managed cultivation of slippery elm in AFS in combination with other medicinal plants (Botanical Plantations 2016).

## *5.3 Mushrooms and Other Forest Edibles*

Studies of woodlot management in the Midwest indicate that active management of such woodlands can significantly increase productivity and biodiversity (Moser et al. 2009), but the majority of private woodlands in the region are not actively managed. Of the 6 million hectares of privately owned forest in Missouri, less than 10% are managed (USFS NWOS 2015). Promotion of NTFPs in non-industrial private forests provides incentives for landowners to manage their forests as healthy ecosystems. Well managed forests can be more profitable and more resilient to potential impacts of climate change. Managing for understory plants may help to reduce risk of wildfires and regular long term silvicultural management for timber can be tailored to support additional goals such as maple syrup production or cultivation of medicinal plants. Small diameter and low value trees removed for timber stand improvement, particularly in oak-hickory forests, can be used for the cultivation of mushrooms.

In 1999, UMCA began a research program investigating best practices for growing shiitake (*Lentinula edodes*) and other forest farmed mushrooms, some of which have nutritional and medicinal benefits. The cultivation of log-grown shiitake mushrooms encourages forest farming and can be an opportunity for farmers interested in developing an additional enterprise. A comprehensive shiitake grower's guide was produced and outreach and growers' workshop offered to prospective growers

**Fig. 14.4** Nameko mushrooms fruiting on a raft of half buried black cherry (*Prunus serotina*) logs which were inoculated in spring of 2015 at the Horticulture and Agroforestry Research Center (HARC) in New Franklin, MO and had excellent flushes of mushrooms in both the fall of 2015 and 2016. Photo: Joe Krawczyk, Field and Forest products

(Bruhn and Hall 2008; Bruhn and Mihail 2009). A nationwide survey of shiitake mushroom producers was conducted to analyze the U.S. shiitake mushroom industry by taking into consideration the forces that influence competition based on Porter's five forces model. Forest farmed shiitake mushrooms are grown primarily as a side business and sold locally. Trends in demand are increasing and prices are high. Barriers to success in the shiitake mushroom business include demanding work requirements, the need for a serious commitment to produce and market shiitake mushrooms, a 1-year time lag between investment and a return on investment, and insufficient production and marketing information (Gold et al. 2008).

Sustained research efforts with native morel (*Morchella esculenta*) and exotic burgundy truffle (*Tuber uncinatum*) by UMCA over several years have not yet led to results that would merit releasing grower recommendations or promoting them as viable species for cultivation in AFS in the region (Mihail et al. 2007; Bruhn and Hall 2011). A number of other mushrooms currently under trial at UMCA show potential as an agroforestry specialty crop, among these native oyster (*Pleurotus* spp.), hen of the woods/maitake (*Grifola frondosa*), combs tooth/lion's mane (*Hericium* spp.) mushrooms, exotic reishi (*Ganoderma lucidum*), and nameko mushroom (*Pholiota microspora*) (Fig. 14.4). Ongoing research at Cornell University is also evaluating the production and market potential of several of these species (Cornell 2016). To date, UMCA trials have demonstrated that most of these can be successfully grown in the region. However, as they are virtually unknown and have little or no existing market presence, major challenges remain to conduct the outreach, promotion and consumer education to stimulate the "pull" of customer demand and cultivate sufficient producer interest to grow markets and nurture an industry for any of these as new specialty crops for agroforestry.

## 6 Conclusions

In this chapter, citing research and outreach from the work of UMCA and many others, the authors have provided an overview highlighting the importance and potential contribution of specialty crops for agroforestry. Expanding access to well researched perennial specialty crops and expanding markets for their products can contribute to more widespread adoption of a range of agroforestry practices and ultimately to the long-term economic and environmental sustainability of farming systems throughout the Midwest and beyond. UMCA research and development efforts have followed a strategic approach focusing on several key areas of development and testing of improved cultivars, developing viable markets, and promoting and supporting producers.

Numerous challenges for the development of emerging specialty crops have been identified and are being addressed. In the early stages, some priming is often required to promote interest, stimulate demand, and catalyze the innovation that can fuel the growth of a specialty crop industry. Access to improved cultivars, solid production guidelines, reliable product supply, growing consumer demand, and sound financial decision support tools are assisting the growth of the specialty crop industry and having positive impacts up and down the supply chain. With adequate and reliable supply from growers, processors and entrepreneurs are more likely to invest and expand. In turn, existing and potential growers are more likely to expand production if there are active processors and clear consumer demand – a "market-pull" based strategy for increased production, supply, and demand.

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# Part III
# Environmental Services in Multifunctional Landscapes

# Chapter 15
# Trees on Farms for Livelihoods, Conservation of Biodiversity and Carbon Storage: Evidence from Nicaragua on This "Invisible" Resource

**Eduardo Somarriba, Geovana Carreño-Rocabado, Freddy Amores, Willan Caicedo, Samuel Oblitas Gillés de Pélichy, Rolando Cerda, and Jenny C. Ordóñez**

## 1 Introduction

More than 2 billion people are reliant on smallholder agriculture throughout the tropics, representing 83% of the world's agricultural population, many of whom are also among the world's poorest (Lowder et al. 2014). Climate change is currently affecting agriculture and food security and is putting millions of people at risk of hunger and poverty in different regions of the world (FAO 2016). For example, assessments carried on the coffee sector in Mexico, Brazil and Nicaragua predict that impacts associated with climate change will be even more severe than those from the drop in coffee prices. For instance, Laderach et al. (2011) estimate a reduction in land suitable for coffee production in Nicaragua between 20 to 60% by 2050 as rising temperatures will force the abandonment of low-altitude cultivation areas. Expansion of coffee cultivation into higher altitudes will put additional pressure on the conservation of important protected areas and headwaters of major river systems. The livestock sector will also suffer from a reduction in the productivity and quality of pastures and an increase in parasites and diseases which can both be attributed to climate change (FAO 2016).

Agroforestry systems, and in general, trees on farms (TonF), and trees outside the forest (De Foresta et al. 2013) can be a good alternative for achieving sustainable and climate-smart agriculture. Decisions on the management of tree cover in

E. Somarriba (✉) · F. Amores · S. Oblitas Gillés de Pélichy · R. Cerda
Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), Turrialba, Costa Rica
e-mail: esomarri@catie.ac.cr

G. Carreño-Rocabado · W. Caicedo · J. C. Ordóñez
Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), Turrialba, Costa Rica

World Agroforestry Centre – ICRAF, Turrialba, Costa Rica



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the farm are usually made at the household level, but most scientific and technical agroforestry literature focuses on the agroecosystem level. Noteworthy examples include food crops, shaded coffee and cocoa, home gardens, swidden agriculture, and silvopastoral systems (Somarriba et al. 2013; Vaast and Somarriba 2014). More research is needed on the extent and management of TonF at the household level. Observation at this scale is necessary because: the household is the final beneficiary and evaluator of success or failure of the farming operation; it is the link between markets and the governance of the territory/watershed; and it is also the link between plot-level interventions (for instance, changes in tree cover in crop fields and pastures) and impacts at the landscape level, for instance, in biological connectivity and regulation of the hydrological cycle (DeClerck et al. 2010).

Trees on farms are widespread all over the world, but are generally not included in regular inventories of tree and forest resources (Perry et al. 2009; Sloan and Sayer 2015). In Central America, for instance, 54% of agricultural land has up to 30% of tree cover (Zomer et al. 2009, 2014). TonF are the result of three processes: (1) retention of residual trees from the natural forest; (Harvey and Haber 1999), (2) selection (and protection) of valuable trees from natural regeneration (Somarriba 2012; Pinoargote et al. 2016) and (3) active planting of selected species at specific locations on the farm (Somarriba and Beer 2011; Somarriba et al. 2016). Trees can be dispersed or in lines (Chacón and Harvey 2008), in patches or in regular plantation arrangements, solitary or in groups, with variable or regular density. They are present in pastures, in agricultural fields, in linear plantings (boundaries, internal divisions, on both sides of roads and water courses, in windbreaks), and in patches of forest. Tree-crop interaction may occur simultaneously, as with shade trees in a coffee plantation, or sequentially, as in the numerous fallow systems around the world (Cairns 2007).

TonF offer farmers a regular flow of valuable goods (Cerda et al. 2014), provide soil cover and help to maintain soil fertility and crop productivity, diversify the production of goods (timber, fruits, etc.) and reduce the financial risk of the household, reduce vulnerability to contingencies (Chambers and Leach 1989; Ramirez et al. 2001), store carbon in wood, and provide other cultural and aesthetic benefits (Kuyah et al. 2016b). At the landscape level, TonF increase biological connectivity (Chacón and Harvey 2008; Harvey et al. 2008) and help to regulate the hydrological cycle. Approximately two-thirds of wood fuel in developing regions comes from TonF (Smeets and Faaij 2007). TonF contribute to the supply of timber, and may reduce deforestation (Iiyama et al. 2014). TonF are also an asset, a savings account that increases farm value and that can be drawn upon to cope with unexpected needs (Chambers and Leach 1989). Farmers actively use and manage their TonF (Amores 2016; Pinoargote et al. 2016; Somarriba et al. 2014, 2016), and have considerable knowledge on tree management (Haglund et al. 2011; Cerdán et al. 2012). However, many studies also point out the ample room for improvement, especially in the proper use of basic silviculture and tree husbandry to increase yield, quality and value of tree products (Jiménez 2012; de Sousa et al. 2016). TonF are important in land sparing strategies to avoid the loss of natural forests (Quandt 2016).

Despite all these benefits, TonF are still invisible to land use planners, decision makers, governments, and extension staff providing technical assistance to farmers. In this chapter we demonstrate, with quantitative data, the presence and contributions of TonF to farmers' livelihoods (tree production and its value), conservation of tree biodiversity (species richness and abundance), and carbon storage in aboveground tree biomass in 90 farms covering 781 ha and five major land uses in two municipalities of North-Eastern Nicaragua. Our study assessed the (1) botanical composition, species richness, abundance and size distribution of TonF at both the farm and land use level, (2) contribution of TonF to family livelihoods, conservation of tree biodiversity and carbon storage, and (3) how different combinations of land use, tree cover and diversity, and crop and tree production and value result in different farm typologies. The study area is part of the Nicaragua-Honduras "Sentinel Landscape", a long term observatory of the impact of land use intensification and other drivers affecting the presence of trees and forests on farms and in the landscape (http://www.cifor.org/sentinel-landscapes).

## 2 Study Sites and Methodology

### *2.1 Location and Sampling*

We studied TonF in two rural municipalities in Nicaragua: El Tuma-La Dalia (TLD) and Waslala (13.08° – 13.20° N, 85.22° – 85.44° W), both located between 400–720 m altitude, and with 2200–2500 mm year$^{-1}$ rainfall respectively (PDTW 2014; Dávila et al. 2017). Soils are classified as alfisols and ultisols with a clay-loam texture, pH between 5.8 and 6.2, and medium to high fertility (Leguía et al. 2014; Ayestas 2013). Population density in TLD (96 inhabitants km$^{-2}$) is more than double that in Waslala (37 inhabitants km$^{-2}$); food for family consumption is produced in the farm in Waslala and bought in TDL (Leguía et al. 2014). Pastures, field crops for the production of rice-maize-beans (generically referred to as "basic grains"), and home gardens are present in most farms in both municipalities, whereas shaded coffee is prevalent in TLD and cocoa plantations in Waslala.

We inventoried trees in 90 farms, including 781 ha of cultivated area. Trees present in five major land uses were fully censused: (1) pastures with native and introduced grass species, (2) shaded coffee plantations, (3) shaded cocoa plantations, (4) crop fields planted to basic grains and (5) home gardens. Trees were not censused in forests patches, fallow fields, and small plots of minor crops, however the surface area of these land uses was measured. In this chapter, the term "farm area" refers to cultivated farm area; the terms "total farm area or whole farm area" refer to the summation of the cultivated areas plus forests (fallows, old secondary forests, riparian, and mature forests) and other farm areas such as swamps, gorges, minor crops, etc. Total farm area measured in this study amounted to 952 ha. All land use areas were calculated based on a detailed map of each farm (perimeter, all internal divisions and fields) elaborated in close cooperation with the farmer using GPS and ArcGIS 10.1.

## 2.2 Field Measurements and Calculations

All trees were identified to the species level, and they were sorted according to uses (timber, fruit, firewood, services) and dbh (diameter at breast height, 1.3 m above the ground). Height was measured for all trees with dbh ≥ 10 cm or dbh ≥ 5 cm for fruit trees. Additionally trees were sampled for the estimation of aboveground carbon using transects of 2000 $m^2$. Carbon stored in aboveground tree biomass was estimated using dbh measurements and species-specific allometric equations for 61% of tree species found in the farms; a generic allometric equation was used for the remaining tree species (details on Caicedo 2016).

Detailed interviews with farmers provided information on crop and tree management practices, yields, costs, and prices of tree products in local markets. Standing timber volume was estimated using dbh, commercial tree height, and a commercial form factor of 0.6 (Amores 2016). Timber harvest volume was assessed by counting all tree stumps in the farm, dating the year of harvest (with the aid of the farmer), and measuring the diameter of the stump. Further methodological details are provided elsewhere (Amores 2016; Caicedo 2016; Oblitas 2016).

We assessed the contribution of tree products to both farm income and self-consumption in terms of gross income (GI), net income (NI), net cash flow (CF), value of domestic consumption (VDC), and family benefit (FB), which represents the total benefits considering sales and on-farm consumption (Imbach 1987; Cerda et al. 2014). Financial indicators are given in United States of America dollars (USD).

## 2.3 Analytical Methods

Tree diversity was evaluated in term of species richness, abundance and botanical composition, using pooled data from both municipalities. Species richness in 1 ha of farm area was estimated based on a subset of 53 plots with sampling transects covering exactly 1 ha (Amores 2016; Caicedo 2016; Oblitas 2016). Similarity between land uses in terms of tree species, botanical composition and abundance was evaluated with analysis of variance using Bray-Curtis distance matrices and non-multidimensional scaling ordination. All analyses were performed using the R packages Vegan and DiversityR. The taxonomic similarity between farms was also evaluated with the Morisita-Horn similarity index (Magurran and McGill 2011).

Comparisons between land uses in terms of tree population density, stand basal area, carbon stocks, agroforestry production, and financial indicators were carried out using generalized and mixed linear models using farm as random effect. Means were compared using Fisher's LSD test at $p = 0.05$. Statistical analyses were performed using Infostat (Di Rienzo et al. 2011). Additional methodological details are presented in Amores (2016), Caicedo (2016) and Oblitas (2016).

Given that crop and tree outputs (agroforestry and financial) at the farm level depend on the particular combination of land uses, area by land use, and management intensity level, farming system typologies were developed using 37 farm-level indicators that spanned (1) farm size and distribution of land uses in the farm; (2) agricultural productivity; (3) financial productivity; (4) tree abundance and tree products; and (5) tree carbon (C) stocks, and species diversity. Farm typologies were developed using a hierarchical clustering analysis with Ward's method and Bray-Curtis distances. All variables, with the exception of proportions, were skewed and therefore transformed using $\log_{10}$. All variables were standardized before clustering.

# 3 Results

## 3.1 Farms and Land Uses

The farms were small, averaging 10.57 ha, with pastures accounting for 53% of total area, followed by forest patches and basic grains (13% each); if fallows are included as part of the cropping cycle of basic grains, the area dedicated to the production of grains increases to 16.5% of total area (Table 15.1). This study included farms up to 100 ha in total farm area, but most farms were less than 13 ha (Fig. 15.1). The particular combination of land uses is apparently affected by farm size. For instance, home gardens are significant for farms up to 25 ha in size and basic grains represent a significant portion of cultivated farmland for farms of up to 30 ha but especially so for farms with fewer than 15 ha of total cultivated area. The fraction of cultivated farmland under pastures increased with farm size (Fig. 15.2).

**Table 15.1** Number of farms inventoried with a given land use, area inventoried by land use, percent (%) over total area inventoried, and average area by land use (Mean ± standard deviation)

| Land uses | N | Area (ha) | % | Mean ± sd |
|---|---|---|---|---|
| Pastures | 60 | 508.0 | 53.39 | 8.47 ± 13.0.4 |
| Forests[a] | 44 | 125.7 | 13.21 | 2.86 ± 5.0.2 |
| Basic grains | 63 | 123.2 | 12.95 | 1.96 ± 2.1 |
| Coffee | 41 | 73.3 | 7.70 | 1.79 ± 1.7 |
| Cacao | 31 | 59.3 | 5.92 | 1.91 ± 2.4 |
| Fallows[a] | 40 | 33.6 | 3.53 | 0.84 ± 1.1 |
| Homegardens | 85 | 16.5 | 1.73 | 0.19 ± 0.2 |
| Other crops[a] | 34 | 11.8 | 1.24 | 0.35 ± 0.3 |
| Total farm | 90 | 951.38 | 100 | 10.57 ± 12.9 |

[a]Trees were not inventoried in these land uses. Basic grains included maize (*Zea mays*), beans (*Phaseolus vulgaris*) and rice (*Oryza sativa*). Other crops included: bananas, cassava (*Manihot esculenta*), various vegetables, annato (*Bixa orellana*), taro (*Colocasia esculenta*), sugar cane (*Saccharum officinarum*), and small fruit orchards (*Citrus lemon*, *Citrus sinensis*, *Citrus maxima*).

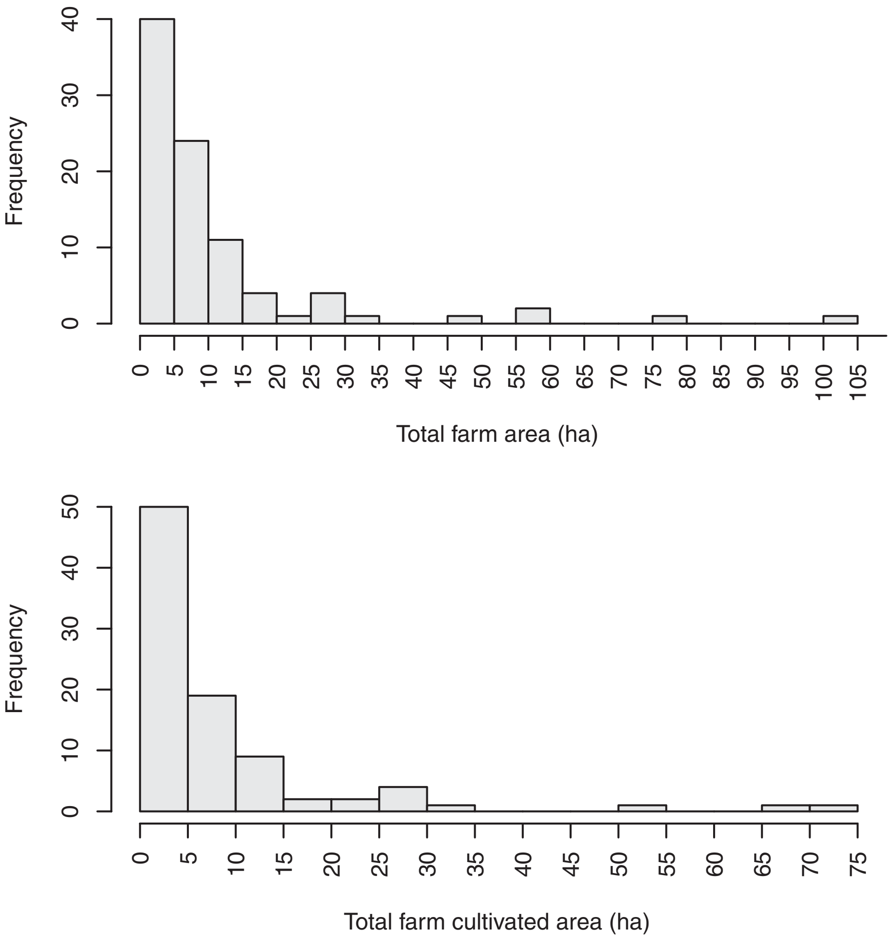


**Fig. 15.1** Relative frequency distribution of farm size: total area and cultivated area (pastures, coffee, cocoa, basic grains, homegardens). Data from 90 farms in the municipalities of Tuma – La Dalia and Waslala, Nicaragua, year 2015

## *3.2 Trees by Farm: Stocking, Agroforestry Production, Financial Indicators and Species Richness*

We identified and measured a total of 32,195 trees belonging to 264 species. An average farm (considering all sizes and land uses) had 8.7 ha of cultivated land, containing 74 trees $ha^{-1}$, with a basal area of 3.7 $m^2$ $ha^{-1}$. Biomass carbon stock was roughly 167 Mg C $farm^{-1}$ in aboveground tree biomass, 5.5 Mg $ha^{-1}$ in firewood biomass and 7.8 $m^3$ $ha^{-1}$ in standing timber. On average, farmers harvested 0.72

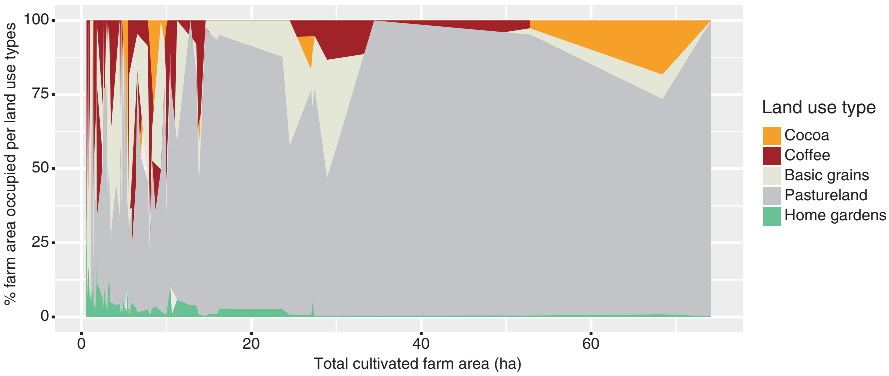


**Fig. 15.2** Land use area by farm size in the municipalities of Tuma – La Dalia and Waslala. Nicaragua

trees ha$^{-1}$ year$^{-1}$, consumed 1 Mg year$^{-1}$ of firewood per family, sold 1% of total fruit produced but lost of up to 74% of total fruit production (Table 15.2).

About 36% of tree species produced timber; 29%, firewood; 17%, fruit; 14%, services (e.g., shade or restoration of soil fertility); and 4%, posts and other products. Of the species, 75–78 were identified as timber species (the most important being *Cordia alliodora, Cedrela odorata* and *Platymiscium dimorphandrum*), 36–38 as fruit species (those most frequently consumed: *Mangifera indica*, *Persea americana*, *Citrus sinensis*, *Citrus reticulata* and *Bactris gasipaes*). The most important firewood tree species were *Guazuma ulmifolia, Senna siamea, Lonchocarpus minimiflorus, Inga oerstediana, Spathodea campanulata* and *Morinda panamensis* (Amores 2016).

Trees on farm generated a family benefit of USD 544 ha$^{-1}$ year$^{-1}$, of which, 86%, or USD 469 ha$^{-1}$ year$^{-1}$ represents on-farm consumption. The farms have some USD 6000 ha$^{-1}$ of standing timber and USD 850 ha$^{-1}$ of firewood. On average, by farm, fruits contribute 34% of the family benefit; firewood, 29%; timber, 28%; and posts, 9%. Farmers harvest on average one timber tree per hectare per year. Fruit trees provide a steady monthly supply of fruits for family consumption and sale all year round, helping to mitigate family food needs (Fig. 15.3). Unfortunately, farmers lose 65–82% of the fruit produced on the farm (Table 15.2). Species accumulation curves based on sampled area indicates that, at the landscape level, 76% of total species richness is recorded once 200 ha of farmland have been sampled (Fig. 15.4a, b).

**Table 15.2** Trees on farms: stocking (population density, basal area, and carbon in aboveground biomass), agroforestry production and financial indicators

| Variable | Mean ± sd |
|---|---|
| **Population density and carbon stock** | |
| Cultivated farm area (ha) | 8.7 ± 12.9 |
| Population density (trees $ha^{-1}$) | 74 ± 54 |
| Basal area ($m^2$ $ha^{-1}$) | 3.7 ± 2.5 |
| Total C stocks dispersed trees (Mg C $farm^{-1}$) | 111 ± 156 |
| C stocks dispersed trees (Mg C $ha^{-1}$) | 14.2 ± 9.8 |
| Total longitude of tree lines (m lines $farm^{-1}$) | 1123 ± 1176 |
| Longitude of tree lines (m lines $ha^{-1}$) | 190 ± 153 |
| Total C stocks trees in lines (Mg C $farm^{-1}$) | 55.6 ± 68.8 |
| **Agroforestry production** | |
| VMP ($m^3$ $ha^{-1}$) | 7.8 ± 7.2 |
| Firewood (Mg $ha^{-1}$) | 5.5 ± 4.0 |
| Oranges (Units $ha^{-1}$ $year^{-1}$) | 3052 ± 7040 |
| Various fruits (Units $ha^{-1}$ $year^{-1}$) | 2806 ± 4263 |
| Various fruits (kg $ha^{-1}$ $year^{-1}$) | 234 ± 549 |
| Timber harvest (trees $ha^{-1}$ $year^{-1}$) | 0.72 |
| Firewood family consumption (Mg $year^{-1}$) | 2.6 ± 0.3 |
| Fruit production consumed (%) | 25 |
| Fruit production sold (%) | 1 |
| Fruit production lost (%) | 74 |
| **Financial indicators (US dollars)** | |
| CC (USD $ha^{-1}$ $year^{-1}$) | 20.2 ± 31.8 |
| KC (USD $ha^{-1}$ $year^{-1}$) | 19.1 ± 24.8 |
| GI (USD $ha^{-1}$ $year^{-1}$) | 42.3 ± 50.8 |
| CF (USD $ha^{-1}$ $year^{-1}$) | 0.3 ± 40.6 |
| NI (USD $ha^{-1}$ $year^{-1}$) | −18.4 ± 41.5 |
| VCD (USD $ha^{-1}$ $year^{-1}$) | 199.9 ± 203.2 |
| FB (USD $ha^{-1}$ $year^{-1}$) | 200.2 ± 203.6 |
| ValMP (USD $ha^{-1}$) | 1415 ± 966 |
| VLP (USD $ha^{-1}$) | 381.9 ± 283 |

Pooled data from municipalities Tuma-La Dalia and Waslala, Nicaragua. Inventory 90 farms in year 2015, total surveyed cultivated farm area 871 ha. Data on C stocks are medians; remaining variables mean ± standard deviation

Various fruits measured in Units $ha^{-1}$ $year^{-1}$ = aguacate (*Persea americana*), mango (*Mangifera indica*), coco (*Cocus nucifera*), pera de agua (*Syzygium malaccense*), guayaba (*Psidium guajava*), sonzapote (*Licania platypus*), melocotón (*Averrhoa carambola*), guanábana (*Annona muricata*). Other fruits measured in kg $ha^{-1}$ $year^{-1}$ = pejibaye (*Bactris gasipaes*), nancite (*Byrsonima crassifolia*) and jocote (*Spondias purpurea*)

*CC* cost in cash, *KC* cost in kind (mostly family labor, but also some inputs and materials obtained from the farm), *GI* gross income, *CF* net cash flow, *NI* net income, *VCD* money value of domestic consumption, *FB* family benefit, *VMP* standing timber volume, *ValMP* value of standing volume of timber, *VLP* value of standing firewood

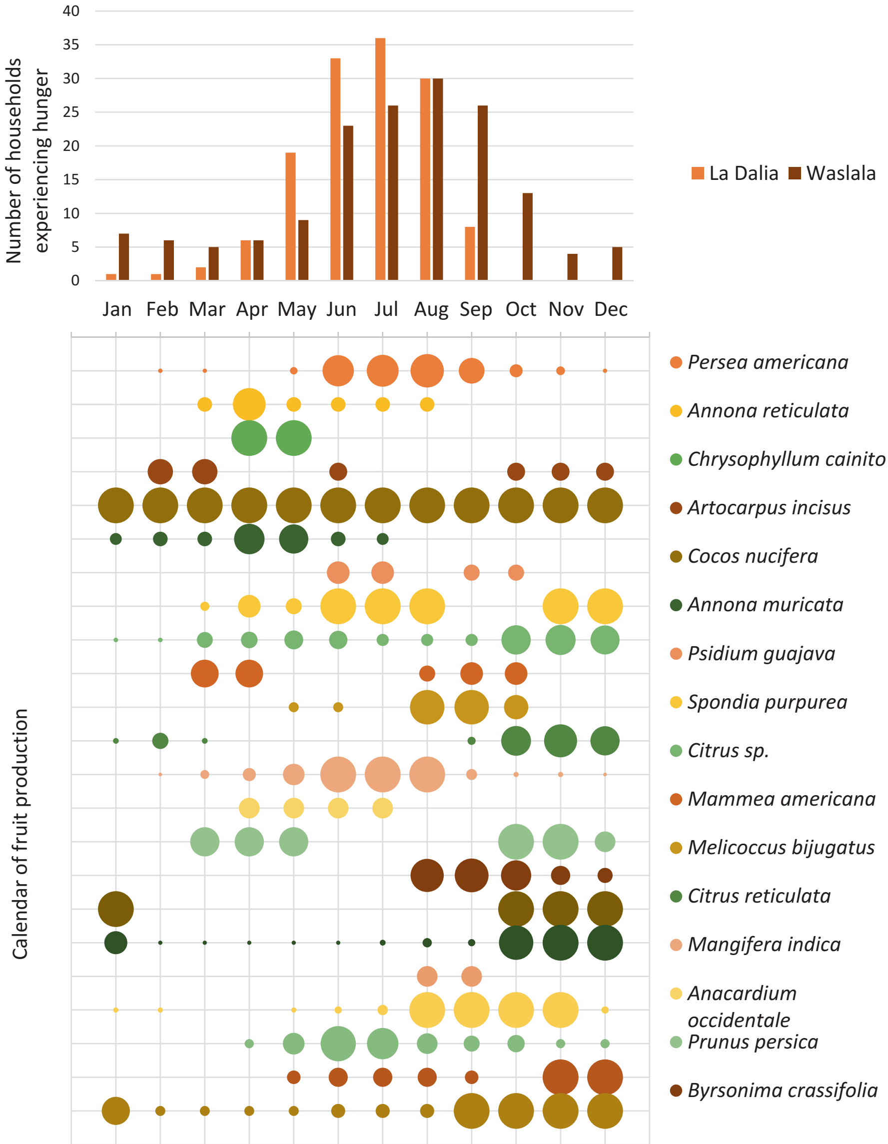


**Fig. 15.3** Monthly food insecurity and availability of fruits from trees in small farms in the municipalities Tuma – La Dalia and Waslala. Nicaragua. Colors identify fruit tree species and circle size indicate the amount of fruit available in a given month

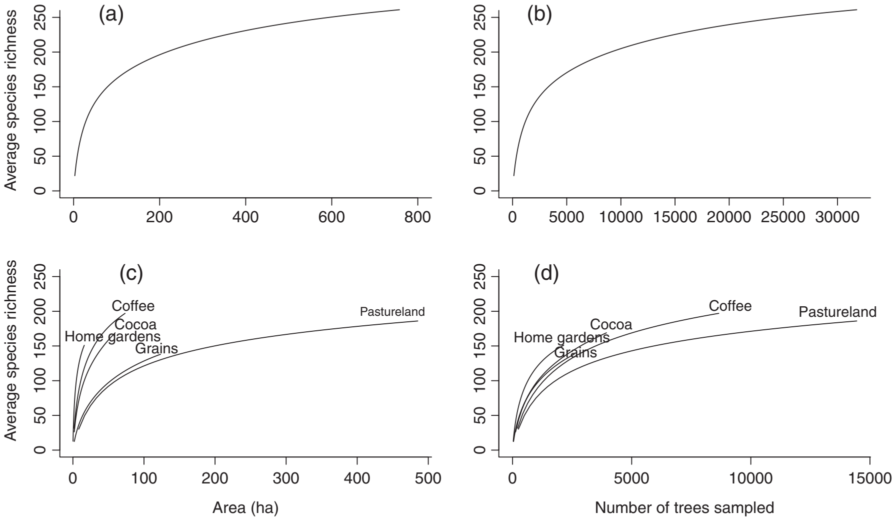


**Fig. 15.4** Species accumulation curve for trees by farm (**a** and **b**) or by land use (**c** and **d**), based either on tree-counts (**b** and **d**) or in sampling area (**a** and **c**), in the municipalities of Tuma – La Dalia and Waslala. Nicaragua

## *3.3 Trees by Land Use: Stocking, Agroforestry Production, Financial Indicators and Species Richness*

Tree stocking differed according to land use. Tree population density and basal area by land uses decreased in the following order: cocoa > coffee > grains > pastures > home gardens. For instance, tree population density (trees ha$^{-1}$) decreased from 138 trees ha$^{-1}$ in coffee plantations to 31 trees ha$^{-1}$ in grain fields (Table 15.3).

Production of fruits, standing timber and standing firewood were higher in shaded coffee plantations, followed by cocoa, pastures, grains and homegardens. Trees contributed more to on-farm consumption than to income generation. Overall family benefit derived from trees followed the same pattern of production: coffee > cocoa > pastures > grains > homegardens. In terms of cash flow, shaded coffee and homegardens were the only land uses with positive values. Tree production in all land uses presented negative net incomes (Table 15.3).

Tree botanical composition was rather similar among coffee, cacao, grains and pastures; however, homegardens had a distinct botanical composition, different from other land uses. TonF species richness per hectare followed the order: (coffee = cacao) > pastures > (grains = homegardens). The expected number of tree species in 1 ha of each land use varied between 10–30 species per hectare (Table 15.4). Rarefaction curves indicate that the sampling effort in this study does not capture total expected richness in homegardens, cocoa and coffee plantations (Fig. 15.4c, d).

**Table 15.3** Trees on farms by land use: population density, basal area, agroforestry production and financial contribution

| Variable | Cacao | Coffee | Basic grains | Pastures | Homegardens |
|---|---|---|---|---|---|
| **Population density (trees $ha^{-1}$)** | | | | | |
| Total | 108.8 ± 85.83 b | 155.1 ± 87.01 a | 37.66 ± 49.51 c | 46.03 ± 29.24 c | 183.64 ± 111.58 a |
| Fruits | 36.59 ± 49.99 b | 54.36 ± 55.83 b | 6.76 ± 8.46 c | 7.26 ± 10.06 c | 114.55 ± 87.96 a |
| Firewood | 29.66 ± 27.88 a | 38.37 ± 21.44 a | 8.87 ± 11.5 c | 13.43 ± 11.3 c | 35.05 ± 30.34 a |
| Timber | 38.69 ± 35.7 b | 55.19 ± 45.38 a | 22.92 ± 34.24 c | 23.21 ± 19.05 cd | 34.98 ± 30.19 bc |
| Posts | 3.81 ± 4.36 bc | 5.97 ± 8.52 ab | 2.02 ± 2.89 c | 1.69 ± 2.64 c | 9.29 ± 6.16 a |
| Service | 5.0 ± 4.92 b | 6.37 ± 7.53 b | 2.46 ± 2.47 b | 2.2 ± 2.85 b | 20.1 ± 24.45 a |
| **Basal area ($m^2$ $ha^{-1}$)** | | | | | |
| Total | 5.57 ± 3.48 b | 8.2 ± 4.17 a | 2.15 ± 3.17 c | 2.14 ± 1.33 c | 6.99 ± 6.2 ab |
| Fruits | 1.11 ± 1.69 b | 1.41 ± 1.58 b | 0.31 ± 0.36 b | 0.25 ± 0.27 b | 3.74 ± 4.47 a |
| Firewood | 1.42 ± 0.96 a | 1.8 ± 0.86 a | 0.51 ± 0.65 b | 0.58 ± 0.48 b | 1.77 ± 2.04 a |
| Timber | 2.81 ± 1.98 ab | 3.77 ± 2.81 a | 1.45 ± 2.45 cd | 1.18 ± 0.87 d | 2.02 ± 2.31 bc |
| Posts | 0.54 ± 0.56 a | 1.82 ± 4.25 a | 0.46 ± 0.44 a | 0.31 ± 0.44 a | 0.74 ± 1.19 a |
| Service | 0.59 ± 0.55 a | 0.4 ± 0.39 abc | 0.25 ± 0.2 bc | 0.2 ± 0.32 c | 0.45 ± 0.46 ab |
| **Agroforestry production** | | | | | |
| VMP ($m^3$ $ha^{-1}$) | 13.06 ± 9.89 a | 17.07 ± 13.54 a | 6.13 ± 10 b | 5.0 ± 4.36 b | 7.52 ± 9.31 b |
| Oranges (Units $ha^{-1}$ $year^{-1}$) | 7578 ± 12,243 bc | 10,970 ± 26,284 ab | 2501 ± 4114 c | 1060.7 ± 1155 c | 14,255 ± 12,037 a |
| Mango (Units $ha^{-1}$ $year^{-1}$) | 3997 ± 7914 abc | 4768 ± 6768 ab | 851 ± 935 bc | 680 ± 1124 c | 15,862 ± 17,643 a |
| Avocado (Units $ha^{-1}$ $year^{-1}$) | 1609 ± 2044 b | 1792 ± 2738 bc | 849 ± 1211bc | 328 ± 466 bc | 5825 ± 4264 a |
| Other fruits1 | 4947 ± 8682 bc | 6344 ± 7218 b | 1000 ± 1567 c | 1006.4 ± 1376 c | 18,016 ± 18,806 a |
| Other fruits2 | 780.7 ± 1046 ab | 477 ± 956 b | 66.91 ± 50.04 b | 144.74 ± 258 b | 1224.6 ± 1577 a |
| Firewood (kg $ha^{-1}$ $year^{-1}$) | 8063 ± 5740 a | 10,891 ± 5778 a | 2881 ± 4106 b | 3616 ± 3367 b | 11,187 ± 13,888 a |

(continued)

**Table 15.3** (continued)

| Variable | Cacao | Coffee | Basic grains | Pastures | Homegardens |
|---|---|---|---|---|---|
| **Financial indicators** | | | | | |
| GI (USD $ha^{-1}$ $year^{-1}$) | 69.3 ± 74.36 b | 78.25 ± 80.86 b | 15.5 ± 8.84 b | 9.13 ± 8.4 b | 297.11 ± 281 a |
| CC (USD $ha^{-1}$ $year^{-1}$) | 49.69 ± 47.38 ab | 48.55 ± 55.86 ab | 26.37 ± 26.95 bc | 12.12 ± 14.15 c | 67.5 ± 109.47 a |
| KC (USD $ha^{-1}$ $year^{-1}$)\| | 40.31 ± 57.04 b | 37.76 ± 42.11 b | 25.02 ± 68.22 b | 7.64 ± 11.26 b | 140.67 ± 240.59 a |
| CF (USD $ha^{-1}$ $year^{-1}$) | −32.4 ± 41.93 b | 13.34 ± 101.62 b | −22.5 ± 29.17 b | −10.5 ± 15.05 b | 186.08 ± 295.68 a |
| NI (USD $ha^{-1}$ $year^{-1}$) | −59.4 ± 55.44 a | −25.6 ± 95.6 a | −31.5 ± 68.29 a | −13.05 ± 15.86 a | −73.22 ± 307.81 a |
| VCD (USD $ha^{-1}$ $year^{-1}$) | 460.4 ± 580.68 b | 384.1 ± 428.95 b | 121.5 ± 162.54 b | 83.46 ± 83.63 b | 973.52 ± 1463.96 a |
| FB (USD $ha^{-1}$ $year^{-1}$) | 439.7 ± 577.33 b | 394.1 ± 412.9 b | 112 ± 146.96 b | 77.83 ± 76.91 c | 1024.3 ± 1453.33 a |
| ValMP (USD $ha^{-1}$ $year^{-1}$) | 4867 ± 3849.94 a | 6576 ± 5210.05 a | 2361 ± 3851.27 b | 1924.7 ± 1683.87 b | 2898.8 ± 3585.03 b |
| VLP (USD $ha^{-1}$ $year^{-1}$) | 564.4 ± 401.82 a | 762.4 ± 404.49 a | 201.7 ± 287.49 b | 253.13 ± 235.73b | 783.07 ± 972.16 a |

Municipalities Tuma – La Dalia and Waslala, Nicaragua. 2015

Means (± standard deviation) with same letter along the row are statistically similar (LSD Fisher, $p < 0.05$). Other fruits1 (measured in Units $ha^{-1}$ $year^{-1}$) = coco (*Cocus nucifera*), pera de agua (*Syzygium malaccense*), guayaba (*Psidium guajva*), sonzapote (*Licania platypus*), melocotón (*Averrhoa carambola*), guanábana (*Annona muricata*). Other fruits2 (measured in kg $ha^{-1}$ $year^{-1}$) = pejibaye (*Bactris gasipaes*), nancite (*Byrsonima crassifolia*) and jocote (*Spondias purpurea*) *CC* cost in cash, *KC* cost in kind (mostly family labor), *GI* gross income, *CF* net cash flow, *NI* net income, *VCD* money value of domestic consumption, *FB* Family benefit, *VMP* standing timber volume, *ValMP* value of standing timber, *VLP* value of standing firewood, *USD* United States of America Dollars

**Table 15.4** Trees on farm species diversity and carbon stock in aboveground biomass by land use types in the municipalities Tuma – La Dalia and Waslala, Nicaragua

| Land use | Tree abundance | $S_{obs}$ | $S_{est}$ | Sampling effort (%) | S $ha^{-1}$ ± standard deviation | Shannon | C (Mg $ha^{-1}$) |
|---|---|---|---|---|---|---|---|
| Coffee | 8656 | 197 | 275 | 72 | 30 ± 6 | 2.48 ± 0.45 | 19 (36%) |
| Cocoa | 3942 | 169 | 267 | 63 | 28 ± 8 | 2.45 ± 0.66 | 13 (26%) |
| Pastures | 14448 | 186 | 249 | 75 | 19 ± 7 | 1.75 ± 0.84 | 11 (22%) |
| Homegardens | 2148 | 151 | 202 | 75 | NA | 0.55 ± 0.36 | 4 (8%) |
| Basic grains | 2587 | 138 | 203 | 68 | 10 ± 6 | 1.04 ± 0.53 | 4 (7%) |

Tree abundance, observed species richness ($S_{obs}$), jackknife estimated S ($S_{est}$), sampling effort based on observed and estimated S, observed species richness in 1 ha of transect-sampled farm land, Shannon diversity (± standard error), carbon stock in aboveground tree biomass (C), in parenthesis the percentage of total farm carbon stock in a given land use

## *3.4 Farm Typologies*

Six farming system typologies (FS1–FS6), grouped in three broad farm types (T1–T3), were identified. Summaries of farm typologies were prepared using average values for all indicators and given a color scale from green to red (heath map) to show high and low values for each indicator (Table 15.5).

**T1: Small diversified farms and cash crops (coffee or cacao):** Characterized by small farms (0.6–10.3 ha, average ~2.6–3.5 ha), includes two sub-types:

1. ***S1: Small diversified farms***, mainly allocate land to the production of basic grains, but also include pastures and cash crops. They have high productivity of roots-tubers (*Manihot esculenta, Colocasia* and *Xanthosoma sagitifolium*) and bananas (8.6 Mg $ha^{-1}$ $year^{-1}$), animal products (1.4 Mg $ha^{-1}$ $year^{-1}$) and tree products such as citrus (~7300 unit $ha^{-1}$ $year^{-1}$), fruits (~5200 units $ha^{-1}$ $year^{-1}$ and 547 kg $ha^{-1}$ $year^{-1}$, mainly peach palm), timber (5.1 $m^3$ $ha^{-1}$) and medium productivity of firewood (5.3 Mg $ha^{-1}$). These small farms with a very high density of shade of small trees (md = 114 tree $ha^{-1}$) and bananas in coffee and cocoa plots, have a high gross income per ha (1167 US$ $ha^{-1}$ $year^{-1}$), but the lowest income per farm of all groups (1670 US$ $farm^{-1}$ $year^{-1}$), derived from various sources, and they have the lowest integration to markets of all groups. Tree diversity is medium (median = 34 species $farm^{-1}$) and tree C stocks per farm are low in dispersed trees (26 Mg $farm^{-1}$) and tree lines (28 Mg $farm^{-1}$) but on a per area basis, they are medium (14.3 Mg $ha^{-1}$).
2. ***FS2: farms that produce mainly cash crops (coffee or cacao) combined with basic grains*** with the highest productivity of basic grains (2.8 Mg $ha^{-1}$ $year^{-1}$) and animal products (1.5 Mg $ha^{-1}$ $year^{-1}$) and high productivity of cash crops (860 kg $ha^{-1}$ $year^{-1}$). These farms have medium tree densities (85 tree $ha^{-1}$) for production of mainly timber (4.5 $m^3$ $ha^{-1}$), firewood (8.0 Mg $ha^{-1}$) and somewhat less for citrus (~3100 units $ha^{-1}$) and fruits (~2800 unit $ha^{-1}$ and 239 kg $ha^{-1}$). These farms generate a medium-low income per farm (4668 US$ $farm^{-1}$ $year^{-1}$)

and the highest income per ha (1832 US$ ha$^{-1}$ year$^{-1}$), derived mainly from basic grains and cash crops, and they have a medium market orientation. Dispersed tree species richness is medium (40 species farm$^{-1}$) and tree line plantations are almost absent. Given the small farm size, C stocks at the farm level are low (54.5 Mg farm$^{-1}$) but they are higher on a per area basis (18.1 Mg ha$^{-1}$).

**Table 15.5** Mean values per farm typology for 37 farm-level indicators that spanned (1) farm size and distribution of land uses in the farm; (2) agricultural productivity; (3) financial productivity; (4) tree abundance and tree products; and (5) tree carbon (C) stocks and species diversity

| Indicators | Small farms with cash crops, diversified | | | | Medium farms with pastures, diversified | | | | Farms with large tree stocks | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | FS1 | | FS2 | | FS3 | | FS4 | | FS5 | | FS6 | |
| *Farm size and Land Use* | n | Mean | n | Mean | n | Mean | n | Mean | n | Mean | n | Mean |
| Total farm area (ha) | 24 | 2.58 | 16 | 3.49 | 17 | 8.58 | 11 | 7.46 | 9 | 8.08 | 13 | 41.11 |
| % area basic grains | 19 | 0.40 | 7 | 0.46 | 14 | 0.23 | 11 | 0.44 | 5 | 0.13 | 7 | 0.14 |
| % area homegarden | 23 | 0.07 | 15 | 0.05 | 17 | 0.05 | 9 | 0.03 | 9 | 0.02 | 12 | 0.01 |
| % area cocoa-coffee | 18 | 0.27 | 16 | 0.55 | 11 | 0.19 | 4 | 0.10 | 9 | 0.59 | 8 | 0.07 |
| % area pasture | 11 | 0.38 | 5 | 0.34 | 16 | 0.59 | 8 | 0.46 | 7 | 0.28 | 13 | 0.68 |
| % area forest | 6 | 0.20 | 5 | 0.20 | 10 | 0.08 | 7 | 0.21 | 4 | 0.06 | 12 | 0.18 |
| *Agricultural productivity* | | | | | | | | | | | | |
| Total farm production (kg) | 24 | 3466 | 16 | 8909 | 17 | 8399 | 11 | 7255 | 9 | 8929 | 13 | 20663 |
| Staples and pulses (kg ha$^{-1}$) | 18 | 1791 | 7 | 2767 | 14 | 2331 | 11 | 2348 | 6 | 1354 | 7 | 1488 |
| Root tubers and bananas (kg ha$^{-1}$) | 19 | 8665 | 14 | 4994 | 11 | 4713 | 4 | 2419 | 8 | 1656 | 9 | 4346 |
| Cash crops (kg ha$^{-1}$) | 18 | 384 | 16 | 860 | 12 | 200 | 4 | 278 | 9 | 1122 | 8 | 416 |
| Animal products (kg ha$^{-1}$) | 19 | 1402 | 11 | 1452 | 17 | 1103 | 10 | 671 | 9 | 936 | 13 | 669 |
| Farm livestock (AU) | 4 | 0.3 | 3 | 0.3 | 11 | 1.2 | 5 | 1.8 | 5 | 0.5 | 13 | 6.3 |
| Farm poultry (heads) | 19 | 17 | 12 | 27 | 17 | 28 | 7 | 21 | 8 | 15 | 12 | 30 |
| *Financial productivity* | | | | | | | | | | | | |
| Total farm income ($) | 24 | 1670 | 16 | 4668 | 17 | 4716 | 11 | 5090 | 9 | 7070 | 13 | 16073 |
| Farm income area ($ ha$^{-1}$) | 24 | 1167 | 16 | 1832 | 17 | 779 | 11 | 965 | 9 | 927 | 13 | 526 |
| Proportion income staples and pulses | 18 | 0.36 | 7 | 0.46 | 14 | 0.27 | 11 | 0.58 | 6 | 0.11 | 7 | 0.21 |
| Proportion income root tuber and bananas | 19 | 0.10 | 14 | 0.09 | 13 | 0.09 | 4 | 0.04 | 8 | 0.05 | 9 | 0.03 |
| Proportion income cash crops | 18 | 0.16 | 16 | 0.38 | 12 | 0.11 | 4 | 0.03 | 9 | 0.57 | 8 | 0.07 |
| Proportion income tree products | 24 | 0.29 | 16 | 0.22 | 17 | 0.18 | 11 | 0.13 | 9 | 0.18 | 13 | 0.12 |
| Proportion income animal products | 19 | 0.20 | 11 | 0.09 | 17 | 0.24 | 10 | 0.16 | 9 | 0.08 | 13 | 0.38 |
| Proportion income poultry | 19 | 0.04 | 11 | 0.03 | 17 | 0.03 | 7 | 0.02 | 8 | 0.01 | 12 | 0.01 |
| Proportion income livestock | 4 | 0.16 | 3 | 0.07 | 11 | 0.24 | 5 | 0.21 | 5 | 0.07 | 13 | 0.31 |
| Market orientation | 22 | 0.32 | 16 | 0.55 | 17 | 0.45 | 11 | 0.43 | 9 | 0.63 | 13 | 0.69 |
| *Tree abundance and productivity* | | | | | | | | | | | | |
| Farm basal area | 24 | 7.8 | 16 | 11.5 | 17 | 22.4 | 11 | 6.3 | 9 | 42.5 | 13 | 47.1 |
| Citrus (units ha$^{-1}$) | 21 | 7272 | 16 | 3118 | 17 | 1343 | 9 | 518 | 9 | 2462 | 13 | 606 |
| Fruits (units ha$^{-1}$) | 24 | 5286 | 16 | 2838 | 17 | 1795 | 11 | 908 | 9 | 3263 | 13 | 577 |
| Fruits (kg ha-1) | 20 | 547 | 15 | 239 | 14 | 134 | 7 | 86 | 9 | 79 | 13 | 20 |
| Firewood (kg ha$^{-1}$) | 24 | 5348 | 16 | 8019 | 17 | 5161 | 11 | 1709 | 9 | 10735 | 13 | 2685 |
| Timber (m3 ha$^{-1}$) | 24 | 5.1 | 16 | 4.5 | 17 | 2.9 | 11 | 1.0 | 9 | 6.1 | 13 | 1.6 |
| *Tree diversity and C stocks* | | | | | | | | | | | | |
| Spp. Richness trees dispersed | 24 | 34 | 16 | 40 | 17 | 50 | 11 | 29 | 9 | 58 | 13 | 75 |
| Spp. Richness trees lines | 20 | 9 | 4 | 5 | 17 | 9 | 10 | 11 | 9 | 13 | 13 | 16 |
| Density dispersed trees (tree ha$^{-1}$) | 24 | 114 | 16 | 85 | 17 | 59 | 11 | 29 | 9 | 96 | 13 | 29 |
| Farm C stocks dispersed trees (Mg) | 24 | 26.4 | 16 | 54.5 | 17 | 114.0 | 11 | 36.2 | 9 | 179.5 | 13 | 352.2 |
| C stocks dispersed trees (Mg ha$^{-1}$) | 24 | 14.3 | 16 | 18.1 | 17 | 13.1 | 11 | 4.5 | 9 | 25.3 | 13 | 10.9 |
| Density tree lines (tree m$^{-1}$) | 20 | 0.18 | 4 | 0.17 | 17 | 0.27 | 10 | 0.26 | 9 | 0.23 | 13 | 0.23 |
| Farm C stocks tree lines (Mg) | 20 | 27.8 | 4 | 2.5 | 17 | 45.0 | 10 | 39.9 | 9 | 94.2 | 13 | 114.1 |
| C stocks tree lines (Mg m$^{-1}$) | 20 | 0.052 | 4 | 0.024 | 17 | 0.039 | 10 | 0.062 | 9 | 0.099 | 13 | 0.040 |

**T2: Medium diversified farms with pastures with low tree cover**: Characterized by small-medium farms (1.4–27.2 ha) that combine the production of basic grains with pastures, includes two sub-types:

1. ***FS3: Small scale cattle ranching*** with an average farm size of 8.5 ha, main land use are pastures and small areas for basic grains and cash crops. They have high productivity of basic grains (2.3 Mg $ha^{-1}$ $year^{-1}$) and animal products (1.1 Mg $ha^{-1}$ $year^{-1}$). With medium market orientation, total gross income per farm (4716 US\$ $farm^{-1}$ $year^{-1}$) and per ha (779 US \$ $ha^{-1}$ $year^{-1}$) is medium-low; mainly derived from staples (27%), livestock (24%), animal products (24%) and tree products (18%). Tree densities (59 tree $ha^{-1}$) as well as productivity of tree products are intermediate among all groups. Thanks to their larger size, tree diversity (50 species $farm^{-1}$) and C stocks both in dispersed trees (114 Mg $farm^{-1}$) and high density tree lines (45 Mg $farm^{-1}$) are higher than those of smaller farms.
2. ***FS4: medium farms with basic grains and pastures*** with average farm size of 7.5 ha, these farms have high productivity of basic grains (2.4 Mg $ha^{-1}$ $year^{-1}$), but the lowest productivity in all other agricultural activities. These farms have similar number of animals as the small cattle ranching farms (0.15–6.1 Animal Units, AU) but productivity of animal products is low (0.7 Mg $ha^{-1}$ $year^{-1}$). Income is intermediate on both per farm (5090 US\$ $farm^{-1}$ $year^{-1}$) and area basis (965 US \$ $ha^{-1}$). Tree cover (basal area = 6.3 $m^2$) is the lowest of all groups, and tree density is low (29 trees $ha^{-1}$) but similar to that in large cattle ranching farms. Consequently they also have the lowest productivity of tree products, the lowest tree diversity (median = 29 species $farm^{-1}$) and low C stocks (36.2 Mg $farm^{-1}$). Albeit the lower tree cover these farms do have some high density tree line plantings (0.26 tree $m^{-1}$), and tree C stocks on line plantations (40 Mg $farm^{-1}$) comparable to small scale cattle ranching.

**T3: Farms with large tree stock**: There are two groups with rather different strategies in terms of farm sizes and land use allocation that result in the highest tree diversity, highest tree stocks, and highest C stocks at the farm level):

1) ***FS5: medium sized farms*** (6–11.3 ha) ***almost exclusively for production of cash crops*** with the highest productivity of cash crops (1122 kg $ha^{-1}$ $year^{-1}$). These farms mostly from La Dalia are market oriented, and cash crops (coffee) is the main income source (75%), generating the second highest income per farm (7070 US\$ $farm^{-1}$ $year^{-1}$) after large farms, and with intermediate income per hectare (927 US\$ $ha^{-1}$ $year^{-1}$). High tree stocks composed of high density dispersed trees (96 tree $ha^{-1}$) and tree lines are translated into high productivity of citrus (~2462 units $ha^{-1}$ $year^{-1}$), fruits (~3263 units $ha^{-1}$ $year^{-1}$) timber (6.1 $m^3$ $ha^{-1}$) and particularly firewood (median ~11 Mg $ha^{-1}$). Tree diversity is high (58 species $farm^{-1}$) as well as C stocks both on a per farm (180 Mg C $farm^{-1}$) and per land area basis (25.3 Mg C $ha^{-1}$). A sizeable amount of C is also stored in tree line plantations (94 Mg C $farm^{-1}$).

2) ***FS6: large cattle ranches*** (16–102 ha) specialized on livestock production with extensive cattle ranching systems. These farms generate the highest total production (20.6 Mg farm$^{-1}$ year$^{-1}$) and income per farm (~16,000 US $ year$^{-1}$, derived from livestock, animal products and basic grains), but productivity per land area is low (e.g. financial productivity 526 US$ ha$^{-1}$ year$^{-1)}$. In these farms pasture land with low tree densities (median 29 tree ha$^{-1}$), and tree lines are the main contributors to high C stock per farm (352 Mg C farm$^{-1}$ in dispersed trees and 114 Mg C farm$^{-1}$), but with low C stocks on a per area basis (10.9 Mg C ha$^{-1}$). These farms have the highest tree diversity (median 75 species farm$^{-1}$) but the lowest productivity of tree products: citrus (~606 units ha$^{-1}$ year$^{-1}$), fruits (~577 units ha$^{-1}$ year$^{-1}$), firewood (md ~ 2.7 Mg ha$^{-1}$) and timber (md = 1.6 m$^3$ ha$^{-1}$).

# 4 Discussion

## *4.1 Importance of Trees on Farms*

This study demonstrates that TonF are important for livelihoods in terms of domestic consumption and overall family benefits, but not in generating net incomes or cash flow. In order to increase income and cash flow the sale of tree products should be increased and tree management should be optimized (Mallya 2013; Cerda et al. 2014; Pinoargote et al. 2016), especially in shaded coffee and in homegardens. Our study demonstrates that tree density in all land uses is high, but there is more room to increase tree density at the farm level, especially of those species which have an attractive market, e.g. high quality timber trees. Other studies conducted elsewhere in tropical regions have shown, for instance, that farmers with larger farms are willing to manage trees for timber production (Sebastian et al. 2014). More timber trees can be retained or planted in pastures, especially in linear plantings such as living fences, farm boundaries and along internal roads and paddock divisions (Plath et al. 2010; Esquivel et al. 2014).

Farmers produce timber even in small-scale fallows (Marquardt et al. 2013; Robiglio et al. 2013). Although we found a modest timber harvest ratio at the farm level (<1 trees ha$^{-1}$ year$^{-1}$), we also found a considerable standing timber volume, which indicates that timber harvest could be improved in a sustainable way. Studies in Central America with naturally regenerated *Cordia alliodora* in cocoa plantations have shown that timber is accumulated at a rate of 1 m$^3$ ha$^{-1}$ year$^{-1}$ of total timber volume for every 1 m$^2$ ha$^{-1}$ of basal area of the shade canopy, and at least 3 trees ha$^{-1}$ year$^{-1}$ are harvested in these agroforestry systems (Somarriba et al. 2014).

Land uses influenced most of the variables measured in this study. Although our results support previous studies in that the most complex systems (i.e. coffee plantations) have a higher tree contribution in terms of species diversity and tree products, we also show that simple systems such as basic grains and homegardens contain important tree resources. For instance, homegardens maintained high tree species diversity in spite of their small size: in homegardens almost each new individual recorded in our study belongs to a different species. At the landscape level, the five land use types complemented each other in their species composition, a pattern that has also been observed in other tropical regions (Kindt et al. 2004). Cocoa and coffee shade tree species composition were more similar among them, while at the same time they were very dissimilar to the other three land uses. Understanding how farm diversification and configuration (i.e. number of land uses by farm and farm area allocated to each land use) influence the abundance and botanical composition of trees on farm and their contributions to livelihoods and the environment, will help to design productive landscape that optimize food production and the provision of other ecosystem services.

The establishment of more trees in different land uses can also increase the fuelwood supply and avoid the extraction of wood from forests (Ndayambaje et al. 2013). Most on-farm production of fruits is lost due to poor market development (Almendarez et al. 2013); home consumption of fruits and other edible products from woody species is critical for food security, as has been shown in many agro-ecological zones e.g. in dryland Africa (Kehlenbeck and McMullin 2015; Agúndez et al. 2016). To increase fruit sales, farmers should identify the most suitable and valuable fruit tree species, use asexual propagation techniques to ensure the reproduction of high quality trees, and identify good markets (Roshetko 2013). Fruit and timber trees are usually in high demand by farmers when asked about their preferences to plant trees in their farms (Orozco et al. 2008). In the case of fruit trees, increased emphasis should be placed on tree domestication strategies, product development, trading and marketing (Chifamba 2011). Development programs should try to promote tree planting on farms in order to reduce vulnerability by enabling lower income farmers to gain disposable assets they can use to meet contingencies (Chambers and Leach 1987).

Trees on farms are a sound strategy to sequester and store carbon in wood biomass. In our study the median of carbon stock was around 167 Mg C farm$^{-1}$, about 20 Mg C ha$^{-1}$, which is consistent when compared with specific land uses such as shaded coffee (Pinoargote et al. 2016), but lower than cocoa plantations in the same study area (Somarriba et al. 2013). Our results are similar to carbon stocks found in farms in Kenya (Henry et al. 2009; Kuyah et al. 2016a). TonF have the potential to contribute to global strategies to mitigate climate change, in comparison to schemes involving forest-based emissions mitigation (REDD), Reducing Emissions from All Land Uses (REALU), using more effective, efficient and equitable management approaches (Dogra 2011; Schnell et al. 2015b). However, small farm sizes require several farmers to organize in cooperatives or similar organizations to trade significant quantities of carbon and to be able to pay all transaction costs (Henry et al. 2009).

Despite the demonstrated contributions of TonF to domestic consumption, modest income generation, reduction of vulnerability to contingencies, conservation of tree biodiversity and carbon sequestration, more efforts are needed to promote the establishment of trees at the farm level (Lovell et al. 2010). The potential role of incentives such as payments for ecosystem services (Rudel et al. 2016), and the creation of conditions to increase the net incomes and cash flow in smallholder farm economies need to be assessed and promoted (Etongo et al. 2015). Providing farmers with sound technical advice on TonF silviculture and farmer managed regeneration may also increase the role of trees on farmers' livelihoods (Regmi and Garforth 2010; Oeba et al. 2012; Iiyama et al. 2017). Econometric studies show that the decision to grow trees is not necessarily the same as deciding the number of trees grown. Land certification, as an indicator of tenure security, increases the likelihood that households will grow trees, but is not a significant determinant of the number of trees grown. Other variables, such as risk aversion, land size, adult labor availability, and education of household head, also influence the number of trees grown (Mekonnen and Damte 2011).

### *4.2 Farm Typologies Influence the Contribution of TonF to Livelihoods*

Farm typologies reflected well the main farming systems in the study area, when farms have a main production strategy (e.g. basic grains, coffee-cocoa as a cash crop, or pastures) but this does not hinder a high degree of diversification with various land uses in one farm. Tree cover in absolute terms was related to farm size (more clearly seen at the extremes of land sizes) but not unequivocally. Studies in temperate zones show that tree habitats on farms are dependent of farm size and biophysical conditions (Lovell et al. 2010). In parkland systems in Burkina Faso, land use and farming system strongly influence tree diversity and management (Bayala et al. 2011). Similar results have been observed in farms in Ethiopia (Mengistu and Hager 2010), and in Benin, West Africa, with tree density and diversity being inversely correlated with farm size (Fifanou et al. 2011). Studies in various countries in Africa show that farmers know what trees they want and they have specific purposes for trees within their farming system. For example, fuelwood trees are not the first choice of farmers, while they are more interested in planting fruit and/or multipurpose trees that produce poles, construction material, and perhaps fodder. The planting of trees by farmers appears also to be dependent on the wood resources available to the household: when population density is low and there is access to forest or woodland, there is not a strong incentive for the planting of trees on farms. Other factors may explain where in the farm, farmers are willing to plant trees. For example, farmers plant fruit trees in the homegarden in response to either concern about livestock grazing or fear of fire in the fallow fields (Warner 1993).

In this Chapter, the three broad farm types illustrated how farm outcomes depend on the combination of land availability, land use allocation, and management. The best results in terms of tree cover, C stocks and tree diversity were obtained in medium (minimum of 6 ha) and large farms, but with very different strategies. In medium farms the specialization towards coffee-cocoa systems with a high density of useful trees was translated into high tree cover, C stocks, diversity and tree products on both per ha and per farm basis. On the other hand, large farms with extensive cattle ranching had the lowest tree cover per ha but the highest tree C stocks and diversity at the farm level thanks to their large land areas. Very small farms have the most intensified production per unit land for crops, tree products and economic output. Still given their limited land availability, the total production per farm was low, as well as tree stocks and diversity. Medium size farms that produce basic grains and pastures have the most suboptimal performance both in crop and tree products productivity. In some cases, these medium farms have comparable or lower tree cover and C stocks than very small farms. It is important to assess the factors that underlie the suboptimal performance in these medium size farms to identify entry points for improvement.

The patterns observed in farm typologies also have implications to discuss entry points for interventions at the landscape level that aim to maintain or increase tree cover and its related services and products (Welsch et al. 2014). Very small (FS1, FS2) and medium farms with high tree cover of useful trees (FS5) are certainly hotspots for tree cover and diversity at the landscape scale, but perhaps there is a limited scope to increase tree cover and C stocks at landscape scales. For instance in many cases the limits for tree cover (shade) have already been reached and it might be difficult to extend forest areas due to constraints in management, labor and capital (medium farms) and land for the very small landholdings. In these systems increasing diversity and tree productivity is likely related to introduction and replacement of some tree species, and improved management of the existing shade. The largest scope for improvement in terms of absolute increases in tree cover, C stocks and diversity at the landscape scale seems more effective in medium size farms with suboptimal management (FS3, FS4) and large farms with extensive cattle ranching (FS6). Given the low tree cover in these farms, and their large areas, modest increases can have profound impacts at the landscape scale. Moreover it is clear that the suboptimal management and little selection of useful trees can be optimized to increase productivity of tree products.

### *4.3 Methods for Assessing TonF*

Assessing trees outside the forests (TonF are just one example of these) has been limited by the lack of appropriate classification systems and the complex nature of the resource which involves consideration of both tree cover (on which the definition of forest is based along with plot size) and land use (Kleinn 2000). Fortunately, recent studies have provided a sound classificatory framework for classifying trees outside the forest (De Foresta et al. 2013). At local scales, this classificatory scheme has proven to be effective (Schnell et al. 2015a), however, time- and cost-efficient methods for large scale assessments of trees on farms (and other types of trees outside the forests) have yet to be developed (Kleinn 2000; Schnell et al. 2015b).

For future monitoring of the tree cover and biomass, the combination of field surveys and remote sensing appear to be the most promising (Schnell et al. 2015b). Several research studies using remote sensing for monitoring TonF have been conducted recently, but very few include comparative studies to optimize sampling strategies for TonF. Methods combining remote sensing and field surveys appear to be very favorable (Liknes et al. 2010), especially when remote sensing techniques that assess both the horizontal and vertical structures of tree resources are applied. For example, two-phase sampling strategies with laser scanning in the first phase and a field survey in the second phase appear to be effective for assessing TonF resources (Kleinn 2000; Kleinn et al. 2005). However, TonFs often exhibit different characteristics than forest trees. Thus, to improve TonF monitoring, there is often a need to develop models, e.g. for biomass assessment, that are specifically adapted to this tree resource (Schnell et al. 2015a; Kuyah et al. 2016a).

Our study highlights the importance of the analysis of economic indicators suitable for rural families, such as the value of domestic consumption and family benefit, not only the evaluation of net income. The promotion and management of trees on farms must be based in balancing synergies and tradeoffs (e.g. between provisioning and regulatory ecosystem services), and private and social net benefits (Tisdell 1985; Ndayambaje et al. 2013; Esquivel et al. 2014). Strategies to encourage smallholder farmers to increase the use of trees on their farms have to account for the farmers' ecological and socioeconomic conditions (Kuyah et al. 2016b), market prices for tree products (Godoy 1992), and knowledge on sound management practices. For instance, pastures containing the right combination of tree species can produce a temporal pattern of fruit and fodder availability to livestock during the dry season, but care must be taken to avoid excessive shading that reduces pasture productivity (Ango et al. 2014).

## 5 Conclusions and Recommendations

The evidence presented in this chapter demonstrates that trees on farms (TonF) are frequent, abundant and very important for rural livelihoods and for the environment. However, in spite of their importance and widespread presence in all farms around the world, trees on farms are invisible in global agendas (such as REDD+, FAO/FRA, UN conventions on biological diversity and on water, sustainable development goals) and in national agendas (such as legal, institutional, policy and development frameworks affecting TonF in sustainable rural development). For instance, TonF are not adequately represented in most forestry legislation and in institutional structures related to forestry and agricultural resources. They are noticeably absent in policies and public and private programs, in university and technical education plans, in training of technical extension providers to farms, and in farmer field school programs and other models of education for producing families in rural environments. Even worse, trees on farms are regulated as if they were trees in the forest, resulting in over-regulation and control (Van Leeuwen and Hofstede 1995), cumbersome bureaucracy, high transaction costs, illegality, low prices, high risks and underutilization of the resource (Sibale et al. 2013).

The lack of an enabling environment for the promotion of TonF is due to:

- lack of quantitative data on stocks and costs at scales meaningful for policymakers
- gaps in knowledge of drivers and processes influencing the presence, management and use of trees on farms
- lack of tools to assess tree-based interventions
- lack of effective communication and concerted actions among key stakeholders to achieve change.

To achieve changes in national policies and regulations, it is necessary to work with stakeholders influential in policy formulation and implementation, such as national and subnational government institutions, the Ministries of Environment, Agriculture and Forestry, NGOs working on land-use planning and development programs based on agroforestry interventions; representatives of the agricultural subsectors (coffee, cocoa, livestock, maize, beans), and all value-chain actors, farmer organizations (van Leeuwen and Hofstede 1995) and the donor community. A small set of key, immediate actions can be recommended:

1. Elevate the visibility of trees on farms in key groups at global and national levels.
2. Promote an important cultural change in farmers and ranchers: the "tree on the farm" as a crop and not as something provided by nature that needs no management.
3. Demonstrate that trees on the farm have a valuable place in the current era of intensification of agriculture and livestock, which normally leads to elimination of trees in agricultural fields and pastures.
4. Improve the legal and institutional framework of the trees on farms and include it in public policies and programs of promotion and support. Experiences from different countries should be collated, analyzed and used to develop broad recommendations applicable in a wide range of socio-cultural and economic conditions.

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# Chapter 16
# Intensive Silvopastoral Systems: Economics and Contribution to Climate Change Mitigation and Public Policies

**Julián Chará, Julián Rivera, Rolando Barahona, Enrique Murgueitio R., Claus Deblitz, Ernesto Reyes, Rogerio Martins Mauricio, Juan José Molina, Martha Flores, and Andrés Zuluaga**

## 1 Introduction

It is predicted that the world's demand for animal protein will continue to grow during the following decades as a result of the increase in population and income per capita, and the greater percentage of people living in urban areas (Pingali and McCullough 2010; Rae and Nayga 2010; Alexandratos and Bruinsma 2012). The

J. Chará (✉) · J. Rivera · E. Murgueitio R.
Centro para la Investigación en Sistemas Sostenibles de Producción Agropecuaria, CIPAV, Cali, Colombia

Mainstreaming Sustainable Cattle Ranching Project, Bogotá, Colombia
e-mail: julian@fun.cipav.org.co

R. Barahona
Universidad Nacional de Colombia, Medellín, Colombia

C. Deblitz · E. Reyes
Agri benchmark Network-Thünen Institute of Farm Economics, Braunschweig, Germany

R. M. Mauricio
Universidade Federal de São João del Rei, São João del Rei, Brazil

J. J. Molina
Centro para la Investigación en Sistemas Sostenibles de Producción Agropecuaria, CIPAV, Cali, Colombia

Reserva Natural El Hatico, Cali, Colombia

M. Flores
Fundación Produce Michoacán, Morelia, Mexico

A. Zuluaga
Mainstreaming Sustainable Cattle Ranching Project, Bogotá, Colombia

FEDEGAN, Bogotá, Colombia



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demand for meat is expected to grow by 73%, and milk and dairy products by 58%, from 2010 to 2030; this will lead to an increase in the global cattle population from 1.7 to 2.4 billion by 2030 (Alexandratos and Bruinsma 2012). Due to this projected increased demand and production, agriculture and livestock will continue representing an important economic sector in the world with an emphasis in developing countries (Alexandratos and Bruinsma 2012).

Latin America has had the highest growth in beef production during the last two decades. Cattle population in this region increased from 178 to 395 million heads during the last four decades and currently provides 39% of the world's meat production from grassland-based systems (Neely et al. 2009; Alexandratos and Bruinsma 2012). This growth has created threats for the environment and climate as it has occurred at the expense of natural ecosystems and has a significant contribution to the emissions of greenhouse gases (GHG), primarily methane (Steinfeld et al. 2006).

In Latin America, cattle ranching has traditionally relied on extensive systems, with low stocking rates (less than 0.6 Animal Units $ha^{-1}$) and grass monocultures (González et al. 2015). In Brazil, the country with highest sector growth in recent years, approximately 159 million hectares are used for cattle grazing (Barretto et al. 2013), of which more than 100 million are cultivated monoculture pasturelands (IBGE 2006; Guarda and Guarda 2014).

Besides its environmental impact, this type of monoculture production system provides limited feed quality during extreme seasonal events (high temperatures and drought), due to limited shade, poor soil quality, limited access to water, and poor animal condition and performance. In more developed countries cattle production has moved towards more intensive, large-scale, and specialized production units using mixed fodder species as well as grains and feed supplements (Robinson et al. 2011). This livestock intensification, although it alleviates the pressure to increase the area of rangeland, exacerbates the need for more cropland to be devoted to food production in other regions of the world, putting pressure on the land and natural resources (Pingali and McCullough 2010). However, as stated by Mottet et al. (2017), high grain intake (6–20 kg per kg of beef) is only found in feedlot beef production that generates just 7% of global beef output. The other 87–93% volume comes from different production systems where grass and leaves represent 48% of dry matter intake (Herrero et al. 2013), which emphasizes the importance of pasture for livestock production.

To a great extent, negative effects of cattle production are caused by inadequate practices and due to the fact that cattle ranching operates as an extractive activity with very low efficiency and poor management (Calle et al. 2012; Gerber et al. 2013). Recently, several studies have demonstrated the role of some forms of natural intensification on the provision of high quality food, the rehabilitation of degraded ecosystems, and the mitigation of climate change, and have proposed their use to increase production without the negative effects of industrialized systems (Calle et al. 2012, 2013; Gerber et al. 2013; Murgueitio et al. 2014).

Silvopastoral systems (SPS) have been proposed to reduce or reverse the negative environmental impact of cattle ranching and increase animal production and economic performance at the same time. Intensive silvopastoral systems (ISPS) include high density of fodder shrubs (>10,000 plants $ha^{-1}$) mixed with grasses that combine these advantages and naturally intensify production, reduce the use of external inputs (e.g., fertilizers and feed supplements), and the carbon footprint of beef and milk production (Chará et al. 2015; Murgueitio et al. 2015b), while improving farms' economic returns (Reyes et al. 2016). These intensive SPS have been promoted in several countries of Latin America. Here we describe the systems used, their advantages and developments, and their requirements in terms of research needs and public policy.

## 2 Intensive Silvopastoral Systems

Among agroforestry systems, those that intentionally combine fodder plants, such as grasses and leguminous herbs, with shrubs and trees for animal nutrition and complementary uses are known as silvopastoral systems (SPS) (Murgueitio et al. 2011). Worldwide, the main SPS include live fences, windbreaks, scattered trees in pasturelands, managed plant succession, fodder tree banks (e.g. areas of concentrated protein-rich fodder crops), cut-and-carry systems, tree plantations with livestock grazing, pastures between tree alleys, and intensive silvopastoral systems (ISPS) (Murgueitio and Ibrahim 2008; Calle et al. 2012).

The main benefits of SPS compared to treeless pastures are: (i) increased efficiency of cattle production per ha (up to 4-fold) (Shelton and Dalzell 2007; Thornton and Herrero 2010; Murgueitio et al. 2011), (ii) reduced dependence on feed concentrates and grains due to the provision of higher quality forages (Mojardino et al. 2010; Barahona et al. 2014; Ribeiro et al. 2016), (iii) improvement of soil properties due to greater uptake and cycling of nutrients from deeper layers of soil, enhanced availability of nutrients from leaf-litter and increased nitrogen input by $N_2$-fixing trees (Nair et al. 2007; Vallejo et al. 2010; Cubillos et al. 2016), (iv) higher storage of carbon in both aboveground and belowground compartments of the system (Nair et al. 2010; Montagnini et al. 2013; Arias et al. 2015), (v) enhanced resilience of the soil to degradation, nutrient loss, and climate change (Ibrahim et al. 2010; Harvey et al. 2013; Murgueitio et al. 2013), (vi) improved habitat quality for biodiversity (Sáenz et al. 2007; Fajardo et al. 2010; Giraldo et al. 2011; Rivera et al. 2013; Montoya-Molina et al. 2016), and (vii) improved animal welfare (Broom et al. 2013).

Intensive Silvopastoral Systems (ISPS) are a type of SPS that combines high-density cultivation of fodder shrubs (4000–40,000 plants $ha^{-1}$) with: (i) improved tropical grasses; and (ii) tree or palm species at densities of 100–600 trees $ha^{-1}$. These systems are managed under rotational grazing with occupation periods of 12–24 h and 40–50 day resting periods, including *ad libitum* provision of water and mineralized salt in each paddock (Calle et al. 2012; Murgueitio et al. 2016; Roberts 2017, Chap. 4, this volume) (Fig. 16.1).

ISPSs respond to the urgent need to transform tropical cattle ranching into an environmentally friendly activity that can be profitable in the short and medium

**Fig. 16.1** ISPS with *Leucaena leucocephala* (density of 10,000 ha$^{-1}$) and *Eucalyptus tereticornis* as windbreaks at 30 m spacing at La Luisa Farm, Cesar, Colombia. The plot in the lower right was grazed the day before (Photo: Luis Solarte)

terms and capable of generating environmental services, rural jobs and provide safe, high-quality food (meat, milk and fruits), hides and wood (Calle et al. 2012; Montes-Londoño 2017, Chap. 3, this volume). These systems are suitable for beef, milk, dual-purpose or specialized cattle farming as well as buffalo, sheep, and goats (Calle et al. 2012).

## *2.1 Agroecological Principles Applied in Intensive Silvopastoral Systems*

Sustainable intensification of bovine livestock for climate change adaptation should apply agroecological principles to increase the efficiency of essential biophysical processes. One key principle of the agroecology strategy is designing agroecosystems that mimic the functioning of local ecosystems to resemble tight nutrient cycling, complex structure, and enhanced biodiversity. These systems can be more productive, pest resistant, and conserve nutrients (Doré et al. 2011; TWN and SOCLA 2015).

Several agroecological principles and strategies are applied at both designing and functioning of ISPS. The most important are: (i) use of several layers of vegetation (herbs, shrubs, trees, and palms) to maximize the transformation of solar energy into biomass, (ii) reduced dependency on agrochemical inputs and energy, emphasizing interactions and synergisms among biological components to enhance recycling and biological control, thus improving overall ecological efficiency and environmental protection (SOCLA 2014), (iii) incorporation and promotion of biodiversity into the system components and its surroundings, (iv) improvement of soil fertility with the presence of trees and shrubs that increase nitrogen fixation, phosphorus solubilization, and uptake of nutrients from deeper soil horizons (Vallejo et al. 2010; Nair 2011), (v) recovery of organic matter content and other important soil characteristics since trees deposit litter, protect soils from direct sunlight, and maintain soil humidity and temperature (McNeely and Schroth 2006), (vi) use of rotational grazing with short occupation and long resting periods to allow the recovery of forage biomass and soil biotic interactions, (vii) use of plants and animal breeds adapted to local conditions to improve resilience and reduce dependency on external inputs (Murgueitio et al. 2015b).

## 3 Contributions of ISPS to Improved Productivity

Grass is the most important feed resource for ruminants in the tropics. Under extensive grazing systems, cattle production is limited due to the poor quality of tropical grasses (with 2.5–7% of crude protein (CP) and 40–50% of dry matter (DM) digestibility) and to the reduced availability during the dry season (Wilkins 2000). As a consequence, cattle growth and milk production are low and decrease even more during the dry season.

Analysis of the continuously growing body of information on ISPS demonstrates that these systems produce more dry matter, digestible energy, and crude protein per ha, and have the capacity to increase milk or meat production while reducing the need of external inputs such as chemical fertilizers and concentrate feeds (Murgueitio et al. 2011; Ribeiro et al. 2016). Due to these characteristics, ISPS can improve productivity of grazing systems and reduce feed expenses in cattle production. The selection of the shrub species is a key factor for a successful ISPS (Calle et al. 2013) since it can provide up to 30% of additional DM in the system with higher nutrient quality and increased nutrient cycling. The most common species currently used are leucaena, *Leucaena leucocephala* (Lam.) de Wit., and the Mexican sunflower, *Tithonia diversifolia* (Hemsl.) A. Gray.

### *3.1* Leucaena leucocephala

*Leucaena leucocephala* is native to the Yucatan Peninsula of Mexico (Shelton 2005) where it was used by pre-Hispanic cultures as a source of food (seeds), wood, and firewood. It is a perennial drought-tolerant leguminous tree that grows well in

**Fig. 16.2** Gyr x Holstein crossbred cattle grazing on an ISPS with *Leucaena leucocephala* in Tinajas Farm, Michoacán, Mexico (Photo: Julián Chará)

tropical and subtropical regions (Radrizzani et al. 2010) and is recognized as a high value fodder for cattle due to its high content of crude protein, its low content of fiber, and its palatability, tolerance to direct browsing by cattle and fast regrowth (Barahona et al. 2014; Kennedy and Charmley 2012; Murgueitio et al. 2015a).

Australian grazers were the first to plant commercial stands of *L. leucocephala* (Dalzell et al. 2006) and the first to cultivate it at high density and integrated to grasses in the 1970s (Shelton and Dalzell 2007). Approximately 200,000 ha of this highly productive grass–legume grazing system for cattle existed in 2010, many of them with more than 30 years in operation (Radrizzani et al. 2010). In Latin America, ISPS with this species have been adopted particularly in Colombia and tropical areas of Mexico, although the species is also used in other silvopastoral arrays in Africa, Cuba, Dominican Republic, Haiti, Central America, Venezuela, Peru, Brazil, Paraguay, and Argentina (Murgueitio et al. 2011). Leucaena is also used in agroforestry systems where it provides shade for coffee and other crops (Montagnini et al. 1992). Figure 16.2 presents an ISPS with Leucaena in Michoacan, Mexico where at least 5000 ha have been planted for both dairy and beef production.

Intensive silvopastoral systems with leucaena have higher production of biomass with higher nutritional quality than traditional monocultures of grasses. In ISPS established in dry regions of Colombia, biomass production, including grasses and leucaena, ranged from 15.6 to 19.2 Mg of dry matter (DM) $ha^{-1}$ $year^{-1}$ and protein production from 2.86 to 3.12 Mg $ha^{-1}$ $year^{-1}$. In Mexico, DM yield in ISPS with leucaena in three farms varied between 3.62 and 4.79 Mg $ha^{-1}$ $rotation^{-1}$, more than three times higher than in an adjacent farm with a monoculture of star grass

**Table 16.1** Nutritional characteristics of *Cynodon plectostachyus* (K. Schum.) Pilg, and *Megathyrsus maximus* (Jacq.) B.K. Simon & S.W.L. Jacobs *var*. Tanzania in ISPSs with *Leucaena leucocephala* var. Cunningham in two regions of Colombia

| | | DM | NDF | ADF | CP | EE | Ca | P | Ash | GE |
|---|---|---|---|---|---|---|---|---|---|---|
| Region | Grasses | % | | | | | | | | *Mcal/kg* |
| Valle del Cauca | *C. plectostachyus* | 21.3 | 73.5 | 45.2 | 9.3 | 0.98 | 0.3 | 0.36 | 10.7 | 4247 |
| | *M. maximus* | 20.3 | 69.2 | 42.5 | 9.5 | 0.83 | 0.38 | 0.27 | 13.4 | 4054 |
| | *L. leucocephala* | 21.9 | 33.9 | 30.6 | 27.2 | 1.71 | 1.33 | 0.24 | 6.9 | 4682 |
| Cesar | *C. plectostachyus* | 22.3 | 66.8 | 35.4 | 9,8 | 0.9 | 0.43 | 0.59 | 8.9 | 3912 |
| | *M. maximus* | 21.9 | 70.1 | 43.6 | 11.1 | 0.8 | 0.45 | 0.26 | 10.2 | 3854 |
| | *L. leucocephala* | 21.8 | 25.5 | 16.6 | 28.4 | 2.56 | 1.39 | 0.27 | 6.7 | 4525 |

*DM* Dry matter, *NDF* Neutral Detergent Fiber, *ADF* Acid Detergent Fiber, *CP* Crude protein, *EE* Ether extract, *Ca* Calcium, *P* Phosphorus, *GE* Gross Energy

(*Cynodon plectostachyus* (K. Schum.) that produced 0.95 Mg of DM ha$^{-1}$ rotation$^{-1}$. During the rainy season, DM production in ISPS per rotation varied from 4.8 to 5.4 Mg ha$^{-1}$ and that of the grass monoculture reached 1.2 Mg ha$^{-1}$ (Solorio-Sánchez et al. 2011).

In addition to the higher production and availability of biomass for cattle, the nutritional quality of this biomass is also improved, as fodder shrubs incorporated into ISPS contain almost three times as much protein as tropical grasses and have low fiber content with values under 41% of neutral detergent fiber (NDF) and 30% of acid detergent fiber (ADF) (Murgueitio et al. 2015a).

Table 16.1 presents information on the nutritional characteristics of two grasses, *Cynodon plectostachyus* (K. Schum.) Pilg, and *Megathyrsus maximus* (Jacq.) B.K. Simon & S.W.L. Jacobs *var*. Tanzania in ISPSs with *L. leucocephala* var. Cunningham in two regions of Colombia.

The low fiber content in *L. leucocephala* generates advantages in terms of dry matter intake by grazing ruminants. This happens because the cell wall content of a plant is one of the physical factors with greater effect on feed consumption. As the fiber has a lower degradation rate in the rumen, it takes up more space in the digestive track (Barahona and Sánchez 2005).

Due to the low fiber content of leucaena, cattle grazing in ISPS with this species tends to have higher DM intake. Barahona et al. (2014) found that DM consumption of steers (250 kg of living weight) grazing in an ISPS with leucaena, *C. plectostachyus* and *M. maximus*, was equivalent to 2.65% of body weight, higher than those in a traditional system that consumed only 2.35%. In another study in Colombia, animals grazing in ISPS also had greater DM intake as a percentage of body weight (2.61% *vs*. 2.04%). The animals in the ISPS also had a higher intake of crude protein (954 g), calcium (62.1 g) and fat (94.2 g) per day than those grazing in a monoculture pasture (499 g, 36.2 g and 69.6 g respectively) (Cuartas et al. 2015).

In ISPSs with rotational grazing, the stocking rate ranges from 2.0 to 4.5 Animal Units (AU of 450 kg), five times higher than that of native grasslands and similar to that of improved grasses with irrigation and fertilization in the tropics (Calle and Murgueitio 2008a; Flores and Solorio-Sánchez 2012).

Due to these traits, in ISPS, production of beef or milk per animal and per hectare is increased. When compared with degraded pastures the amount of meat produced per ha in ISPS increased from 74 kg $year^{-1}$ (stocking rate (SR): 0.55 $ha^{-1}$, daily weight gain (DWG): 370 g) to 1060 kg $year^{1}$ (SR: 3.5 $ha^{-1}$, DWG: 830 g) (Mahecha et al. 2011). As a result, the amount of land required to produce a Mg of meat per year is reduced from 13.5 to 1 ha. Similar results were found in Mexico where production of meat increased from 456 kg $ha^{-1}$ $year^{-1}$ in an improved pasture to 1971 kg in an ISPS (Solorio-Sánchez et al. 2011). In other study Thornton and Herrero (2010) estimated a 2.7- and 4.8-fold increase in milk and meat production respectively when leucaena was incorporated in the diet with a reduction in the amount of GHG per unit of product.

## *3.2* Tithonia diversifolia

*Tithonia diversifolia* (Hemsl.) Gray, commonly known as Mexican sunflower, is a perennial shrub native from Mexico and Central America that is widely distributed around tropical and subtropical areas of America, Africa, and Asia thanks to its adaptation capacity to different environmental conditions (Sampaio et al. 2016). It is cultivated by its ornamental and therapeutic uses in different countries (Hui et al. 2009; Duarte and Bonissoni 2012) and also as green manure to improve soils and as forage for animal nutrition (Tiebre et al. 2012; Mauricio et al. 2014).

One of the most important attributes of this species is its wide adaptation capacity to tropical and subtropical environments and different rainfall regimes. Close to the Ecuadorian line, it grows from sea level up to 2500 m of altitude with rain fall values from 800 to 5000 mm per year (Calle and Murgueitio 2008b). It also has a wide range of adaptation to soil types from sandy- to clay-dominated and with a wide spectrum of fertility and high tolerance to acidic and very acidic soils, and soils with a high content of iron and aluminum (Rivera et al. 2015a; Murgueitio et al. 2015a). *Tithonia diversifolia* has a rapid growth, tolerance to cattle browsing, high yield of DM, and high content of protein, calcium, and phosphorus (Mahecha et al. 2007; Verdecia et al. 2011; Rivera et al. 2015a). Figures 16.3 and 16.4 show ISPSs with *Tithonia diversifolia* and *Cynodon plectostachyus* in San José farm in Ulloa, Colombia and La Pendiente farm in Misiones, Argentina.

In the Amazonian basin of Colombia, a study was carried out to determine the effect of the ISPS with *Tithonia diversifolia* (*ca.* 5000 shrubs $ha^{-1}$), dispersed trees and a mixture of grasses of the genus *Urochloa* and *Brachiaria* (*Urochloa decumbens, U. brizantha* and *B. humidicola*) in the production of milk. The biomass yield per ha for each rotation in the ISPS was 2.43 Mg $ha^{-1}$ (0.36 Mg of *T diversifolia* and 2.06 Mg of grass), 44% higher than the areas with conventional *Urochloa-Brachiaria* pastures (Rivera et al. 2015a). The production of milk was higher in the ISPS (15.4 kg of milk $ha^{-1}$ $day^{-1}$) than in the conventional system (9.74 kg of milk $ha^{-1}$ $day^{-1}$), as a result of the higher carrying capacity (that increased from 1.84 to 2.71 AU $ha^{-1}$) and individual daily production (from 4.59 to 4.92 kg: $p = 0.01$). Milk quality was

**Fig. 16.3** ISPS with *Tithonia diversifolia* and *Cynodon plectostachyus* in San José farm, Ulloa – Valle del Cauca, Colombia (Photo: Fernando Uribe)

**Fig. 16.4** ISPS with *Tithonia diversifolia* and *Cynodon plectostachyus* and Braford (Brahman x Hereford) cattle in La Pendiente farm, Misiones, Argentina (Photo: Julián Chará)

also improved as the production of protein, fat, and total solids were 29, 33 and 36% higher respectively in the ISPS ($p < 0.01$). As a result, the income from milk sales increased by 42.1% compared to conventional pastures (Rivera et al. 2015a).

In Minas Gerais, Brazil, Calsavara et al. (2016) evaluated the nutritional value of *T. diversifolia*, harvested in two growing stages (booting and pre-flowering) and its potential as source of forage for ruminants. Fresh and DM production were higher at booting stage (beginning of the reproductive phase) (41.3 and 8.1 Mg ha$^{-1}$ respectively) than at pre-flowering stage (24.7 and 5.6 Mg ha$^{-1}$ respectively). A similar trend was found in Cuba where DM content of *T. diversifolia* grew from 19.7% at 60 days to 29.5% at 180 days although with a drop in crude protein content from 28.9 to 18% (Verdecia et al. 2011).

# 4 Environmental Aspects

## *4.1 Carbon Capture*

Several studies have demonstrated that tree incorporation in croplands and pastures results in greater net C storage above- and below-ground (Montagnini and Nair 2004; Haile et al. 2010; Montagnini et al. 2013). The estimates of carbon sequestration potential of agroforestry systems are highly variable, ranging from 0.29 to 15.21 Mg ha$^{-1}$ year$^{-1}$ aboveground and 30–300 Mg C ha$^{-1}$ up to 1 m depth in the soil (Nair et al. 2009; Nair 2011). For SPS, the above-ground carbon sequestration potential ranges from 1.5 Mg ha$^{-1}$ year$^{-1}$ (Ibrahim et al. 2010) to 6.55 Mg ha$^{-1}$ year$^{-1}$ (Kumar et al. 1998). These values are a direct manifestation of the ecological production potential of the system, depending on a number of factors, including site and soil characteristics, species involved, stand age, and management practices (Nair et al. 2010). The amount of soil organic carbon (SOC) can be increased between 20 and 100% when $N_2$-fixing tree legumes are incorporated since they promote greater plant productivity (Kaye et al. 2000; Resh et al. 2002; Rhoades et al. 1998). According to Radrizzani et al. (2011) leucaena SPS in Queensland accumulated between 79 and 267 kg ha$^{-1}$ year$^{-1}$ more than adjacent pure grass plots. In a study in Colombia, Arias et al. (2015) found that on average aboveground carbon stock was 13.42 Mg of $CO_2$-eq ha$^{-1}$ in ISPS and 7.55 Mg of $CO_2$-eq ha$^{-1}$ in control sites with conventional pasture monoculture.

## *4.2 Reduction of GHG Emissions*

In cattle production systems, high GHG emissions are largely caused by increased enteric methane production due to low feed digestibility, low productive parameters such as slow growth rates that cause more emissions per kg of meat and high age at slaughter due to more emissions associated to a longer life (Gerber et al. 2013).

Although agriculture and cattle grazing are viewed as major sources of GHG emissions, they also hold a great potential to contribute to mitigation, by reducing emissions and enhancing carbon sinks (Neely et al. 2009). It is estimated that 89% of potential GHG emission reductions from agriculture up to 2030 will be due to reductions in $CO_2$ emissions (Smith et al. 2008).

In this context, GHG emissions from cattle in ISPS are reduced as a result of high efficiency and low emissions per kg of metabolizable energy (ME) consumed. As a result of high ME and crude protein (CP) content and less neutral detergent fiber present in ISPS (Barahona et al. 2014) the $CH_4$ emissions per unit of dry matter consumed and per unit of product are reduced.

According to Archimède et al. (2011) animals fed tropical legumes produced 20% less $CH_4$ ($p < 0.05$) than those fed C4 grasses. When concentrates and part of the basal diet were replaced by leaves of *Leucaena leucocephala*, Thornton and Herrero (2010) estimated that GHG emissions per unit of milk and meat produced were 43% and 27% of the emissions without the legume respectively. In their study, the mitigation potential of this practice was of 32.9 Mt. $CO_2$-eq; 28% coming from the reduction in livestock numbers, and 72% contributed from the carbon sequestration effects (Thornton and Herrero 2010).

Several studies have been carried out in Brazil, Colombia, and Australia, to measure the potential of ISPS based on *Leucaena leucocephala* and *Tithonia diversifolia,* to reduce GHG emissions from cattle in relation to conventional systems. $CH_4$ produced by enteric fermentation has been measured *in vivo* (Molina et al. 2015b, 2016; Ribeiro et al. 2016), *in vitro* (Huang et al. 2011; Molina et al. 2013; Naranjo 2014; Rivera et al. 2015b; Terry et al. 2016), or modelled using the carbon footprint and the GHG balance (Naranjo et al. 2012; Harrison et al. 2015; Rivera et al. 2016).

With regards to enteric emissions, Molina et al. (2016) found that heifers receiving a diet based on *Cynodon plectostachyus* (K.Schum.) Pilg. with 25% inclusion of *L. leucocephala*, had a reduction of 15% in emissions from 30.8 to 26.6 liters of $CH_4$ $kg^{-1}$ of DM consumed. They also reported a reduction in energy loss due to $CH_4$ production in the rumen when *L. leucocephala* was included in the diet. Similar results were found by Molina et al. (2015a) with the inclusion of 24% *L. leucocephala* in a diet based on *C. plectostachyus* and *Megathyrsus maximus*. In both cases, animals with *L. leucocephala* had 15–20% higher DM intake than those with the grass-based diet. This increment in dry matter intake and daily gain however was not accompanied by increased methane emissions per unit of weight gain. Thus, in a kg of weight gain basis, steers in ISPS emit at least 33% less methane than steers in grass-only pastures, whereas emissions per liter of milk could be 50% lower in ISPS (Thornton and Herrero 2010). Increases in meat and milk production and reductions in methane emissions are related to improved nutritional fodder quality in the ISPS compared with pastures in monoculture.

These results are explained because the inclusion of *L. leucocephala* reduces the total Neutral Detergent Fiber and this reduces methane emissions (Archimède et al. 2011). The condensed tannin content of *L. leucocephala* can also explain this reduction (Barahona et al. 2003; Naranjo 2014) since these compounds inhibit the growth of some ruminal microorganisms (Archimède et al. 2011; Huang et al. 2011).

Condensed tannins in *L. leucocephala* are known to be smaller than those present in other legumes (Barahona 1999), and their effect on fibrolytic enzymes is not as pronounced (Barahona et al. 2006) and therefore they do not have noticeable effects on DM and fiber digestibility (Barahona et al. 2003). Rivera et al. (2015a) reported that *in vitro,* a 25% inclusion of leucaena in star grass diets, reduced in 13% the production of $CH_4$ per kg of degraded DM ($p = 0.0016$).

As for *L. leucocephala*, there is a potential to reduce methane emissions with *T. diversifolia* since this species also has low levels of fiber. Molina et al. (2015b) and Donney's et al. (2015) evaluated the effect of the inclusion of *T. diversifolia* on the production of methane in conventional pasture diets. Although there were no differences in the daily emissions of $CH_4$ per day ($p = 0.351$), the emissions per kg of weight gain were reduced from 22.32 kg of $CO_2$-eq kg$^{-1}$ in a diet based on *Brachiaria decumbens* to 4.89 kg of $CO_2$-eq kg$^{-1}$ when *T. diversifolia* was included ($p = 0.002$) (Molina et al. 2015b).

On the other hand, Donney's et al. (2015) found that the dietary inclusion of 20–25% *T. diversifolia* reduced in 10% the *in vitro* production of $CH_4$ per kg of degraded matter in diets based on *Cenchrus clandestinus* and up to 15% in diets based on *Brachiaria* grasses.

In Brazil, Ribeiro et al. (2016) found that the inclusion of *T. diversifolia* at 15.4% of DM had no effect on intake, milk production and composition, nitrogen balance or enteric methane emissions. The high-nutrition qualities of *T. diversifolia* allowed the replacement of 20.8% of sugar cane and 11.4% of concentrate feed with no significant effect on methane production. From this experiment, it was concluded that *T. diversifolia* could be used as high quality forage to replace concentrate for ruminants without side effects on performance and methane production in tropical crossed-breed dairy cows.

In a study comparing three ISPS, one with *Leucaena* and two with *Tithonia*, and three conventional pasture systems located in contrasting regions of Colombia, Rivera et al. (2016) found that on average, ISPS generated 15% less emissions to produce 1 kg of fat and protein corrected milk (FPCM), 20% less to produce a kg of milk fat and 15% less to produce a kg of milk protein than the conventional pastures. The carbon footprint for an ISPS with *Leucaena* and star grass and for a conventional grass monoculture system was 1.96 *vs.* 2.19 kg of $CO_2$-eq kg$^{-1}$ of FPCM respectively. In addition, when balancing GHG emissions with the carbon sequestration it was determined that the ISPS had a net capture of 6.1 Mg $CO_2$-eq ha$^{-1}$ (Rivera et al. 2016).

## 5 Economic Implications

In order to determine the economic implications of introducing these systems in Colombia, four pioneer farms in establishing ISPS were analyzed (World Animal Protection et al. 2014). As a first step, the baseline situation was determined, specified, and quantified showing the farms' status before ISPS implementation; then, a

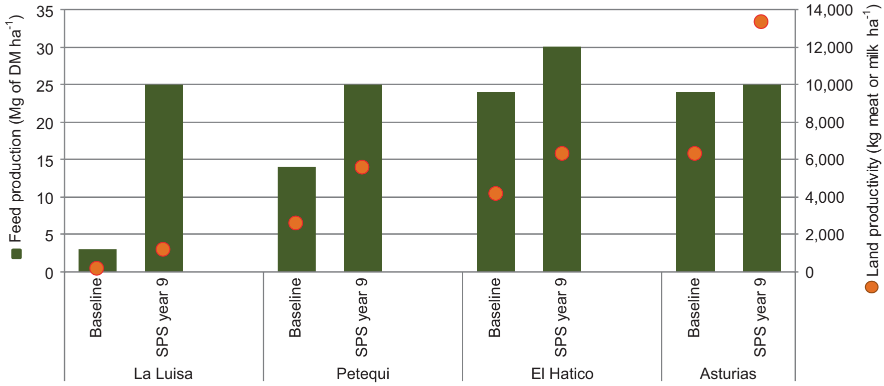


**Fig. 16.5** Feed production and land productivity in farms with ISPS in three regions of Colombia. The baseline scenario represents conventional management of pastures without trees, at year 1

detailed pathway of the introduction of the systems and their implications on productivity and farm economics was assessed and modelled for 10 years (World Animal Protection et al. 2014). Although all farms implemented ISPS in 47–70% of the grazing area in less than 10 years, there was an important variation in the history of the farms since one of them started from degraded pastures with very low productivity while the remaining three had improved grasses and a relatively intensive management with high costs before the introduction of ISPSs. Once the systems were fully established, feed production had an eight fold increase in the farm with the degraded baseline scenario (from 3 to 25 Mg of DM $ha^{-1}$ $year^{-1}$) and from 4 to 79% increase in the farms with a more intensive baseline scenario (Reyes et al. 2016).

In addition to the higher amount of DM available, for these farms the quality of the fodder was also improved due to the inclusion of leucaena, but the most important fact was that the increased biomass yield was obtained with the elimination of the need of nitrogen fertilizers and the reduction of protein feed requirement for cattle. As a result of the improved availability and better quality of biomass, farm productivity in milk or beef per ha increased from 52 to 82% after the introduction of ISPS; on average, milk production raised from 4329 to 8390 kg $ha^{-1}$ $year^{-1}$ (Reyes et al. 2016) (Fig. 16.5).

The implementation of ISPS implied higher investment costs as compared with pasture monocultures. The investment and maintenance cost of ISPS ranged from US$ 2692 to $3187 per ha. Further, for La Luisa farm (beef finishing) and Petequi farm (cow-calf), purchases of animals for the growth of the herd, which generate returns in terms of weaner calves and finished animals at a later stage, also constitute investment costs. From a mid-term perspective, the implementation cost is however compensated by an increase in farm returns due to higher productivity. For dairy farms, once the system is installed, maintenance cost is lowered due to the reduction of external inputs such as fertilizers, mineralized salt, and commercial

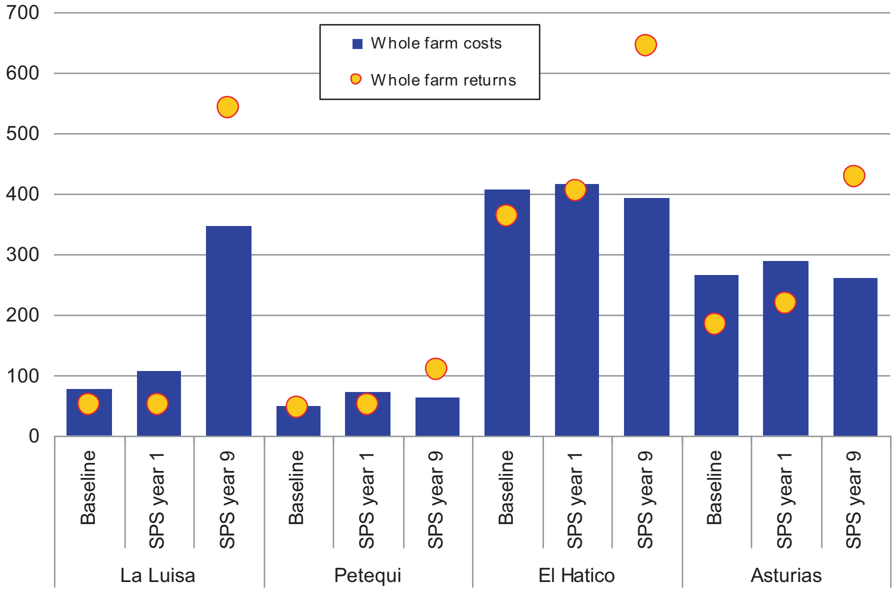


**Fig. 16.6** Impact of ISPS on the returns and costs at whole farm level in three regions of Colombia. Whole farm costs and returns: thousands of US dollars (´000 USD). Size of the farms ranged between 30 (Petequí) and 200 has (La Luisa). The baseline scenario represents conventional management of pastures without trees, at year 1. It can be seen from the Figure that in all cases the annual returns at year 9 substantially increase from those of year 1 (56–72% as shown in text)

feed supplements. After the initial investment and a stabilization period, the higher productivity per hectare generates returns that ensure the economic viability of ISPS. Analyzing income values, after the 6th year, they cover the costs and leave a positive balance in the cash flow, achieving situations of large economic surplus. Figure 16.6 shows the impact of the silvopastoral system on the returns and costs at whole farm level. For this study, the farm income and profitability was 56–72% higher than that of the baseline scenarios (Reyes et al. 2016).

The study demonstrated that the introduction of ISPS increased yield and improved farm profitability as it was also demonstrated by Murgueitio et al. (2015a). However, the first years of establishment are characterized by investments in infrastructure and animals, resulting in reduced cash flow and profitability during this initial period.

## 6 Implications for Public Policy

Despite their on-farm and off-farm benefits, ISPS have not been widely implemented so far due to several barriers, including the lack of technical assistance to farmers that need to adapt the system to local conditions and their high initial cost and technical complexity. According to Calle et al. (2013), ISPS require high initial investment which defies the prevailing view of tropical cattle ranching as a low-investment activity. Additionally, the technical complexity of some ISPS demands a specialized knowledge that is not available among farmers, professionals, conventional academia, or commercial rural extension companies in the field (Calle and Murgueitio 2008b).

Local governments can play a significant role in the access to capital as well as in extension services targeting the management of the systems. The economic analysis provided evidence for the ability of ISPS to create ‘triple-win’ solutions for sustainable livestock production, productivity and profitability gains, environmental improvements, and animal welfare benefits (Reyes et al. 2016).

To encourage ISPS adoption, it is required to increase technical capacity at local level and to improve the accessibility of farmers to technical and financial resources. This should be pursued from national policies including credit lines and incentives such as payment of environmental services. Policies that promote specialized training for extension workers and technicians are also required.

Specialized market incentives (included in the prices paid for products of ISPSs) are also desirable. Small-scale farmers need access to markets and subsidies throughout the certification process. Larger and entrepreneurial producers need incentives and promotion to enter marketing chains (Calle et al. 2012).

A recent FAO study on policies to encourage sustainable farming in Mesoamerica concluded that in the region there are different types of policy instruments that can be used to encourage the development of SPS. These instruments include the strengthening of institutional capacities for research and training and increased technology transfer especially to the farmer organizations with emphasis on the establishment and management of SPS. It also highlights the application of the methodology of agricultural field schools, the design of financial support instruments linked or not to rural credit, payment for environmental services, as used in Colombia (Zapata et al. 2015), and access to different markets. The success of these processes depends on the simultaneous and coordinated implementation of several of them (Acosta et al. 2014). One aspect that is most important in the dissemination of SPS is the dialogue between scientific knowledge and local expertise, and the farmer to farmer exchange through informal meetings or meetings with producers, technicians and scientists to share experiences between different regions and countries with similar problems.

More research is needed to increase the number of species used as fodder shrubs adapted to different soil and climatic conditions in the tropics and subtropics. More knowledge of native trees and pastures and their interactions is also required. In relation to the tree component, technology for the introduction of forest species in ranchlands is scarce, especially in tropical countries. Development of silvicultural practices, markets, and wood-processing techniques for timber produced in silvopastoral systems is insufficient (Calle et al. 2012). The development of such practices will contribute to improve the profitability of the system and to persuade farmers to introduce timber trees in important regions where the market for forestry products is not yet developed.

## 7 Conclusions

Due to its lower dependence on external inputs such as fertilizers and concentrates, and to improved animal production ISPS are a valid alternative to increase productivity and lower environmental burdens of livestock production. Cattle production in Latin America can continue contributing to the economy and livelihoods of many countries (rural populations), and at the same time contribute to protect and restore ecosystems and to meet the pledges of the countries in terms of reduction of deforestation and GHG emissions. ISPS can also contribute to the Sustainable Development Goals (SDG), mainly those related to responsible production and consumption, climate action, life on earth, and zero hunger.

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# Chapter 17
# Enhancing Biodiversity in Neotropical Silvopastoral Systems: Use of Indigenous Trees and Palms

**Zoraida Calle D., Adriana María Giraldo S., Adolfo Cardozo, Adolfo Galindo, and Enrique Murgueitio R.**

## 1 Introduction

Native trees and palms play important roles in tropical livestock systems. These species provide direct benefits through the production of timber and edible fruits for the cattle, and indirect benefits through nitrogen fixation, soil conservation, and the natural biological control of pests. The incorporation of nitrogen-fixing trees is a common practice in agroforestry and silvopastoral systems. However, non-nitrogen-fixing trees also enhance the physical, chemical, and biological properties of soil by adding significant amounts of above and belowground organic matter and by releasing and recycling nutrients in silvopastures (Jose 2009).

Synergies between climate change adaptation and mitigation are particularly likely in projects that promote tree products as a means for diversifying farmer income, improving soil fertility and landscape connectivity, and enhancing resilience to extreme weather events (Matocha et al. 2012; Harvey et al. 2014). A higher

Z. Calle D. (✉)
Fundación CIPAV (Center for Research on Sustainable Agricultural Production Systems), Cali, Colombia

ELTI (Environmental Leadership & Training Initiative), Yale University, New Haven, CT, USA
e-mail: zoraida@fun.cipav.org.co; http://www.cipav.org.co

A. M. Giraldo S. · A. Galindo
Fundación CIPAV (Center for Research on Sustainable Agricultural Production Systems), Cali, Colombia

E. Murgueitio R.
Centro para la Investigación en Sistemas Sostenibles de Producción Agropecuaria, CIPAV, Cali, Colombia

Mainstreaming Sustainable Cattle Ranching Project, Bogotá, Colombia

A. Cardozo
Nueva Cendigranja, Guanare, Portuguesa, Venezuela



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diversity and density of native trees in pastures contributes to the adaptation of cattle ranching to climate change by providing shade, shelter, and welfare to the animals (Broom et al. 2013), while mitigating climate change by storing carbon in the soil and biomass (Chará et al. 2015).

However, relatively few native trees and palms are actively managed by cattle ranchers in the nearly 600 million hectares currently occupied by this activity in Latin America and the Caribbean (Murgueitio et al. 2011). Montagnini et al. (2003) suggested that research on timber trees for silvopastoral systems should focus on identifying high value commercial species that could enhance the growth of pastures while tolerating the disturbances of cattle grazing. However, during the past few decades, the need for reducing heat stress has provided a stronger motivation for ranchers to plant or maintain native trees than their interest in timber as a complementary source of income (Calle et al. 2013).

Researchers should be aware of the context in which this demand for knowledge on native trees is emerging (Calle et al. 2012, 2015a, b). Cattle ranchers generally control large land areas but have insufficient hand labor, and therefore have a limited investment capacity per unit area. This means that they require fast growing, hardy, or resilient species that will not inhibit pasture growth (Murgueitio et al. 2015). Most species with dense canopies will be rejected by cattle ranchers. Wide crown trees will be tolerated as long as they allow sufficient light to reach the ground and sustain grass biomass production underneath. Tree management must be simple, especially during the first years, when the direct benefits of trees are still modest (Vieira et al. 2014).

Many native trees and palms meet these pragmatic criteria. Some palm species such as *Acrocomia* spp. and *Attalea* spp. regenerate in pastures and tolerate fire, herbicides, browsing, and trampling from cattle (Calle and Murgueitio 2008). However, most cattle ranchers have undervalued these accessible resources. Native palms should play a major role in agroforestry for sustainable animal production (Baldizán 2007; Cardozo 2007; Hernández et al. 2007; Murgueitio and Ibrahim 2008), since they complement the herbaceous forage provided by grazing paddocks (Ocampo 1999; Calle and Murgueitio 2008). Their fruits, which are consumed by pigs, cattle, sheep, and domestic fowl (González 2008) are also a strategic resource as these animals feed on them due to their high concentration of fats and protein (Hiane et al. 2005).

All native species that become incorporated into silvopastoral systems will make an important contribution to biodiversity conservation by providing resources for wildlife (Rivera et al. 2013; Montoya-Molina et al. 2016). Endangered or vulnerable tree and palm species that can be deliberately added to cattle ranching systems will have a lower risk of local extinction.

We propose adopting the focal species concept in projects that promote silvopastoral systems in Latin America as a complementary strategy for mainstreaming biodiversity in cattle ranching. In this context, focal species are native trees and palms that can be incorporated directly into silvopastures, live fences, or riparian buffers to enhance biodiversity and environmental services in cattle dominated landscapes. As an example, we mention the 50 focal species promoted by the *Mainstreaming Biodiversity into Sustainable Cattle Ranching* (MBSCRP) Project in Colombia.

In this chapter, we present preliminary data on two native tree species and one palm that have not been studied sufficiently in the context of agroforestry and silvopastoral systems. These species can contribute to the sustainability of livestock production, and cattle ranching offers conservation opportunities for all of them. We first compare the survival and growth performance of the endemic tree *Mimosa trianae* and the highly endangered big-leaf mahogany *Swietenia macrophylla*, planted in live fences in the Cauca river valley of Colombia. Finally, we describe the contribution of *Acrocomia aculeata* palms for livestock production in the Llanos of Colombia and Venezuela.

## 2 Focal Species in Silvopastoral Landscapes

Between 19,000 and 25,000 tree species are believed to exist in the Neotropical region (Slik et al. 2015). Of this enormous diversity, only a few species can adapt to the disturbance regime of cattle ranching. Nitrogen-fixing trees in the Fabaceae family are generally the most prominent multi-purpose species because they provide shade, timber, and fruit, while also enhancing pasture growth. This family includes common large trees such as *Albizia saman* (Jacq.) F. Muell., *Albizia guachapele* (Kunth) Dugand, and *Enterolobium cyclocarpum* (Jacq.) Griseb, which improve habitat structure for wildlife from dung beetles to birds and mammals; the medium sized *Albizia niopoides* (Spruce ex Benth.) Burkart and *Albizia lebbeck* (L.) Benth.; and the hardy *Prosopis* spp., which covers vast, dry, and semi-arid regions of the tropical Americas and provides valuable food sources for cattle, goats, donkeys, and sheep. Throughout the region *Gliricidia sepium* (Jacq.) Kunth ex Walp. and *Erythrina* spp. are very popular as trees for live fences.

Other species provide vital feed for cattle; these include non-nitrogen-fixing leguminous trees such as *Cassia grandis* L. f. and *Cassia moschata* Kunth, and species from different families such as *Crescentia* spp. (Bignoniaceae), *Guazuma ulmifolia* Lam. (Malvaceae) and *Brosimum alicastrum* Sw. (Moraceae), among many others. The genera *Tabebuia* (Bignoniaceae) and *Cordia* (Boraginaceae) include certain valuable timber species with medium to small crowns that grow well as scattered trees or trees in live fences.

Even though these common multi-purpose trees might seem diverse enough for designing silvopastoral systems with biodiversity conservation benefits, some trees and palms with great potential are being left out, including species with high cultural and aesthetic value, fruit trees, and important food resources for wildlife. The focal species approach is based on identifying a group of species with contrasting life histories and habitats, which are representative of other components of biodiversity (Lambeck 1997). An underlying assumption of this approach, widely applied in conservation biology, is that the measures adopted to ensure the conservation of a suite of focal species will benefit other species as well (Nicholson et al. 2013). For example, by choosing the palm *Mauritia flexuosa* as a focal species in a conservation project in Colombia (Proyecto Vida Silvestre), it is expected that other plants and wildlife will benefit from the restoration work done to enhance the habitat for this species.

Two landscape-scale projects that have promoted the implementation of silvopastoral systems together with the restoration of riparian buffers in Colombia have applied an agroforestry version of the focal species concept (Calle and Piedrahita 2007). The *Mainstreaming Biodiversity into Sustainable Cattle Ranching* project (MBSCR),[1] promotes the planting of 50 focal species of native trees and palms of global conservation concern in cattle farms in the five project regions (Calle et al. 2015a, b). Although the intention was to have 10 focal species for each project region, some species are common to two or more regions; therefore more than 10 focal species are planted in some regions. This set of rare, vulnerable, and endemic species includes trees and palms that grow well in open or semi-open environments, valuable timber trees, and species with important ecological, aesthetic, and cultural value.

The MBSCR project seeks to enhance the connectivity between natural ecosystems in cattle dominated landscapes through biological corridors and riparian forests. To achieve this goal, the Project uses a short-term Payment for Environmental Services (PES) to partially offset investment costs in land uses that are compatible with biodiversity (both conservation and productive). Livestock farm owners who opt for conservation (preservation of natural ecosystems or ecological restoration) also receive short-term PES. In recognition of the special effort that must be made to adopt one or several focal species, farmers eligible for PES receive an additional bonus for planting and caring for these native species on their farms.

The focal species of the MBSCR Project belong to 22 families (Table 17.1). The list includes species of Lauraceae (all native tree species), Fabaceae (7 species and 2 genera), Arecaceae (8 species), Bignoniaceae and Meliaceae (4 species each), Anacardiaceae (3), Euphorbiaceae, Malvaceae, Moraceae, Podocarpaceae and Sapotaceae (2 species each), and a single species of the remaining families (Apocynaceae, Boraginaceae, Combretaceae, Escalloniaceae, Fagaceae, Juglandaceae, Lamiaceae, Lecythidaceae, Malvaceae, Urticaceae and Zygophyllaceae).

Most focal species have a variety of uses. Some produce high value nuts (*Caryodendron orinocense* H. Karst.) or edible fruits for humans (*Spondias mombin* L., *Aiphanes horrida* (Jacq.) Burret, *Chrysophyllum argenteum* Jacq., *Pouteria sapota* (Jacq.) H.E. Moore & Stearn, *Pourouma cecropiifolia* Mart.). Other species were chosen for a combination of hardiness and their abundant provision of food resources for wildlife and cattle: *Attalea butyracea* (Mutis ex L. f.) Wess. Boer, *Crescentia cujete* L. and *Croton magdalenensis* Müll. Arg.). A few focal species have significant cultural value (the wax palms *Ceroxylon alpinum* Bonpl. ex DC. and *Ceroxylon quindiuense* (H. Karst.) H. Wendl.). Others provide valuable timber (*Astronium graveolens* Jacq., *Aspidosperma polyneuron* Müll. Arg., *Cordia gerascanthus* L. and *Terminalia amazonia* (J.F. Gmel.) Exell). Some are outstanding

[1] The Mainstreaming Biodiversity into Sustainable Cattle Ranching (MBSCR) Project is a public-private partnership sponsored by The Global Environment Fund with cooperation from the Department of Business, Energy, and Industrial Strategy of the United Kingdom, and managed by The World Bank. Partners in Colombia are Fedegan (Federación de Ganaderos de Colombia), CIPAV, Fondo Acción, and The Nature Conservancy.

**Table 17.1** Focal species of mainstreaming biodiversity into sustainable cattle ranching project

| Family | Scientific name | Conservation status | Habitat structure | Food for wildlife | Cattle feed | Aesthetics | Cultural value | Timber | Conservation value |
|---|---|---|---|---|---|---|---|---|---|
| Anacardiaceae | *Anacardium excelsum* (Bertero & Balb. ex Kunth) Skeels | NT – National | x | x | | | | | |
| Anacardiaceae | *Astronium graveolens* Jacq. | | | x | | | | x | x |
| Anacardiaceae | *Spondias mombin* L. | LC | | x | x | | | | |
| Apocynaceae | *Aspidosperma polyneuron* Müll. Arg. | EN – National | | | | | | x | x |
| Arecaceae | *Aiphanes horrida* (Jacq.) Burret | CR A2cd + 4cd | | x | | x | | | x |
| Arecaceae | *Attalea butyracea* (Mutis ex L. f.) Wess. Boer | LC – National | x | x | x | | | | x |
| Arecaceae | *Ceroxylon alpinum* Bonpl. ex DC. | VU A2c – Global | | x | | x | x | | x |
| Arecaceae | *Ceroxylon quindiuense* (H. Karst.) H. Wendl. | EN A2cd – National | | x | | x | x | | |
| Arecaceae | *Copernicia tectorum* (Kunth) Mart. | | | x | | | | | |
| Arecaceae | *Mauritia flexuosa* L. f. | EN A2ace – Global | x | x | | | | | |
| Arecaceae | *Sabal mauritiiformis* (H. Karst.) Griseb. & H. Wendl. | NT – National | | x | | | | | |
| Arecaceae | *Syagrus sancona* H. Karst. | NT – National | | x | | x | | | |
| Bignoniaceae | *Crescentia cujete* L. | | | x | x | | x | | |

(continued)

**Table 17.1** (continued)

| Family | Scientific name | Conservation status | Habitat structure | Food for wildlife | Cattle feed | Aesthetics | Cultural value | Timber | Conservation value |
|---|---|---|---|---|---|---|---|---|---|
| Bignoniaceae | *Tabebuia chrysantha* (Jacq.) G. Nicholson | | | | | x | | x | |
| Bignoniaceae | *Tabebuia coralibe* Standl. | EN A2cd – National | | | | x | | x | x |
| Bignoniaceae | *Tabebuia rosea* (Bertol.) DC. | | | | | x | | x | |
| Boraginaceae | *Cordia gerascanthus* L. | LC | | | | | | x | |
| Combretaceae | *Terminalia amazonia* (J.F. Gmel.) Exell | | | x | | | | x | x |
| Escalloniaceae | *Escallonia paniculata* (Ruiz & Pav.) Roem. & Schult. | | x | | | | | x | |
| Euphorbiaceae | *Caryodendron orinocense* H. Karst. | EN A2cd-National | | x | | | | | x |
| Euphorbiaceae | *Croton magdalenensis* Müll. Arg. | VU A2acd – National | x | | | | | | |
| Fabaceae | *Albizia guachapele* (Kunth) Dugand | | x | | | | | x | |
| Fabaceae | *Albizia saman* (Jacq.) F. Muell. | | x | | | | | x | |
| Fabaceae | *Caesalpinia ebano* H. Karst. | VU A2cd – National | | | | | x | x | x |
| Fabaceae | *Enterolobium cyclocarpum* (Jacq.) Griseb. | NT | x | | | | | x | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Fabaceae | *Erythrina* spp. (Erythrina poeppigiana (Walp.) O.F. Cook, *Erythrina fusca* Lour., *Erythrina edulis* Triana ex Micheli) | | | x | x | | | | |
| Fabaceae | *Hymenaea courbaril* L. | VU A2ac – National | | x | | | | x | |
| Fabaceae | *Inga* spp. | | x | | | | | | |
| Fabaceae | *Mimosa trianae* Benth. | | x | | | | | x | x |
| Fabaceae | *Pithecellobium longifolium* (Humb. & Bonpl. ex Willd.) Standl. | | x | | | | | | |
| Fagaceae | *Quercus humboldtii* Bonpl. | VU -National | x | x | | | x | x | x |
| Juglandaceae | *Juglans neotropica* Diels | | | | | | | x | x |
| Lamiaceae | *Vitex cymosa* Bertero ex Spreng. | | x | | | | | | |
| Lauraceae | *Aiouea, Aniba, Beilschmiedia, Nectandra, Ocotea, Persea* and other genera | | x | x | | | | | x |
| Lecythidaceae | *Cariniana pyriformis* Miers | CR – National | | | | | | x | x |
| Malvaceae | *Bombacopsis quinata* (Jacq.) Dugand | | | | | | | x | x |
| Malvaceae | *Ceiba pentandra* (L.) Gaertn. | LC – National | x | | | | x | | |
| Malvaceae | *Sterculia apetala* (Jacq.) H. Karst. | | x | x | | | | | |
| Meliaceae | *Cedrela montana* Moritz ex Turcz. | NT – National | | | | | | x | x |
| Meliaceae | *Cedrela odorata* L. | EN – National | | | | | | x | x |

(continued)

**Table 17.1** (continued)

| Family | Scientific name | Conservation status | Habitat structure | Food for wildlife | Cattle feed | Aesthetics | Cultural value | Timber | Conservation value |
|---|---|---|---|---|---|---|---|---|---|
| Meliaceae | *Guarea guidonia* (L.) Sleumer | | x | x | | | | x | |
| Meliaceae | *Swietenia macrophylla* King | CR – National | | | | | | x | x |
| Moraceae | *Ficus* spp. | | x | x | | | | | |
| Moraceae | *Maclura tinctoria* (L.) D. Don ex Steud. | | | x | | | | x | |
| Podocarpaceae | *Nageia rospigliosii* (Pilg.) de Laub. | NT – National | | x | | x | | x | x |
| Podocarpaceae | *Podocarpus oleifolius* D. Don ex Lamb. | VU -National | | x | | x | | x | x |
| Sapotaceae | *Chrysophyllum argenteum* Jacq. | | | x | | x | | x | |
| Sapotaceae | *Pouteria sapota* (Jacq.) H.E. Moore & Stearn | | | x | | | | | |
| Urticaceae | *Pourouma cecropiifolia* Mart. | | | x | x | | x | | |
| Zygophyllaceae | *Bulnesia carrapo* Killip & Dugand | VU – National | | | | x | | x | x |

Note: the conservation status and criteria follow the IUCN nomenclature (IUCN 2016): *CR* critical risk, *EN* endangered, *VU* vulnerable, *NT* nearly threatened, *LC* least concern

**Fig. 17.1** Large nitrogen-fixing trees such as *Albizia saman* (left and right) and *Enterolobium cyclocarpum* (center) enhance habitat structure for organisms as varied as dung beetles and parrots. El Hatico Nature Reserve, Valle del Cauca, Colombia (Photo: Zoraida Calle)

for their beautiful synchronic flowering (*Tabebuia chrysantha* (Jacq.) G. Nicholson and *Tabebuia rosea* (Bertol.) DC. The list also includes a few large trees that enhance habitat structure and promote the rapid recovery of the environmental services provided by dung beetles (*Enterolobium cyclocarpum* (Jacq.) Griseb. and *Albizia* spp.) (Fig. 17.1).

The focal species list includes three exceptions in which all native tree species within certain genera are given focal species status: *Erythrina*, *Inga* (both Fabaceae) and *Ficus* (Moraceae). This means that farmers can choose to plant any species from these genera that adapts well to their lands. Apart from well-known agroforestry trees such as *Erythrina poeppigiana* and *Inga edulis*, these genera include different nitrogen-fixing species that provide abundant food for wildlife. *Ficus* trees are not typical components of agroforestry or silvopastoral systems but most species sustain fruit production throughout the year, providing food resources for wildlife during periods of food scarcity. The other exception in the focal species list are native trees in the Lauraceae family, all of which can be considered focal species. The Lauraceae include many endangered, rare, and endemic species. Almost all of the trees in this family provide high-quality fruits for birds and mammals.

Together, the focal species of the MBSCR Project represent a wide spectrum of tree size and architecture, fruit types, dispersal modes, resources for wildlife, direct uses, environmental services, and aesthetic values. The list provides a starting point for incorporating a wider diversity of woody species in cattle dominated landscapes. This same concept can be applied in other countries.

The following section mentions two timber trees that are prominent focal species of the MBSCR project. Section 4 focuses on a palm that is not common in any of the MBSCR regions and therefore is not a focal species of this project.

## 3 Early Growth and Survival of Two Focal Tree Species

In this section, we present preliminary results on the growth and survival of two valuable trees: *Mimosa trianae* and *Swietenia macrophylla*. Both focal species are actively planted by ranchers in lowland regions where the MBSCR project is being implemented.

### *3.1 Study Area*

El Hatico Nature Reserve is one of the farms that pioneered the use of silvopastoral systems in Colombia in the 1970s. Located at 1000 m above sea level, in the fertile flatlands of the Cauca river valley in Colombia, El Hatico has an average temperature of 24 °C and an average annual rainfall of 800 mm. Even though this area is considered a tropical dry forest *sensu* Holdridge, its physiognomy resembles a subhumid forest as a result of the bimodal distribution of rainfall. This private reserve produces certified organic milk and sugar cane. Therefore, chemical insecticides are not an option for the pest management of trees (Molina et al. 2009; Murgueitio et al. 2011; Calle et al. 2013).

### *3.2 Tree Species*

Big-leaf mahogany, *Swietenia macrophylla* King (Meliaceae) grows in tropical dry forests and humid areas with a pronounced dry season, mostly in flat or moderately undulated areas with an annual rainfall between 1500 and 3500 mm. Saplings and young trees require intense sunlight to achieve their growth potential. Mature trees can reach heights between 35 and 50 m (López-Camacho and Cárdenas López 2002). However, natural populations of *S. macrophylla* have been overexploited because its wood is highly valued for construction, carpentry, boats, and the manufacture of musical instruments (Escobar and Rodríguez 1994). Because deforestation has reduced big-leaf mahogany ranges by more than 30% in South America, this species is considered to be critically endangered in Colombia (Cárdenas López and Salinas 2007) and vulnerable at a global scale (IUCN Red List of Threatened Species. Version 2016–3); it is listed in the CITES Appendix II, which includes species that may become threatened with extinction unless trade is closely controlled.

Natural forests have been the prime target for the exploitation of *S. macrophylla* because long-term efforts to grow the species in plantations have been mostly unsuccessful. The shoot borer or driller worm, *Hypsipyla grandella* Zeller is the main factor limiting the successful establishment of plantations of timber trees of the Meliaceae family in the Neotropics. *H. grandella* larvae attack the apical meristem of big-leaf mahogany trees, causing increased branching and slowing down tree growth (Pérez-Salicrup and Esquivel 2008). The bole of infected individuals becomes deformed as secondary branches dominate.

*Mimosa trianae* Benth. (Fabaceae) is an endemic tree from the Andean foothills of the Orinoco river basin in Colombia. It is a fairly common tree in the eastern slopes of the Eastern Cordillera and the adjacent flatlands. The high demand for its dense timber, regionally used as firewood to broil meat, has put pressure on the natural populations of this species. It has been integrated in cocoa agroforestry and silvopastoral systems. Recently it was introduced in the much more seasonal inter-Andean Cauca river valley (Valle del Cauca) where it is being planted with the aim of providing shade and timber in the short term. Herborized by botanists only eight times since 1856 (ICN 2004, continuously updated), this nitrogen-fixing tree is becoming a key element of silvopastoral systems in Colombia, where, paradoxically, cattle ranching could contribute to prevent its extinction.

## 3.3 *Experimental Planting of* Swietenia macrophylla *and* Mimosa trianae

In April and May of 2013, a total of 190 *Swietenia macrophylla* and 177 *Mimosa trianae* individuals were planted at a 3 m distance between trees in 15 lines located on paddock divisions (13–52 trees per line) and were protected with electric fencing (Fig. 17.2). Two fodder shrubs were planted between trees: *Tithonia diversifolia* in 9 lines and *Cratylia argentea* in the remaining 6 lines. The trees were fertilized once with chicken manure and mechanical weed control was done every 5 months.

The following data were recorded every 5 months after the trees were planted. Live and dead individuals of both species were counted on each live fence. A measuring tape was used to evaluate tree height. Basal diameter was measured 10 cm above the base of the stem in individuals less than 1.30 m tall; diameter at breast height (DBH) was measured in trees taller than 1.30 m. Herbivory and mechanical damage were also recorded. Stem segments were cut in *S. macrophylla* trees attacked by the borer *Hypsipyla grandella*, thus pruning affected tree height measurements. Lateral branches were pruned in *M. trianae* trees, with no effect on tree height.

**Fig. 17.2** Two-year old live fence with *Mimosa trianae* (left and right) and big leaf mahogany *Swietenia macrophylla* (center) at El Hatico Nature Reserve, Valle del Cauca, Colombia

### *3.4 Results*

Three years after planting, 85% of *S. macrophylla* and 89% of *M. trianae* trees had survived in the live fences (Fig. 17.3). For both species, death was caused by trampling and herbivory of cattle and water buffaloes *(Bubalus bubalis)* when the trees were small, and by water stress during the first year, mainly in a paddock located on stony ground. Survival of planted *M. trianae* trees proves the adaptability of this species to the highly seasonal tropical dry forest life zone (annual rainfall of 800 mm), despite being endemic and well adapted to the moist eastern Andean foothills (annual rainfall of 2500–5000 mm). The conditions of the study area are also suitable for big-leaf mahogany *S. macrophylla*, even though tree quality was highly affected by the borer *H. grandella*.

Average height of *S. macrophylla* increased from 0.32 m (when the trees were planted in April 2013), to 4.45 m in June 2016, which is equivalent to an average annual growth of 1.20 m. In the final measurement, tree height varied between 1.2 and 9.1 m (Fig. 17.3). This last number illustrates the growth potential of *S. macrophylla* when it is not attacked by the shoot borer. The height of most studied trees was affected by pruning of the apical segment of the stems in 2014 and 2016, which was done as part of the mechanical control of *H. grandella*. Stem portions between 0.30 and 1 m were removed in each of these events. The growth pattern of the 11 trees that were not attacked by the borer suggests that most of the trees could have reached heights between 5.5 and 7 m toward the end of the study.

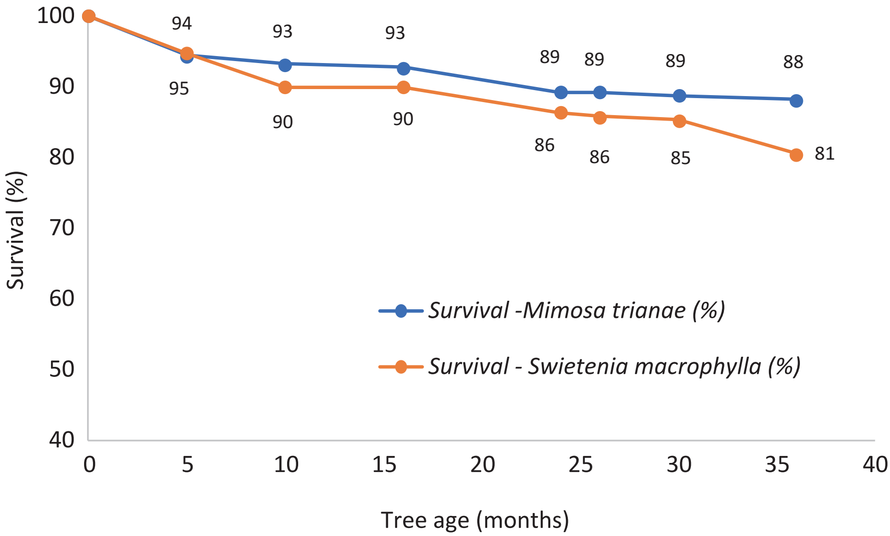


**Fig. 17.3** Early survival of *Mimosa trianae* and *Swietenia macrophylla* in live fences in Valle del Cauca, Colombia

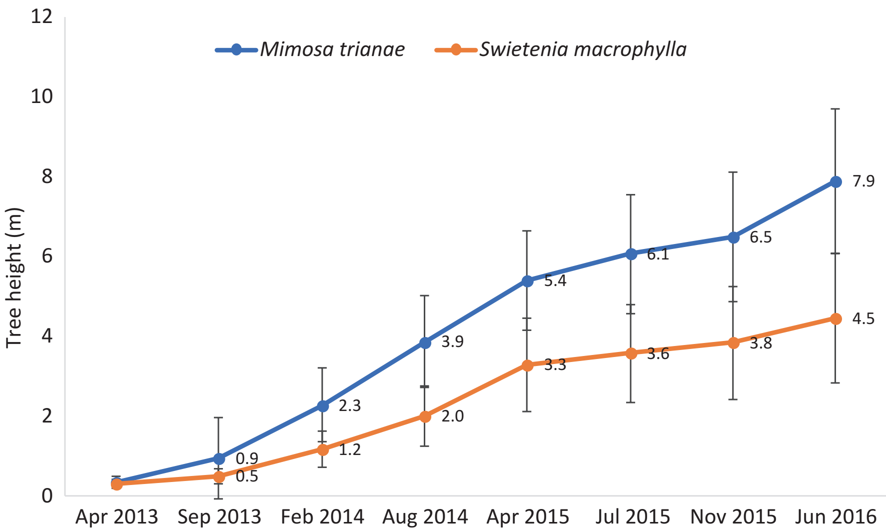


**Fig. 17.4** Height increment of *Mimosa trianae* and *Swietenia macrophylla* in live fences in Valle del Cauca, Colombia

*M. trianae* trees, planted with an initial height of 0.35 m (April 2013), had an average annual height increment of 2.02 m (Fig. 17.4). Three years after planting (June 2016), heights varied between 1.4 and 11.1 m (Fig. 17.4), with an average of 7.8 m. Soil macrofauna seemed to increase under these trees throughout the study, probably as a result of the shade and litter provided by this nitrogen fixing species.

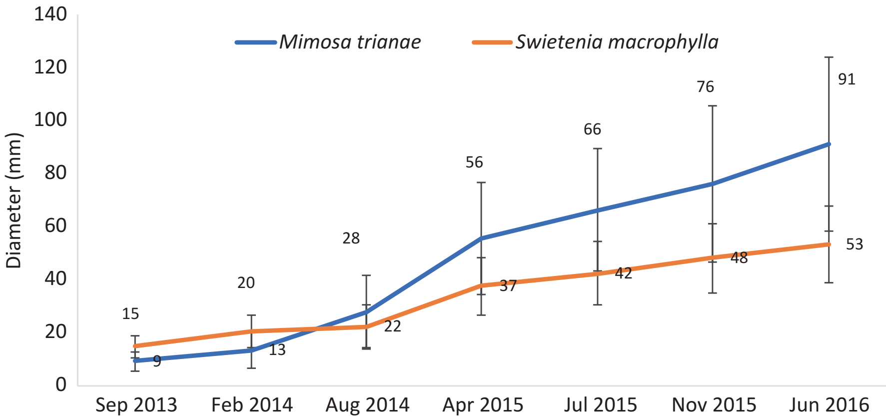


**Fig. 17.5** Diametric growth of *Mimosa trianae* and *Swietenia macrophylla* in live fences in Valle del Cauca, Colombia

Big-leaf mahogany trees, planted with an average initial diameter of 6 mm, had a mean annual diameter increment of 12.8 mm. In the final evaluation of June 2016, diameters between 10 and 108 mm were recorded, with an average of 53.2 mm (Fig. 17.4). *M. trianae* trees, with an average initial diameter of 4 mm, had an average annual increase of 28 mm and reached diameters between 16 and 239 mm in June 2016, with an average of 91 mm (Fig. 17.5).

One of the three paddock areas where the live fences were established had a high density of dispersed adult trees (35 trees $ha^{-1}$, 9–25 m tall). In this sector, *T. diversifolia* shrubs were planted in the *S. macrophylla* and *M. trianae* lines in the first year. The enhanced microclimate of this area probably explains the higher growth rate of the trees compared to other live fences. *M. trianae* trees planted with *T. diversifolia* shrubs showed more vertical growth and less branching than trees in live fences without this nurse plant.

# 4 The Palm *Acronomia aculeata*

## *4.1 General Characteristics*

The palm *Acrocomia aculeata* Jacq. is widely distributed between 50 and 600 m above sea level in strongly seasonal ecosystems with well drained soils throughout Central and South America (Henderson et al. 1995; Abreu et al. 2012). An adult palm produces between 26 and 47 kg of fruit each year, which fall after drying (Scariot et al. 1991, 1995; Francis and Lowe 2000; Acero 2005). Traditionally, cattle ranchers from the flat lowlands known as the *Llanos* in Colombia and Venezuela have valued this palm because it provides fruit for the cattle during the critical dry months (Fig. 17.6).

**Fig. 17.6** Intensive silvopastoral system with *Leucaena leucocephala, Acrocomia* palms and native trees. Apure, Venezuela (Photo: Adolfo Cardozo)

### *4.2 Fruit Production*

Palms such as *Acrocomia* spp. and *Attalea* spp. produce large quantities of energy-rich fruit with sweet pulp, the seeds of which have high levels of protein and essential fatty acids (Ocampo 1999; Cardozo 2008). A barrier for the use of this nutritious and abundant resource is the hard kernel that encloses the seeds. Different methods can be applied to make this high value supplement available for livestock. Kernels can be ground in mills or calcium can be mixed into the seeds to enhance nutrient assimilation. Unlike cattle, which eat the fruits and regurgitate the kernels, pigs have enough strength to grind the kernels and eat the seeds. Traditionally, cattle ranchers in the Llanos fed the whole palm fruit to cattle in enclosures, and allowed the kernels to accumulate on the ground. Later, they would fatten their pigs with the kernels regurgitated by the cattle. Sequential grazing of cattle and free ranging pigs is an alternative application of this method (Fig. 17.7).

Data published by Hernández et al. (2007) and Belén-Camacho et al. (2005) support the following calculations of the contribution of *A. aculeata* to animal feeding. One hectare of grazing pasture with 40 *Acrocomia* palms produces around 1900 kg of dry fruits each year. This fruit crop is enough to provide a daily supplement of 11 kg of fruits for the cattle during the six-month long dry season, without affecting

**Fig. 17.7** Broken seeds of *Acrocomia aculeata*, a high-quality feed (Photo: Adolfo Cardozo)

pasture productivity. Cattle can directly consume 1000 kg of the epicarp and pulp of this fruit crop. Additionally, 230 kg of seeds or nuts would be available for free-ranging pigs within the same paddock. With a supplementation rate of 0.2 kg of nuts per pig per day and a two-month long fattening period, this hectare of land would have the capacity to supplement 19 pigs.

This silvopasture with *Acrocomia* palms can produce 287 kg of oil per hectare each year, 62% contributed by the pulp (177 kg) and the remaining 38% by the seeds (110 kg). The benefit for cattle is illustrated by a study from Ojeda and Escobar (1995), who found that 5% of crude African palm oil (a daily supplement of 80 g per animal) can increase the growth rate of grazing cattle by 9.6%. Another study revealed that small amounts of fat in the diet of milking cows can anticipate the recovery of ovarian activity after calf delivery (Marín-Aguilar et al. 2007). These data suggest that 117 kg of oil per hectare supplied by the *Acrocomia* fruit pulp would provide the daily supplement for 8 animals over 6 months.

## *4.3 Management*

Throughout the Llanos of Colombia and Venezuela, some farmers have managed the regeneration of *A. aculeata* to increase palm density in their grazing lands. Others have planted this species deliberately. Meza et al. (2007) established a multi-strata silvopastoral system with one grass and five woody species, including 30 *A. aculeata* individuals per hectare, planted at 15 m between palms and 20 m between rows. However, crown size and light interception of this palm allow for much higher densities in silvopastures. Galindo and colleagues (unpublished data) recorded 100% survival of *A. aculeata* individuals transplanted directly from dense palm forests into silvopastoral systems in Arauca, Colombia. Given that palm germination and seedling growth are very slow, the careful extraction of young palms is an efficient strategy for establishing wildlife-friendly silvopastoral systems in this region.

## 5 Discussion

Silvopastoral systems throughout the Latin American tropics have been shown to be successful species assemblages from the economic and environmental points of view, when well designed and managed (Murgueitio et al. 2015, 2016). Unfortunately, research on grasses and livestock exceeds by far the generation of knowledge on the woody species that are key elements of these agroforestry systems. So far, the most successful examples involve eucalyptus, pines, and other exotic trees (Bungenstab and Alemeida 2014) with few examples of research on native trees (for a promising exception to this trend, see Andrade et al. 2012, a book that identifies native trees for silvopastoral systems in Brazil).

It is time to develop the native woody species component of silvopastoral systems. The focal species list (Table 17.1) is being used by the MBSCR Project to promote seedling production in nurseries and planting in participating farms. Most cattle ranchers still prefer more conventional (often exotic) woody species. However, the project's pilot farms play an important role in showcasing the focal species. These innovative farmers and early adopters of biodiverse silvopastoral systems, who open their farms to other farmers and extension workers, promote these native species locally.

*Hypsypila grandella* remains a huge barrier for the successful establishment of plantations or agroforestry systems with *S. macrophylla*. Some studies recommend low planting density (Hall and Ashton 2016) while others suggest high densities of this species (Pérez-Salicrup and Esquivel 2008). Even though research on this issue is far from conclusive, the value of mahogany and its low supply in global timber markets compel us to keep searching for management strategies to protect the trees from the shoot borer. Enrichment planting of second growth areas is certainly a viable option. However, the growth rates achieved in open areas indicate that mahogany can be integrated with livestock production. Both low and high density plantings are compatible with cattle systems.

*Mimosa trianae* is certainly an excellent choice for silvopastoral systems since it fulfills all of the attributes that were mentioned in the introduction of this chapter: it is fast growing and hardy, can grow unprotected, tolerates cattle trampling and browsing, and it grows well with grasses. Even without examining its belowground biotic interactions, its resilience and growth rate, coupled with its high wood density, suggest an outstanding carbon sequestration potential for this species. In this sense, *M. trianae* is the perfect focal species for silvopastoral systems. A conventional conservation strategy for *M. trianae* would have involved protecting forests where the tree grows spontaneously and planting it in ecological restoration areas. However, after *M. trianae* revealed its suitability for silvopastoral systems, it has been massively planted in the moist lowlands of Colombia as a shade tree that enhances the growth of grasses, allows farmers to produce high value timber in their paddocks, and provides habitat for beneficial insects and birds.

The highly diverse Neotropical palms have a variety of traditional uses. However, research on palms for silvopastoral systems has not lived up to this diversity and potential. We have also been short on documenting and studying the local innovations of farmers in most ecosystems. Therefore, the challenges of knowledge generation are huge. We know that the kernels that enclose the highly nutritious palm seeds are a physical barrier that demands the manipulation of fruits. A few good examples exist in Latin America. African palm oil has been used successfully as feed for pigs and poultry (Ocampo 1999). Díaz et al. (2010) and Ly et al. (2016) developed standards for using the fruits of the Cuban palm *Roystonia regia* in swine production. All of these successful examples involve a manipulation of the fruit. However, these developments are not adequate for all palm species. For example, wax palms, *Ceroxylon* spp. do not regenerate in livestock systems (Calle et al. 2011; Bernal and Sanín 2013). Only the hardiest and most resilient palms, such as *Acrocomia aculeata*, will be successful under this type of management.

## 6 Conclusions

Throughout the Neotropics cattle dominated landscapes offer the largest opportunity for restoration in terms of land area. The rehabilitation of these lands should involve a combination of sustainable livestock production and ecological restoration. A larger diversity of native trees and palms in the landscape matrix is desirable in both situations. Both livestock production and wildlife can benefit directly and indirectly from a higher density and diversity of native woody plants. At the same time, the conservation of tree and palm species will benefit through enlarged populations in cattle dominated landscapes.

The focal species approach applied to the promotion of silvopastoral systems coupled with the management of regenerating palms and timber trees in pasturelands are promising tools to increase the diversity of native woody species in degraded lands. However, pragmatic criteria such as fast growth, low cost, easy management, and resiliency to extreme weather events will almost certainly outweigh ecological criteria in the final choices made by landowners. Therefore, economic incentives such as payment for environmental services will continue to play a key role in promoting the introduction of native trees and palms of high conservation value in cattle dominated landscapes.

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# Chapter 18
# Perennial Staple Crops and Agroforestry for Climate Change Mitigation

**Eric Toensmeier**

## 1 Introduction

All carbon-sequestering practices are not equal in terms of their sequestration capacity. In general, the more trees, the higher the rate of carbon sequestration. Despite this, agroforestry practices are given little attention in most mitigation literature and tree crops are virtually absent. Likewise, the potential to perennialize a portion of staple crop production has largely been ignored.

There is no single farming practice which is appropriate in all contexts. Rainfall, climate, slope, levels of mechanization and available labor, markets, and more can be important determinants. Yet it seems logical that, where these conditions permit, greater perennialization of agriculture is desirable from a climate mitigation perspective.

This chapter compares the carbon sequestration rates and carbon stocks of various agricultural practices. Co-benefits of perennial crops are reviewed. Perennial staple crops are reviewed including their sequestration rates and yields as compared to annual staples. Examples are presented of agroforestry systems that incorporate perennial staple crops. Drawbacks and trade-offs are reviewed. Finally, an argument is made that perennial staple crops and agroforestry should be priorities in agricultural climate change mitigation efforts, given their powerful per-hectare impact.

E. Toensmeier (✉)
School of Forestry and Environmental Studies, Yale University, New Haven, CT, USA

Project Drawdown, Sausalito, CA, USA
e-mail: toensmeier@gmail.com



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## 2 Carbon Stocks and Sequestration Rates

Annual carbon sequestration rates vary widely between practices. They include sequestration both in aboveground biomass (AGB) and soil organic carbon (SOC). See Table 18.1. The general trend is that systems that incorporate trees, including agroforestry and perennial cropping systems, sequester carbon at a higher rate. In fact, addition of trees to annual cropping or grazing systems can increase sequestration by a factor of 5–10 or more.

Carbon stocks represent the lifetime storage capacity of farming systems. Storage of SOC also varies widely between farming systems, see Table 18.2. Here again, systems with trees have greater climate mitigation impact. Note that these only refer to SOC, and that substantial AGB carbon is also present in agroforestry and perennial crop systems.

**Table 18.1** Carbon sequestration rates of farming systems compared

| System | Region | C sequestration mg $ha^{-1}$ $year^{-1}$ | Type | Reference |
|---|---|---|---|---|
| Improved annual cropping systems | | | | |
| Conservation agriculture | Global | 0.6 | SOC | Srinivasarao et al. (2015) |
| Organic annual cropping | Global | 0.7–1.4 | SOC | Seebert-Elverfeldt and Tapio-Bistrom (2012) |
| Tree intercropping systems | | | | |
| Tree intercropping | Temperate | 3.4 | Both | Udawatta and Jose (2011) |
| Tree intercropping | Tropical | 2.0–5.0 | Both | Nair (2012) |
| Protective systems | Arid and semi-arid | 1.0–8.0 | Both | Nair (2012) |
| Grazing and pasture systems | | | | |
| Managed grazing | Global | 0.3 | Both | Conant (2010) |
| Silvopasture and tree-based systems | | | | |
| Silvopasture | Global | 3.0–10.0 | Both | Nair (2012) |
| Fodder tree blocks | Tropics | 0.1–0.5 | Both | Nair (2012) |
| Perennial crop monocultures | | | | |
| Convert cropland to orchard | Global | 3.5 | Both | IPCC (2000) |
| Multistrata agroforestry systems | | | | |
| Tropical homegardens | Humid tropics | 2–6.5 | Both | Nair and Nair (2014) |
| Shaded perennial crop systems | Humid tropics | 2–9 | Both | Nair and Nair (2014) |
| Multistrata systems, newly planted | Humid tropics | 2–18 | Both | Nair (2012) |
| Multistrata systems, established | Humid tropics | 2–10 | Both | Nair (2012) |

Carbon sequestration rates vary widely between different systems. Systems that incorporate trees tend to have far higher rates of sequestration. Adapted from Toensmeier (2016)

**Table 18.2** Soil carbon stocks of farming systems compared

| Category | Practice | Location | SOC stocks Mg/ha | Reference |
|---|---|---|---|---|
| Annual cropping | Conservation agriculture | India, USA | Up to 20 | Srinivasarao et al. (2015) |
| | Improved annual cropping | Global | 30–50 | Lal (2014) |
| Tree intercropping | Tree intercropping | Tropical humid | Up to 150 | Nair (2012) |
| | Tree intercropping | Temperate | Up to 200 | Nair (2012) |
| | Protective systems | Arid and semi-arid | Up to 100 | Nair (2012) |
| Grazing systems | Improved grazing and pasture management | Global | 30–50 | Lal (2014) |
| | Improved grazing and pasture management | Global | Up to 16 | McSherry and Ritchie (2013) |
| Livestock with trees | Silvopasture | Global | Up to 250 | Nair (2012) |
| | Fodder banks | Tropical | Up to 140 | Nair (2012) |
| Woody polyculture | Multistrata agroforestry | Tropical | Up to 300 | Nair (2012) |

Carbon stocks represent lifetime accumulation and storage of carbon, here in soil organic carbon (SOC). Maximum stocks vary widely between systems, and are higher when trees are incorporated

Thus, wherever possible, perennializing crop and livestock production through the integration of useful trees is desirable from a climate change mitigation perspective. Much emphasis in agroforestry is on making annual crop production more sustainable by incorporating woody plants to help reduce erosion, fix nitrogen, and build biomass and tilth. In most agroforestry systems, the trees themselves do not provide the staple crops. There is room for improvement in this area as well.

## 3 Co-benefits of Perennial Crops

Perennial crops and agroforestry systems do more than sequester carbon. These systems provide many benefits to the farm, the farmer, and the larger ecosystem. Given that other chapters in this volume address the ecosystem benefits of agroforestry systems, this section focuses on benefits from perennial crops only.

Perennial systems often feature habitat elements. For example, converting annual cropland to perennial agriculture can result in a marked increase in habitat for wildlife and reduce nutrient leaching (Pimentel et al. 2012). In fact, erosion and nitrogen leaching in perennial crops are less than 5% of those in annual crops. One reason for this is that perennial crops such as trees are present and using nutrients throughout the growing season, while annuals are only actively using nutrients for a small fraction of this time (Jordan et al. 2007). That is to say, this benefit is not limited to the humid tropics, but occurs through the growing season whether it is year-round or limited by cold or dry seasons.

Desertification is “the process of loss of soil fertility in the semi-arid and in the dry sub-humid regions of the world” (Pasternak 2001). Many perennial crops are well adapted to these conditions and can play a role in combatting desertification while providing the basis for human livelihood (Mtaita et al. 2001).

Perennial cropping systems tend to increase soil organic matter. More soil organic matter means higher fertility, better drought resistance, less vulnerability to erosion, and less loss of nutrients via leaching. Perennial crops also reduce or eliminate the need for tillage of the soil. The elimination or reduction of tillage reduces erosion and increases the complexity and diversity of life in the soil, notably of the highly beneficial arbuscular mycorrhizal (AM) fungi. These mycorrhizae help plants use nutrients more efficiently by capturing and transferring nutrients from plant to plant through their interconnected network of fungal mycelia (Harvey et al. 2014).

Perennial crops have many positive impacts on soils. Overall they can improve the structure of the soil, reduce compaction, improve water cycling and capture, and boost plant growth. Perennial crops may be especially well-suited to address the challenge of soil salinization. Perennial crops increase soil water storage and can thus help to flush salt out of soils (Pimentel et al. 2012). Perennial crops are believed to utilize water and nutrients more efficiently than annual crops (Pimentel et al. 2012).

Perennial crop monocultures require less fossil fuel inputs than annual cropping systems, and agroforestry systems even less, with multistrata systems needing least of all (Kumar 2006). The US National Research Council notes that perennial crops have reduced needs for fuel, fertilizer, and pesticides (Cox et al. 2013).

Perennial crops can restore degraded lands while producing a yield (Lal 2010). Many perennial crops—including staple crops such as mesquite (*Prosopis* spp.)—are halophytes, or salt-loving species, and can produce well in salty areas where it is impossible to grow conventional crops. In *The Coming Age of Agroforestry*, P.K.R. Nair states that “decades of research in India and other places where soil salinization is a major problem has shown that planting salt-tolerant trees on salt-affected soils is one of the best ways of rehabilitating such degraded lands” (Nair 2007).

Perennial farming systems help to reduce runoff and infiltrate groundwater, making water more available for use on-farm and/or downstream (de Leeuw et al. 2014). The increased organic matter content that these practices produce helps to improve the water-holding capacity of agricultural soils (Lal 2014).

Some perennial crops can continue to produce during drought, for example, when shallow-rooted annual crops fail and some trees will go dormant during a drought, but will return to full production the following year if and when the rains resume. Many perennial crops also produce food or fodder during the “hungry season,” which occurs at the end of the dry season but before annual crops begin yielding. Growth that accumulates on trees during healthy and productive seasons provides fuel and timber resources that can be drawn on in drought years. Agroforestry can also provide surpluses and diversified sources of income to be drawn on during hard times (de Leeuw et al. 2014).

## 4 Perennial Staple Crops

Perennial farming systems have higher rates of carbon sequestration and offer numerous benefits to the farm, the farmer, and the surrounding ecosystem. Annual staple crops occupy the great majority of cropland: roughly 1 billion ha of the world's 1.5 billion ha total cultivated land (FAOStat). Perennial staple crops have the potential to perennialize some of this annual cropland. Carbon sequestration rates for perennial staple crops are rare in the literature, but are summarized in Table 18.3. These rates are highly variable, and data are sorely lacking. Nonetheless the carbon sequestration potential of perennial staple crops is clear.

What are the prospects for shifting a sizeable percentage of staple crop production to perennials? To answer this, we must know more about these crops; in particular, how their yield compares to annual staples. Accurate comparison begins by categorizing staple crops by macronutrient profile. These basic nutritional classes are shown here with some of the most widely grown annual crops and the most widely grown perennial staple crops as examples.

- Basic Starch (0–5% protein, 0–5% oil). Annuals include cassava, sweet potatoes, taro, and yams. Perennials include bananas, plantains, breadfruit, aerial tubers, and starchy trunks.
- Balanced carbohydrates (0–15% protein, 0–15% oil, with at least one over 5%). (The carbohydrates are from either starch or sugar.) Annuals include maize, wheat, rice, and potato. Perennials include chestnuts, carob, perennial fruits, nuts, woody legume pods like mesquite, and acorns.
- Protein Crops (16% + protein, 0–15% oil). Annuals include beans, chickpeas, lentils, cowpeas, and pigeon peas. Perennials include perennial beans, nuts, leaf protein concentrates, and edible milks.

**Table 18.3** Carbon sequestration rates of selected perennial staple crops

| Crop | Region | C Sequestration Mg ha$^{-1}$ year$^{-1}$ | Type | Reference |
|---|---|---|---|---|
| *Bactris gasipaes* | Brazil | 5.1 | Both | Schroth et al. (2002) |
| *Ceratonia siliqua* | Portugal | 4.2 | AGB | Gerald et al. (2010) |
| *Cocos nucifera* | Philippines | 0.9 | AGB | Brakas and Aune (2011) |
| *Cocos nucifera* | Vanuatu | 1.2–5.3 | Unclear | Lamade and Bouillet (2005) |
| *Dacryodes edulis* | Cameroon | 7.8 | Both | Egbe and Tabot (2011) |
| *Elaeis guineensis* | SE Asia | 5.0 | AGB | Lasco (2002) |
| *Elaeis guineensis* | Global | 6.1 | AGB | Lamade and Bouillet (2005) |
| *Irvingia gabonensis* | Cameroon | 7.2 | Both | Egbe and Tabot (2011) |
| *Macadamia integrifolia* | Australia | 0.8 | AGB | Murphy et al. (2013) |
| *Musa* spp. | Philippines | 6.2 | AGB | Brakas and Aune (2011) |
| *Schinzophyton rautanenii* | Cameroon | 8.5 | Both | Egbe and Tabot (2011) |

Perennial staple crops provide carbohydrates, fats, and protein, along with high levels of carbon sequestration

- Protein-Oil Crops (16% + protein, 16% + oil). Annuals include soybeans, peanuts, sunflower seeds. Perennials include seeds, beans, nuts, and fruits such as almond, Brazil nut, pistachio, walnut, hazel, and safou.
- Oil Crops (0–15% protein, 16% + oil). Annuals include canola, poppy seed, maize, cottonseed, sunflower, peanut. Perennials include high-oil fruits, seeds, and nuts, such as olive, coconut, avocado, oil palm, shea butter, pecan, and macadamia. Some perennial oil crops are consumed whole as fruits and nuts, while others are exclusively pressed for oil (and some are used fresh and for oil).

These macronutrient categories are the basis for crop categories in Table 18.4. Data sources for protein and oil content of staple crops are from Chapters 12 to 16 of Toensmeier (2016).

It's difficult to accurately compare fruits, nuts, tubers, grains, trunk starches, and the other interesting food categories perennial staples provide. First, yields must be converted to an edible portion basis by removing inedible skins (e.g. banana peels), inedible seeds (e.g., avocado pits), shells (e.g. Brazil nut shells), or inedible fiber (e.g. sago palm trunks). Then yields must be converted to dry weight, as staple fruits (for example) have a far higher water content than grains or beans, making for inaccurate comparisons. Ideally, once edible-portions, dry weight yields are obtained, average yields could be compared. Unfortunately, FAO Statistical Service, an excellent source of global average yield data, does not track yields of many perennial staple crops. This leaves comparison of published yield ranges, which tend to show wide ranges and are far less useful for appraisal. Nonetheless they provide a general sense of competitive potential. Table 18.4 exhibits selected staple crops and their yields on an edible portion, dry weight basis.

The calculations used to provide the dry weight data are shown in Toensmeier (2016), Appendix B, which shows reported average yields and yield ranges, percent edible portion, percent water, and references for all data for 60 perennial and 17 annual staple crops, along with the calculated results shown in Table 18.4.

It can be seen that there are certainly tropical perennial staple crops with competitive yields. Cold-climate perennial staples are not yet ready to replace annuals in monocultures, though they could potentially show overyielding when intercropped with annual crops.

## 5 Perennial Staple Crops in Agroforestry Systems

While perennial staple crops have potential to mitigate climate change by perennializing staple crop production, monoculture plantations can create serious social and ecological problems (Gliessman 2015). Fortunately, perennial staple crops are already featured in many agroforestry systems across many climates.

Perennial staple crops can be integrated in annual cropping systems in multiple ways. Strips of perennial staples can be alternated with annual crops, planted on contour or on stabilized terrace edges, or used as field boundary plantings. They can

**Table 18.4** Perennial and annual staple crop yields compared

| Basic starch crop yield compared (0–5% oil and protein) | | | | | | |
|---|---|---|---|---|---|---|
| Crop | Life form | Climate | Avg. global yield mg/ha | Yield mg/ha | Product | Reference |
| *Manihot esculenta* cassava | Annual | Tropical | 4.1 | 3.2–29.1 | Tubers | PROSEA |
| *Metroxylon sagu* Sago palm | Perennial | Humid tropics | | 5.0–25.0 | Dry trunk starch | PROSEA |
| *Musa spp.* banana | Perennial | Humid tropics | 3.1 | 0.8–21.0 | Fruit | PROSEA |
| *Artocarpus altilis* breadfruit | Perennial | Humid lowland tropics | | 6.1–19.0 | Fruit | PROSEA |
| *Dioscorea alata* white yam | Annual | Lowland tropics, semi-arid to humid | 3.2 | 2.2–8.1 | Tubers | PROSEA |
| *Prosopis spp.* topical mesquites | Perennial | Arid to semi-arid tropics | | 9.0–49.5 | Pods | Pasiecznik et al. (2001) |
| *Zea mays* maize | Annual | Worldwide | 4.4 | 0.9–18.0 | Grain | PROTA |
| *Bactris gasipaes* Peach palm | Perennial | Humid tropics | | 8.8–13.2 | Fruit | Clement (1989) |
| *Oryza sativa* Rice | Annual | Humid worldwide | 3.8 | 2.6–13.1 | Grain | PROTA |
| *Solanum tuberosum* potato | Annual | Humid worldwide | 5.3 | 5.5–8.3 | Tubers | PROTA |
| *Cajanus cajan* pigeon pea (annual) | Annual | Tropics | 0.7 | 0.9–6.8 | Beans | PROTA |
| *Vigna unguiculata* cowpea | Annual | Global annual | 0.5 | 0.9–6.2 | Beans | PROTA |
| *Erythrina edulis* chachafruto | Perennial | Highland tropics | | 1.9–5.1 | Beans | Duarte (2002) and Florez et al.(1998) |
| *Phaseolus vulgaris* common bean (pole) | Annual | Global annual | | 0.9–4.8 | Beans | PROTA |

(continued)

**Table 18.4** (continued)

| Basic starch crop yield compared (0–5% oil and protein) | | | | | | |
|---|---|---|---|---|---|---|
| Crop | Life form | Climate | Avg. global yield mg/ha | Yield mg/ha | Product | Reference |
| *Phaseolus lunatus*<br>Lima bean (pole) | Perennial | Tropics | | 2.7–4.5 | Beans | PROTA |
| *Prunus dulcis*<br>almond | Perennial | Temperate Mediterranean | 0.5 | 6.4[a] | Nuts | Duncan et al. (2011) |
| *Pinus pinea*<br>Italian stone pine | Perennial | Mediterranean | | 6.2[a] | Nuts | Crawford (1994) |
| *Caryodendron orinococense*<br>inche | Perennial | Lowland humid tropics | | 2.3–5.8 | Nut kernels | Duke (2001) |
| *Helianthus annuus*<br>sunflower | Annual | Global annual | 1.4 | 1.0–5.7 | Seeds | PROTA |
| *Glycine max*<br>soybean | Annual | Cold temperate, tropical | 2.1 | 0.9–4.6 | Beans | PROSEA |
| *Elaeis guineensis*<br>African oil palm | Perennial | Humid tropics | | 5–8.7 | Oil | Miccolis et al. (2014) |
| *Persea americana*<br>avocado | Perennial | Tropical and subtropical lowlands and highlands, mediterranean, humid | | 0.2–6.6 | Oil | Human (1987) |
| *Cocos nucifera*<br>coconut | Perennial | Humid tropics | | 2–4 | Oil | Ohler (1999) |
| *Dacryodes edulis*<br>safou | Perennial | Humid to semi-arid tropical lowlands | | 2–4 | Oil | El Bassam (2010) |
| *Bactris gasipaes*<br>Peach palm | Perennial | Humid tropical lowlands | | 2–3 | Oil | Clement (1989) |

Here we compare perennial vs. annual staple crops. Note that "annual" includes some perennials grown as annuals. All yields calculated based on dry weight of edible portion basis. Crops are arranged in descending order of yield. This table compares the top five yielding crops in each staple crop macronutrient category. Average global yields are from FAOStat. Not all crops are tracked by FAO and thus average yields are not available for all listed species

[a]Almond and stone pine are irregular bearers, with high yields as shown here followed by one or more years of lower yields

**Table 18.5** Sample tree intercropping systems featuring perennial staple crops

| Type of system | Region | Description | Perennial staple crops |
|---|---|---|---|
| Strip intercropping | Global, often temperate or Mediterranean | Rows of woody or perennial crops alternating with annual crops. | *Carya illinoiensis, Castanea mollissima, Citrullus colocynthus, Corylus* spp., *Hippophae rhamnoides, Juglans* spp., *Olea europaea, Pistacea vera* |
| Farmer-managed agroforestry system | Niger | Natural regeneration of woody plants in annual crop field, with *Acacia* field borders | *Acacia colei, Adansonia digitata, Moringa oleifera* |
| Sloping agricultural land technique | Asia | Contour hedgerows between rows of annual and perennial crops | *Castanea mollissima, Juglans* spp., *Musa* spp., *Persea americana, Xanthoceras sorbifolium* |
| Living terrace edges (*metepantli*) | Mexico | Stone terrace edges stabilized with perennial crops including *Prosopis* and *Agave* | *Agave* spp., *Prosopis* spp. |
| Productive riparian buffers | USA | Perennial vegetation along waterways at cropland edge | *Carya illinoiensis, Juglans nigra* |
| Irregular intercropping: Parkland | Sahel | Trees interspersed with annual crops and livestock. | *Adansonia digitata, Blighia sabida, Borassus flabellifer, Elaeis guineensis, Parkia biglobosa, Vitellaria paradoxica.* |
| Windbreaks | Global | Woody vegetation strip to reduce wind impact | *Acacia colei, Artocarpus altilis, Cajanus cajan, Ceratonia siliqua, Hippophae rhamnoides,* and *Metroxylon sagu.* |
| Long-rotation swidden | Mesoamerica | Intensive Maya *milpa* with perennial crop phases | *Anacardium occidentale, Brosimum alicastrum, Pachira aquatica, Persea americana* (Ford and Nigh 2015) |

These agroforestry systems featuring perennial staple crops sequester carbon at high rates, while providing both annual and perennial staple foods. Adapted from Toensmeier 2016, Appendix A

serve as windbreaks or riparian buffers. Perennial staples are scattered in irregular patterns in annual crop fields in many regions. They can also serve as components of long-term swidden rotations. See Table 18.5 for examples.

Perennial staples also have a role to play in agroforestry livestock systems. Livestock graze the understory of many orchards and plantations, notably coconuts. Perennial staples may be grown in silvopasture systems, and in some cases the staple crops drop to the pasture to be consumed by livestock without a human intermediary, as in the famous Iberian *dehesa* systems. See Table 18.6 for examples.

**Table 18.6** Sample silvopastoral and livestock systems featuring perennial staple crops

| Type of system | Region | Example | Perennial staple crops |
|---|---|---|---|
| Orchard and plantation grazing | Pacific | Cattle grazing under crop trees | *Cocos nucifera* |
| Silvopasture | Global | Trees in pastures for human food or fodder | *Ceratonia siliqua, Quercus ilex, Prosopis* spp. |
| Perennial crops as feed | Mediterranean | Carob cultivated as livestock feed | *Ceratonia siliqua* |
| Restoration agriculture | USA | Elements of silvopasture, alley cropping, and multistrata agroforestry | *Castanea* spp., *Corylus* spp. |

These systems integrated perennial staple production into livestock operations. The staple crop may serve as feed for livestock, or food for humans. Adapted from Toensmeier 2016, Appendix A

**Table 18.7** Sample fully perennial systems featuring perennial staple crops

| Type of system | Region | Example | Perennial staple crops |
|---|---|---|---|
| Multistrata agroforestry | Global humid tropics | Intensive, diverse home multistrata systems | *Anacardium occidentale, Artocarpus altilis, Cajanus cajan, Cocos nucifera, Dioscorea bulbifera, Musa* spp., *Persea americana, Psophocarpus tetragonobolus* |
| Multistrata agroforestry | Pacific region | Intensive agroforests | *Artocarpus altilis, Cocos nucifera, Inocarpus fagifer, Musa* spp. |
| Multistrata agroforestry | Global tropics | Shade commodity crops with productive overstory | *Artocarpus altilis, Bactris gasipaes, Cocos nucifera, Dacryodes edulis, Erythrina edulis, Macadamia integrifolia, Musa* spp., *Persea americana,* etc. |
| Woody agriculture | USA | Coppiced hedgerows of woody staples, with mechanized harvest | *Carya* spp., *Castanea* spp., *Corylus* spp. |

Multistrata systems provide the highest level of carbon sequestration of any farming system. Many already feature perennial staples as a basic component. Adapted from Toensmeier 2016, Appendix A

Many multistrata agroforestry systems incorporate perennial staples. Tropical homegardens around the world feature staples like bananas, avocados, and coconuts. Intensive agroforestry systems (diversified, larger-scale staple crop multistrata systems) are common on Pacific islands, typically focused on coconut and breadfruit. Staple crops are also often grown in the overstory of shade crop plantations, as in bananas and macadamias over coffee or cacao. Woody agriculture is a staple crop system under development in the US, featuring woody staple crops, mechanically harvested and coppiced on a 10-year rotation. See Table 18.7 for examples.

## 6 Drawbacks and Tradeoffs

Numerous drawbacks limit the widespread adoption of perennial staple crops, and to a lesser degree, agroforestry systems. In colder climates, lower yields of perennial staple crops currently limit scaling up. Arid and semi-arid climates likewise limit agroforestry, though there are perennial staple crops for dry tropical and temperate regions.

Agroforestry systems and livestock-tree crop integration can also complicate the use of farm machinery for management and harvesting (Wojtkowski 1998). In arid regions, trees may not be appropriate because their transpiration can lower water tables and reduce stream flow resulting in a negative impact on downstream agricultural yield and overall ecosystem health (though as stated in co-benefits of perennial crops above, trees can also provide positive impacts on water availability and local climate). These impacts are particularly potent with monoculture tree plantations (Jackson et al. 2005). For example, in recent dry years almonds and pistachios were reported to compete fiercely for water with annual crops and salmon rivers in California (Barringer 2014).

Costs of establishment are higher than other agricultural mitigation strategies. This is particularly true for multistrata systems (WOCAT 2007). In addition, perennial crops will often not bear for many years after planting (Duke 2001).

Human staple diets are unlikely to change rapidly, limiting the potential adoption of perennial staple crops. Fortunately, this can be addressed in part by feeding perennial staples to livestock to replace annual crops like maize and soybeans. Given that a third of annual cropland is used to grow grain to feed livestock, this could be a significant contribution (Steinfeld et al. 2006).

## 7 Conclusions

Climate change is a critical challenge for the twenty-first century. It is important to understand that some agricultural mitigation practices have far more impact on a per-hectare basis than others, and it is important to act on that knowledge. The high cost of establishing perennial staple agroforestry systems is balanced by their high rate of sequestration. This rate is not only more desirable than the loss of soil organic carbon associated with conventional annual crop production, but it is also often 5–10 times higher than carbon-sequestering annual crop production practices like conservation agriculture. Perennial staple crop agroforestry systems also provide numerous ecological and agroecological co-benefits. While far from the only tools in the “carbon farming” toolkit, these are among the most powerful. They will not be right in every context, but should be a priority for education and extension, research, targeted financing, Payment for Environmental Service programs, and market and price incentives.

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# Chapter 19
# Carbon Sequestration in Temperate Silvopastoral Systems, Argentina

**Pablo L. Peri, Natalia Banegas, Ignacio Gasparri, Carlos H. Carranza, Belen Rossner, Guillermo Martínez Pastur, Laura Cavallero, Dardo R. López, Dante Loto, Pedro Fernández, Priscila Powel, Marcela Ledesma, Raúl Pedraza, Ada Albanesi, Héctor Bahamonde, Roxana Paola Eclesia, and Gervasio Piñeiro**

## 1 Introduction

The current importance of silvopastoral systems (SPS) in different regions of South America is determined by the extent of silvopastoral practices in the field and the amount of research that is carried out (Peri et al. 2016). In Argentina, SPS provide multiple products (e.g., food, wood, fodder) and services (e.g., maintenance of soil fertility, control of erosion, microclimate improvement, biodiversity enhancement, watershed protection). Another environmental benefit associated with SPS is their potential for carbon sequestration. Data on C storage in forests are essential for understanding the importance of a rapidly increasing level of $CO_2$ in the atmosphere and its potential effect on global climate change. Interest in research that improves our understanding of carbon (C) sequestration is increasing. This interest is partly

P. L. Peri (✉)
EEA INTA Santa Cruz-Universidad Nacional de la Patagonia Austral (UNPA), Río Gallegos, Santa Cruz, Argentina

CONICET, Buenos Aires, Argentina
e-mail: peri.pablo@inta.gob.ar

N. Banegas
Ciclos Biogeoquímicos, IIACS-CIAP-INTA Leales, Tucumán, Argentina

Facultad de Agronomía y Zootecnia de la Universidad Nacional de Tucumán, San Miguel de Tucumán, Tucumán, Argentina

I. Gasparri · P. Powel
IER-Universidad Nacional de Tucumán, San Miguel de Tucumán, Tucumán, Argentina

C. H. Carranza · D. R. López · M. Ledesma
Instituto Nacional de Tecnología Agropecuaria (INTA)-Estación Forestal INTA-Villa Dolores, Córdoba, Argentina

B. Rossner
EEA INTA Montecarlo, Montecarlo, Misiones, Argentina



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driven by Article 3.4 of the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC), which allows countries to count sequestration as a contribution to reducing greenhouse gas emissions (IPCC 2001). Given the vast area of land currently managed as ruminant production systems in Argentina, the potential for climate change mitigation through C sequestration by SPS is huge. Thus, the payment for environmental services for C sequestration in SPS can be an important incentive for ensuring their widespread adoption. Estimates of native forest C storage under different management practices are required for calculating a regional and national greenhouse gas balance.

Carbon sequestration involves the net removal of $CO_2$ from the atmosphere and storage in long-lived pools of C. Such pools include the above-ground plant biomass; below-ground biomass such as roots, soil microorganisms, the relatively stable forms of organic and inorganic C in soils and deeper subsurface environments, and the durable products derived from biomass (Nair et al. 2009).

This chapter from leading researchers and professionals in SPS is a compendium of original research articles, case studies, and regional overviews that summarizes the current state of knowledge on carbon sequestration of SPS in native forests and tree plantations in Argentina and make recommendations on policies to promote SPS.

G. M. Pastur
CONICET, Buenos Aires, Argentina

L. Cavallero
Instituto Nacional de Tecnología Agropecuaria (INTA)- Estación Forestal INTA-Villa Dolores, Córdoba, Argentina

CONICET (Consejo Nacional de Investigaciones Científicas y Técnicas) - CCT Córdoba, Córdoba, Argentina

D. Loto
UNSE-CONICET, Santiago del Estero, Argentina

P. Fernández
Ciclos Biogeoquímicos, IIACS-CIAP-INTA Leales, Tucumán, Argentina

R. Pedraza
Facultad de Agronomía y Zootecnia de la Universidad Nacional de Tucumán, San Miguel de Tucumán, Tucumán, Argentina

A. Albanesi
FAYA-UNSE, Santiago del Estero, Argentina

H. Bahamonde
EEA INTA Santa Cruz-Universidad Nacional de la Patagonia Austral (UNPA), Río Gallegos, Santa Cruz, Argentina

FAYA-UNSE, Santiago del Estero, Argentina

EEA INTA Paraná, Paraná, Argentina

IFEVA-Universidad de Buenos Aires, Buenos Aires, Argentina

R. P. Eclesia
EEA INTA Paraná, Paraná, Argentina

G. Piñeiro
IFEVA-Universidad de Buenos Aires, Buenos Aires, Argentina

## 2 Main Silvopastoral Systems in Argentina

In Argentina, there is a wide range of SPS that have been established for a variety of purposes, using several species in different spatial and temporal configurations. The main types of SPS are summarized in Table 19.1. This range of productive systems indicates how farmers have integrated tree and pasture/grassland species in their land use systems to reach higher production per unit of land area, risk avoidance, product diversification, and sustainability.

In the provinces of Corrientes and Misiones (Mesopotamia region), SPS with highly productive pine trees and $C_4$ grasses[1] have mainly been adopted by cattle farmers as an alternative to diversity production and to increase profitability as compared with traditional farming systems. The high demand for beef production in the Delta region during the recent past has led to the need to move from the traditional plantation systems to more intensive SPS that combine production of wood and cattle. In this riparian region, the focus is on the establishment of poplars and willow-based SPS aiming at production of high quality sawn wood, veneers and wood pulp, as well as biomass for bio-energy.

In the western Chaco region, SPS in mixed native forests and degraded savannas are being designed to specifically address the problem associated with dense shrub thickets and overstocked secondary forests caused by livestock overgrazing, over logging, changes in the fire regime, and fencing (Kunst et al. 2006). In Chaco, SPS are established using the mechanical treatment called "low intensity roller-chopping" (RBI) based on a mechanical disturbance that improves the system productivity while biodiversity, soil properties and advance regeneration of trees are preserved.

In northern Patagonia, 82,000 ha have been afforested with exotic coniferous species. Although pine forest plantations have shown to be a profitable and competitive activity compared to extensive livestock raising after 40 years of state promotion, only 10% of the regional potential has been achieved. It comprises the cattle culture of the region, which in the last 10 years began to promote SPS based on the conversion of plantations initially established on natural grasslands in the forest-steppe ecotone (Caballé et al. 2016). Another extensive system in Patagonia includes SPS in native *Nothofagus antarctica* forest, which has become an economically, ecologically, and socially productive alternative.

## 3 Carbon Sequestration in Silvopastoral and Grazing Cattle Systems of the Chaco Region

Agroecosystems, like livestock production systems in the Chaco region, represent an important alternative to C sequestration and are a viable business activity for the producer. It is important to evaluate and analyze results in these systems, especially

[1] As for example, *Brachiaria* spp., *Pennisetum* spp., *Axonopus* spp. (Editor's Note).

**Table 19.1** The importance of main silvopastoral systems reported for Argentina

| Region | Systems described | Main tree species component | Main understory component | Main livestock component | Extent, comments |
|---|---|---|---|---|---|
| Mesopotamia | Silvopastoral | Mainly evergreen, *Pinus taeda*, *P. elliotti*, hybrid pines | *Brachiaria brizantha*, *Axonopus* sp. | Cattle (Bradford, Brangus) | Mainly small and medium-sized farms as an alternative to diversify production, cattle raising as their main activity |
| Delta | Silvopastoral | Deciduous *Populus* sp., *Salix* sp. | Natural grasslands, *Lolium multiflorum*, *Brommus catharticus* | Cattle (Aberdeen Angus, Hereford) | From small and medium-sized farmers for diversification alternatives to forest companies aiming at quality wood production |
| Chaco | Silvopastoral, forest and degraded savanna grazing | Mixed and secondary native forest of *Schinopsis lorentzii*, *Aspidosperma quebracho-blanco*, *Prosopis* sp. | Native grasslands, *Cenchrus ciliaris cv. Texas* (Buffel grass); *Panicum maximum* (Gatton panic). | Large farmers: cow-calf operations (criollo, British and half Zebu breeds). | Low intensity 'roller-chopping' (RBI) to manage mainly shrub communities (secondary forests and shrub thickets) is proposed at production level. |
| | | | | Small farmers: mixed, cattle and goats | |
| Patagonia | Silvopastoral | *Pinus ponderosa* | Natural grasslands, mainly *Festuca pallescens* and wetlands | Criollo goat, cattle (Hereford), sheep (Merino) | Transhumance livestock based on goats. Low adaptation of SPS compared with detailed research information and numbers of production units. |
| | Silvopastoral, Forest grazing | Deciduous *Nothofagus antarctica* native forest | Natural grasslands, naturalized species such as *Dactylis glomerata*, *Trifolium repens* | Cattle (Hereford), sheep (Corriedale) and mixed (cattle + sheep) | Extensive production |

Adapted from Peri et al. (2016)

in the Argentinian Chaco region which suffered a great ecosystem transformation from agriculture expansion in the last few decades.

The significantly high annual deforestation rates in the Chaco forest during the last few decades (Zak et al. 2004; Britos and Barchuk 2008; Hoyos et al. 2012; Conti et al. 2014; Vallejos et al. 2014; Gasparri et al. 2015), have drastically affected the forest's carbon storage capacity. It has been estimated that deforestation in the semi-arid Chaco region has caused the emission of 15.65 Gg C $year^{-1}$ between 1996 and 2005[2] (Gasparri et al. 2008). In the southwestern area of this region, where agricultural practices are constrained by scarce precipitation, the expansion of intensified grazing lands is one of the most frequent causes of deforestation (Zak et al. 2004; Hoyos et al. 2012).

The intensification of livestock raising systems involves the replacement of native forest with introduced pastures maintaining a low or even negligible proportion of larger trees for livestock shading (Carranza and Ledesma 2005). The elimination of the shrub layer negatively impacts the survival of tree saplings, decreasing the regenerative ability of native forests (Barchuk et al. 2005; del Moral et al. 2007). This land use change has increased landscape fragility in the face of unfavorable climatic events, such as droughts (Carranza and Ledesma 2005). In 2007, the approval of a new legislation which protects native forests (National Law 26.331) caused a considerable decrease in deforestation rates of Chaco forests. However, this new legislation also promoted social conflicts between the productive sector, which felt it limited its productive activities, and society, which supported the restrictions imposed on productive activities where the ecosystemic services provided by native forests were compromised.

## *3.1 Organic Carbon Stock in Native Forests Under Different Intervention Intensity*

In 2015, the national agencies that promote conservation (Ministry of Environment and Sustainable Development) and production (Ministry of Agro-industry), adopted general guidelines for Forest Management Incorporating Livestock (hereafter 'FMIL') in areas where sustainable management is allowed (Category II of the Law 26.331). These guidelines were adopted with the aim of organizing productive activities in native forests while maintaining their capacity to provide ecosystem services. To this end, only low-impact interventions on the tree and shrub layers are allowed. Specifically, the intensity, periodicity, and extent of interventions on native forest must be carefully regulated. The FMIL guidelines include (i) areas intended for intensive forage production (affecting <10% of field area); (ii) areas intended for conserving native forest and increasing its connectivity at the landscape level (affecting ~30% forest area); and (iii) areas of low-impact logging and livestock

[2] 1 Gigagram = 1,000,000,000 g, or 1,000,000 kg, or 1000 Megagrams (SI units) (Editor's Note).

raising where the shrub layer can be reduced to release resources that ultimately increase forage production (affecting ~60% field area). In the areas of low-impact logging and livestock raising, logging and shrub clearing should be carried out with rotational cycles adjusted to natural growth rates. The management plan must define the rotation time (e.g., time period between successive logging events), the management unit (e.g., forest area that will be intervened every year), the minimum diameter of each species that can be harvested (should be adjusted based on biomass recovery between rotation times), and other considerations related to the maintenance of forest ecosystem functions. Besides rotation time and management unit, the intensity of the interventions in the shrub layer (e.g. percentage of biomass or cover reduction) must be defined as well.

After the application of the new guidelines of FMIL, it is expected that the field structure will be conformed as a mosaic in which each management unit will have a heterogeneous configuration depending on the time elapsed after the last low-impact intervention of the tree and shrub layers. Forage production will vary depending on the recovery of the cover of woody layers. Within the FMIL guidelines, the carbon stock of each management unit will vary depending on the intervention dynamics, but the carbon stock at field level should be constant, since carbon dynamics will be balanced between management units with time since the last intervention. Although data on carbon storage capacity of fields with the application of FMIL guidelines are not yet available in the Arid Chaco region, it is possible to infer the carbon sequestration ability of forests under the following interventions based on published literature:

(a) Mature forest of *Aspidosperma quebracho blanco* without interventions for at least the last 110 years.
(b) Mature forest of *A. quebracho blanco* managed according to the new guidelines for FMIL:

  - Core of native forest reserve and corridors: intangible area affecting at least 30% of forest area in the field.
  - Area of intensive forage production: sowing of megathermic (C4 metabolism) forage species (*Cenchrus ciliaris* cv texas 4464, *Panicum maximum* cv gatton panic, *Panicum coloratum* or *Cenchrus ciliaris* cv biloela) is allowed and can affect 10% of field area.
  - Low-impact management area: annual logging is allowed in management units of 1/30 of this area, with logging rotation times of ~30 years, and should leave a remnant basal area of 7 $m^2$ $ha^{-1}$ and a remaining canopy cover >30%. Low-impact management activities can affect ~60% of field area.

(c) Traditional Silvopastoral System (hereafter 'TSS') evenly affecting all field areas, in which few large trees remain to provide shade to cattle.

The estimation of the carbon storage capacity of native forest under different intervention pressures will allow managers/scientists to evaluate if the new guidelines promoted by national agencies can balance productive activities with the conservation of native forests. The estimations of carbon storage capacity shown here were based on published carbon stock data (Conti et al. 2014) of a mature forest dominated by *A. quebracho blanco Schltdl* ("Quebracho blanco") in Chancaní Forest Reserve, Córdoba Province, Argentina (c. 31°17′ –31°50′ S and 65°16′–65°32′ W), and on structure data from permanent plots installed for a research project (PICTO 2014-0050). Carbon storage estimations were done for plant (tree, shrub, and herbaceous layers) and soil (<0.30 m deep) components, which are the most dynamic, among others.

Total carbon stock of *A. quebracho blanco* mature forest was estimated by predicting dry biomass of trees by using allometric models which include diameter at breast height (DBH), height, and wood specific gravity as predictor variables (Table 19.2). Carbon stock of shrub and herbaceous layers, and of soil (0–0.3 m) was derived from published literature (Table 19.2). The C content of the woody biomass was 50% of the dry biomass (Brown 1997; Conti et al. 2014). Assuming the mature forest is in dynamic equilibrium, a constant value of carbon stock was assigned.

To estimate carbon stock in a field managed according the new FMIL guidelines, simulations were conducted using a hypothetical field with the carbon stock per hectare of the mature forest. 30% of the hypothetical field area was dedicated to forest reserves and corridors, thus carbon stock was assumed constant and equal to that of the mature forest. 10% of the hypothetical field was assigned to intensive forage production, and thus the harvest of the trees <20 cm and >40 cm of DBH was simulated, which resulted in a 17% of remaining canopy cover of *A. quebracho blanco* and *Prosopis flexuosa*. Dry biomass of remaining individuals was estimated by allometric models (Table 19.2). For the herbaceous layer, a constant carbon stock was assigned by averaging values estimated for *Cenchrus ciliaris* cv Texas 4464 pastures and native forage species from published literature (Table 19.2). Soil organic carbon stock was taken from Conti et al. (2014) who estimated it for open woodlands. The remaining 60% of the hypothetical field was divided into 30 management units. In one management unit per year over 31 years, the logging of tree species (e.g., *A. quebracho blanco* > 35 cm DBH, and individuals of accompanying species >25 cm DBH, such as *Prosopis flexuosa* D.C., "algarrobo", *Ziziphus mistol* Griseb, "mistol", *Geoffroea decorticans* Gill, "chañar" and *Parkinsonia praecox* Ruiz & Pav, "brea") was simulated, leaving a remnant basal area of 7 $m^2$ $ha^{-1}$. After each intervention, annual radial growth of remaining trees species was predicted using the specific allometric functions (Table 19.2). Using the estimated DBH, the height of remaining individuals was inferred through allometric functions and fitted for each species by using the structure data obtained in mature forest plots. Estimated DBH and height values were used to predict dry biomass of tree species through the same allometric models used for the mature forest (Table 19.2). Management of the shrub layer was done by simulating the removal of ~70% of shrub cover in rotation times of 6–7 years. The growth simulation of the shrub layer was done using a lineal function which raises shrub cover from 30% to 45% in 7 year periods. The complete simulation of low-impact forest intervention and subsequent annual growth was performed for 30 years until the logging of all management units was complete and the rotation cycle of the area under low-impact management began again. Soil car-

**Table 19.2** Published literature from which the allometric models used to predict dry biomass, volume and radial growth were extracted

| Estimation | Predictor variables | Species or/component | References |
|---|---|---|---|
| Dry biomass | DBH, Height | *Aspidosperma quebracho blanco* | Gaillard de Benítez et al. (2002) |
| Volume | DBH, Height | *Prosopis flexuosa, Geoffroea decorticans, Parkinsonia praecox* | Iglesias and Barchuk (2010) |
| Volume | DBH, Height | *Ziziphus mistol* | Gaillard de Benítez (1994) |
| Dry biomass | Volume | *P. flexuosa, G. decorticans, P. praecox, Z. mistol* | Atencia (2003) |
| Height | DBH | *A. quebracho blanco* | Unpublished data, long term plots research project (PICTO 0050-2014) |
| | | *P. flexuosa* | |
| Radial growth (DBH) | Time | *A. quebracho blanco* | Juárez de Galindez et al. (2006) |
| Radial growth (DBH) | Time | *P. flexuosa* | Perpiñal et al. (1995) |
| Dry biomass | Time | Shrub layer | Conti et al. (2014) |
| Annual dry biomass production | Average constant value assigned | Herbaceous layer (high forage species and others) | Ferrando et al. (2013) |
| | | | Namur et al. (2014) |
| | | | Carranza and Ledesma (2005) and Carranza et al. (2000) |
| Organic Carbon Stock | Average constant value assigned | Soil (0–0.3 m) | Conti et al. (2014) |
| | | | Carranza et al. (2012) |
| | | | Bonino (2006) |

Articles from which the constant values assigned to herbaceous and soil components were taken are also shown

bon stock in the area under low-impact management was assumed constant, and the value used was the estimated for Conti et al. (2014) in secondary forest.

To infer carbon stock in a TSS, the total area of a hypothetical field was assigned to intensive forage production, leaving trees with a DBH between 20–40 cm, resulting in 17% remaining canopy cover. Dry biomass of remaining individuals was estimated by allometric models (Table 19.2). For the herbaceous layer a constant carbon stock was assigned by averaging values estimated for *Cenchrus ciliaris* cv Texas 4464 pasture from published literature (Table 19.2). Soil organic carbon stock was taken from Conti et al. (2014) who estimated it for open woodlands.

The results of the simulations showed that mature forest of *A. quebracho blanco* can store 67.65 Mg ha$^{-1}$ of organic carbon in the most dynamic components (standing above-ground plant biomass and soil). According to the simulations, a hypothetical field managed under the new guidelines of FMIL would store 17.1% less carbon than the mature forest (Table 19.3). This decrease in the carbon storage capacity would mainly be due to the reductions in tree density and shrub cover. On the other hand, a hypothetical field managed as a traditional silvopastoral system

**Table 19.3** Average carbon pools (Mg ha$^{-1}$) of dynamic plant and soil components in native forests with different degrees of intervention (i.e., anthropic pressure)

| | | Forest management with livestock integrated | | | |
|---|---|---|---|---|---|
| | Mature forest | Low impact forest intervention | Forest reserves and corridors | Intensive forage production | Traditional silvopastoral system |
| Intervened area (%) | 0 | 60 | 30 | 10 | 100 |
| C in aboveground standing biomass of tree species | 13.60 | 7.42 | 13.60 | 6.34 | 6.34 |
| C in aboveground standing biomass of shrub species | 11.83 | 4.44 | 11.83 | 0.00 | 0.00 |
| C in aboveground standing biomass of herbaceous species | 0.20 | 1.00 | 0.20 | 1.50 | 1.50 |
| Soil organic carbon $_{0–0.1m}$ | 19.80 | 19.46 | 19.80 | 9.97 | 9.97 |
| Soil organic carbon $_{0.1–3m}$ | 22.22 | 23.20 | 22.22 | 7.14 | 7.14 |
| **Total organic carbon** | **67.65** | **56.1** | | | **24.95** |

(TSS) would be able to store less than a third of the organic carbon that the mature forest can store (Table 19.3). This dramatic decrease in carbon sequestration is due to the total elimination of the shrub layer and the scarce number of remnant trees. It should be noted that because only above-ground standing plant biomass and 0–0.3 m soil layers were included in the simulations, total carbon stock is underestimated. Moreover, including the organic carbon stored in the biomass of roots could significantly increase the differences recorded between the mature forest and TSS (Vogt and Vogt 1998; Peri et al. 2010; Reich et al. 2013). Consequently, the new guidelines promoted by national agencies could be a better alternative than the TSS, because they offer a better balance between production and conservation in terms of carbon sequestration ability.

Due to the availability of data and published information, carbon stock estimations were made with data of a mature native forest growing in the Chancaní Forest Reserve. However, well conserved forests are very scarce in the Arid Chaco. In this region, secondary forests and open woodlands with different degrees of degradation are the most frequent communities (Zak et al. 2004; Britos and Barchuk 2008; Hoyos et al. 2012; Conti et al. 2014). Therefore, carbon stock estimations in the hypothetical field where the new guidelines of FMIL are applied are overestimated. In degraded communities, the new guidelines for FMIL should aim to recover, or even restore, the forest physiognomy, which has a greater productive capacity and resilience. Therefore, the main goal of FMIL application in degraded forests should be to increase carbon stock levels compared to the initial situation.

In the context of climate change, there is a growing need to recover the carbon storage ability in native forests. However, instead of maintaining carbon stocks, the carbon sequestration capacity of TSS decreases in the long term. This is because tree regeneration is unlikely in TSS, where younger individuals which would restock senescent adults are lost at the expense of introduced pastures. In grass dominated communities, the recruitment of new individuals of tree species is unlikely because of the high competitive ability of forage grass species (Ledesma and Carranza 2009). Similarly, the maintenance of the carbon stock in fields applying FMIL, in the medium/long term, will depend on management practices aimed at ensuring forest regeneration, among others. Tree restocking should be carried out through temporary enclosures or strategic grazing management. To ensure the maintenance of carbon stocks, the basal area remaining after each forest intervention should not be lower than 7 $m^2$ $ha^{-1}$. The minimum basal area kept between interventions should not be modified from one rotation to another, and consequently the time elapsed between forest interventions could increase depending on the occurrence of extraordinary events (e.g., droughts, pest outbreaks) that affect growth rates. Therefore, modifying the intervention rotation times in terms of the occurrence of extraordinary events, or depending on the trees' growth rates, could stabilize the system's carbon storage capacity, and thus, its capacity to provide ecosystem goods and services.

Soil C and N contents were evaluated during 6 years in a silvopastoral system (*Prosopis alba* with a tropical pasture *Chloris gayana* cv Epica INTA-Pemán) and an adjacent open grazing beef cattle system with the same pasture of the Chaco region. Both systems were divided into six paddocks and grazed from May to March. The stocking rate was 2 heifers $ha^{-1}$. Organic carbon (OC) stored at 100 cm of depth was 84.7 Mg C $ha^{-1}$ and 64.6 Mg C $ha^{-1}$ for silvopastoral (SP) and open grazing system (PS), respectively. The amount of C stored in SP was distributed 33, 39 and 28% in 0–20, 20–50 and 50–100 cm, respectively. In PS the distribution was 32, 36 and 32% for the same soil layers (Fig. 19.1).

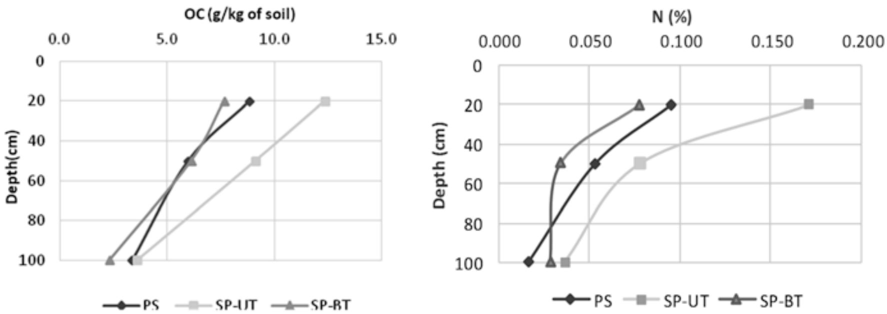


**Fig. 19.1** Mean values for organic carbon (OC) and nitrogen (N) in a silvopastoral system of *Prosipis alba* with *Chloris gayana cv Epica-INTA Pemán* and pure grazing system of *Chloris gayana cv Epica-INTA Pemán* at different soil depths. References: PS, grazed system in adjacent open pasture; SP-UT, silvopastoral system under treetops; SP-BT, silvopastoral system between treetops

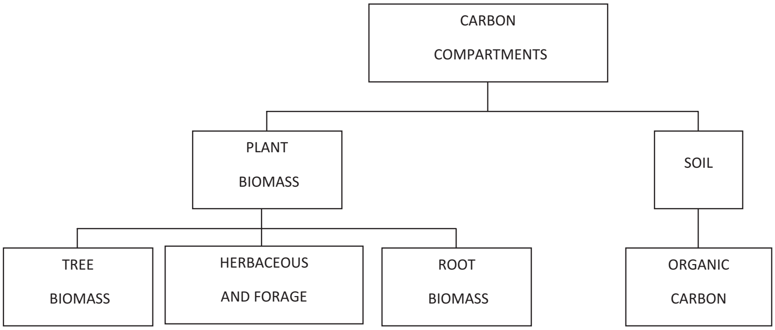


**Fig. 19.2** Carbon compartments evaluated in a grazed and hayed system with *Chlorys gayana cv Finecut*, and native vegetation

Mean values of N content were 6.9 and 6.6 Mg ha$^{-1}$ for SP and PS, respectively. In SP the N distribution was 37, 31 and 32% for 0–20, 20–50 and 50–100 cm soil depth, respectively. In PS the distribution for each soil depth was 35, 41 and 24% (Fig. 19.1). In the SP system, the highest C and N concentration was under treetops representing 50–57% of OC and N stored (Fig. 19.1) due a greater residues input and microbial activity.

In another long-term evaluation, the C stocks in native vegetation and four grazing systems with a tropical pasture (*Choris gayana cv Finecut*) in a saline soil were studied. The systems were (i) grazed plots without Nitrogen-fertilizer (G); (ii) grazed plots with added N-fertilizer (GF); (iii) hayed plots without N-fertilizer (H), and (iv) hayed plots with added N-fertilizer (HF). Each grazed plot (G and GF) was grazed on rotation (10 ± 3 days of grazing and 35 ± 6 days of rest in the growing season) at a stocking rate of 3 steers ha$^{-1}$. In the winter, deferred grass was grazed for 38 ± 11 days in each plot. Pasture is consumed as it becomes available and can also be left to be consumed later, a practice known as deferment (Bathgate et al. 2009). Animals received energy and protein supplements in winter (1.4% live weight), including *Chloris gayana* cv Finecut hay (1.5 kg steer$^{-1}$ day$^{-1}$), and only energy supplements were given in summer (0.8% live weight). Every year, the GF plot was treated with 100 kg urea ha$^{-1}$ in November, after the first grazing. The animals did not have access to the hayed plots (H and HF) and the pasture was clipped at 15 cm above the ground three times during the rainy season (October to March). Finally, every year, the HF plots were treated with 100 kg urea ha$^{-1}$ in November after a cleaning cut. In this case, C compartments were evaluated: above- and below-ground biomass and soil (Fig. 19.2).

After 5 years of evaluation, the native vegetation presented the highest C content (168.3 Mg ha$^{-1}$). Mean values of total C content in cattle systems were: 119.5, 116.3, 115.5, and 110.3 Mg ha$^{-1}$ for GF, G, HF, and H, respectively (Fig. 19.3).

Higher C content in GF was related to greater C inputs. Soil C sequestration rates were 2.78, 2.04, 1.88, and 0.65 Mg C ha$^{-1}$ year$^{-1}$ for GF, G, HF, and H, respectively. Grazed systems showed higher C contents than hayed treatments (GF vs HF and G

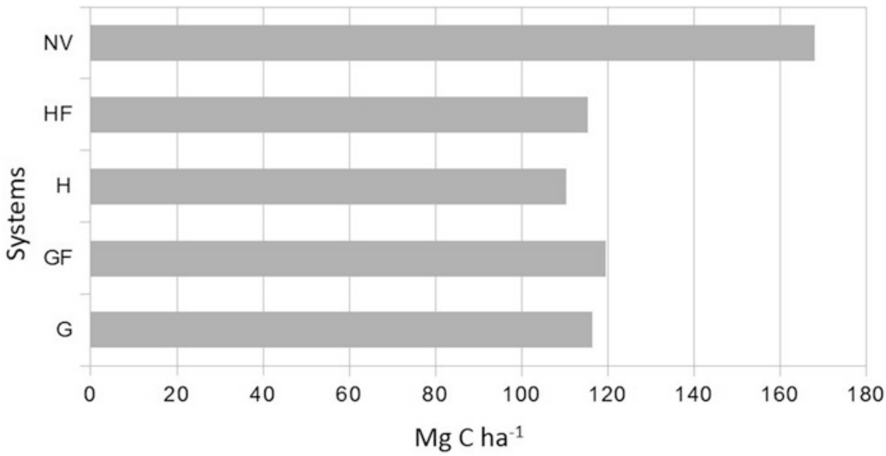


**Fig. 19.3** Total carbon content in a grazed and hayed system with *Chlorys gayana* cv *Finecut*, and native vegetation. Reference: NV, native vegetation; G, grazed system; GF, grazed and fertilized system; H, hayed system; HF, hayed and fertilized system

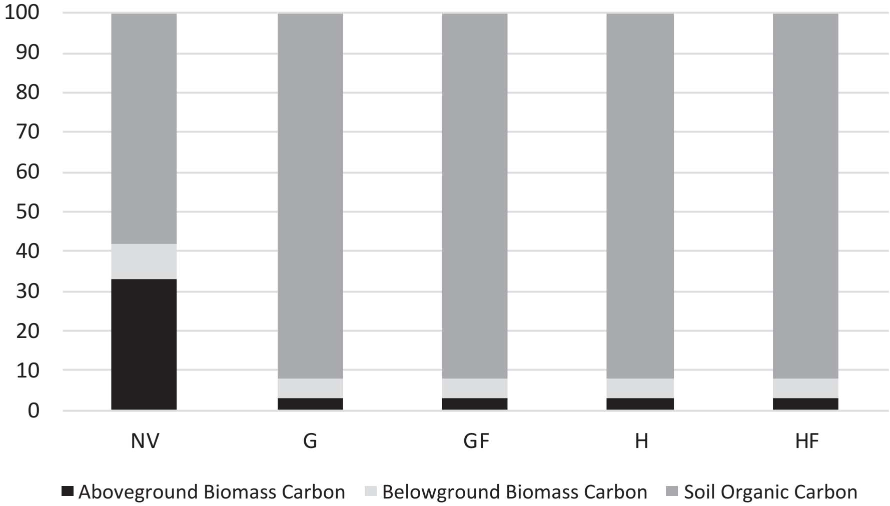


**Fig. 19.4** Distribution of carbon (C%) among different compartments. Reference: NV, native vegetation; G, grazed system; GF, grazed and fertilized system; H, hayed system; HF, hayed and fertilized system

vs H) and fertilized systems were superior to non-fertilized systems. The C distribution among compartments was also important (Fig. 19.4).

Above-ground biomass represented an important C compartment in NV, accounting for 32.6% of C stock. In cattle systems with *Chloris gayana* cv Finecut, this compartment represented 2.9% of C stock. Below-ground biomass (roots) was 8.4%

of C stock in NV, whereas in grazed and hayed systems it represented 4.9–5.2% of the total C stock. The OC in soil represented the most important compartment in the evaluated cattle system with a tropical pasture (*Chloris gayana* cv Finecut), accumulating 91–92% of the C, finding the higher percentage in GF and the lowest in H. In NV, soil organic carbon represented 58.9% of the total C stock.

### *3.2 Implications of Silvopastorals in Carbon Balance in the Dry Chaco: Opportunities and Uncertainties*

Although promotion of silvopastoral systems (SPS) from government and research institutions has been increasing over the last decade, studies on them in the Dry Chaco are still incipient, especially in relation to the impacts at regional scales (Peri et al. 2016). For example, studies that estimate the impact of implementing SPS on carbon stocks and its implications for the carbon balance of the region are lacking. In addition, under the framework of SPS, landowners implement contrasting practices, from only retaining some large trees with African pastures cultivation, to more integrative and conservative systems. As a consequence, the positive impacts of the SPS depend largely on the landowner's decisions and perceptions, and on the initial natural vegetation.

As an approach to estimating the potential regional impact of implementing SPS with different objectives on carbon stocks, we simulated forest structure modification (e.g., above-ground biomass removal and retention) of different SPS using information from twenty permanent forest plots collected in 2007 and situated across the Dry Chaco rainfall gradient (Gasparri et al. 2008) (Fig. 19.5). We defined three alternatives of SPS implementation based on personal experience, guides of

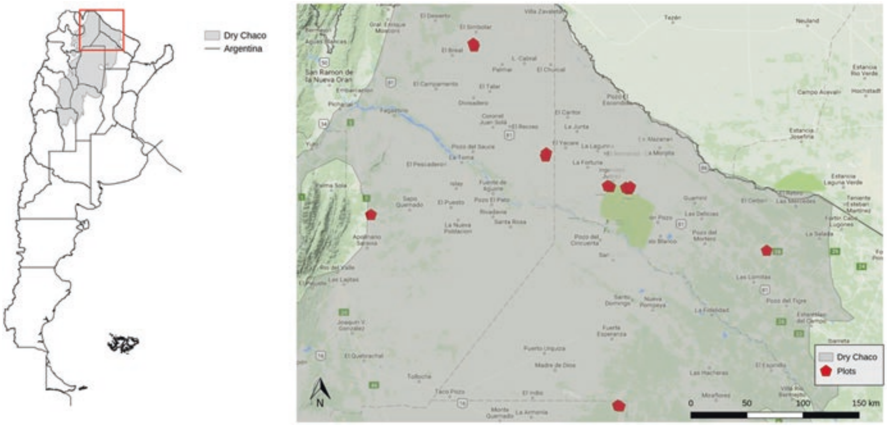


**Fig. 19.5** Dry Chaco in the north of Argentina. The selection shows the study area where twenty plots were selected (pentagonal red points)

the national program "manejo de bosques con ganaderia integrada" ("managing forests with integrated livestock"), and literature (MAGyP, SAyDS 2015). We used the forest plot data as the initial scenario and simulated the removal of trees under three scenarios: (T1) in which we applied a silvicultural rule to conserve all trees with DBH >20 cm, and conserved shade for cattle, a common situation in cattle farms; (T2) in which we conserved all the trees with DBH >20 cm plus 30% of the undergrowth forest aboveground biomass (AGB) (10–15 cm DBH) in order to conserve species for regeneration; and (T3) in which we simulated the removal of all the individuals with a DBH < 20 cm and cut 30% of the large trees with DBH > 20 cm for forestry production. Besides this treatment that represented alternative decisions, we differentiated the plots for the initial biomass in "good" and "poor" forest condition, based on the AGB stock, classifying "poor" forest as that with <90 Mg $ha^{-1}$ of AGB (Fig. 19.6). We assumed that 50% of the biomass was carbon (Gasparri et al. 2008).

Considering that many of the implementation rules for SPS are based on leaving trees using practical rules (minimum cutting diameter in forestry), we found that the initial condition of the forest is a critical factor for sustainable management. In Dry Chaco, producers establish SPS by seeding tropical pastures in natural forests using the roller-chopping techniques, generally leaving tree species with straight stems (Kunst et al. 2006). If the condition of the original forest is good, producers have the opportunity to maintain good structure in their SPS, saving large quantities of biomass (and carbon) and potentially conserving other ecosystem services in the forest. In the case of degraded sites or woody encroached areas, possibilities of reaching a SPS structure with a suitable number of trees per hectare are constrained and other techniques must be considered.

The dry Chaco region has high soil and climatic heterogeneity with patches of grassland and woodland, allowing for different soil textures and topography. Some research has reported that encroachment of natural grasslands by overgrazing cattle was a strong disturbance two centuries ago, modifying the original landscape of Chaco to a more shrubland physiognomy (Grau et al. 2015). Soil condition and land use legacy determining areas more suitable for grassland or woodland could be an important factor for configuring SPS ecosystems. The 26.331 national law limits percentages at farmer scale for conversion, but under encroachment conditions it is worth seeing if there are other possibilities for productive and environmental performance, such as sites with pastures and portions of forest with establishment of native species for regeneration or even for SPS with native tree plantings.

Carbon decreases for each decision (treatments) from the starting scenario vary from −9% for T2 in good forests to −47% in T3 in poor forests (Fig. 19.6). This reduction is a trade-off between increasing forage availability for cattle, and diverting light and nutrients to the herbaceous component with the roller-chopping technique. T2 may seem like the more conservative option from a carbon perspective (9 and 18% decreases on good and poor conditions respectively) but it is difficult to see in real farm situations, perhaps because it is hard to apply with the current technology and leave undergrowth homogeneously on a plot with the roller. The T3 and T1 are more like the practices ordinarily used by cattle farmers. The practices cen-

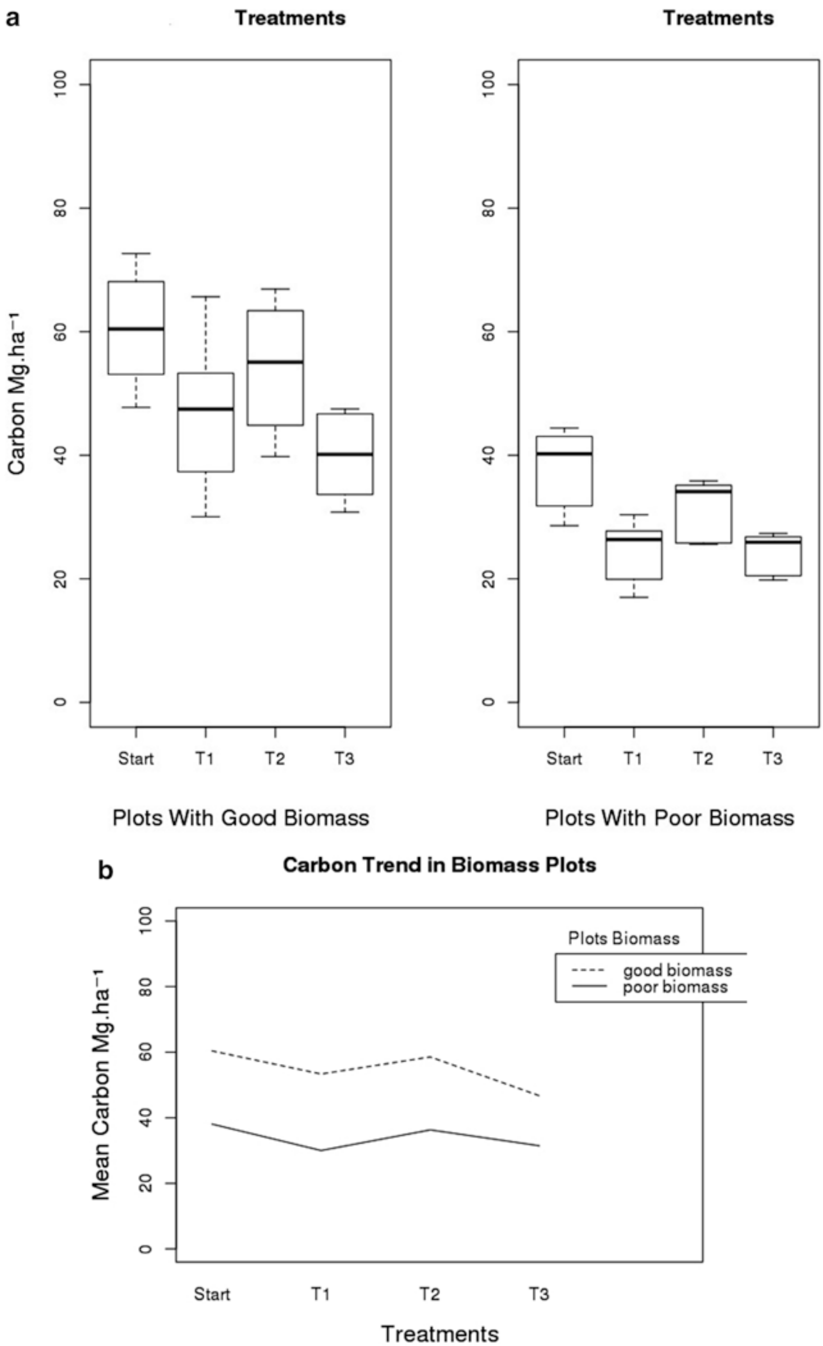


**Fig. 19.6** (**a** and **b**) Boxplot of sites with good biomass and poor biomass and the three treatments, T1, T2 and T3 as described in text. Below, interaction plots/above-ground biomass

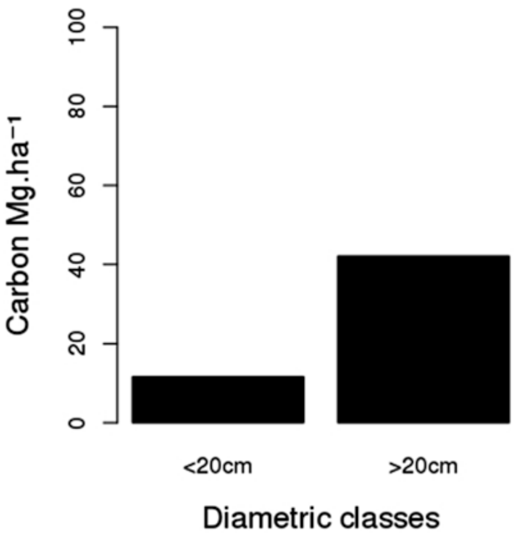


**Fig. 19.7** Diametric tree classes. The <20 cm class have trees that stock less biomass above-ground than >20 cm class trees

tered in the retention of large trees allow increases in forage production but also compromise the future of the system by not promoting regeneration and the long-term viability of tree populations.

In the short-term carbon balance, undergrowth does not represent a major stock of biomass (Fig. 19.7), but could play a key role in the perpetuity of these systems. The retention of small trees could be a partial solution to including more species, but might not guarantee the retention of saplings of the main tree species (e.g *Schinopsis lorentzi*, *Aspidosperma quebracho-blanco*, or *Bulnesia Sarmientoi*). Regeneration of large tree species in a SPS of the Dry Chaco emerge as a problem in these systems and needs more attention. In addition, the solution needs to address landowners' negative perceptions of woody vegetation regeneration which represents a depletion of the forage production and is actively controlled.

At the moment, there are no reliable methods for monitoring SPS implementation using remote sensing. Therefore, to estimate the carbon balance impact of SPS implementation we used information on area included in the management plans subsidized by the 26.331 national law (information consulted to SAyDS). Even if these stats do not consider farms that implement SPS on their own, without funding from the law, we consider these data are the best proxy for estimations of SPS implementation. Between 2010 and 2014 there have been management plans for approximately 200,000 ha in the provinces of the Chaco region. From this, 50,000 ha have been implemented each year, and we used this area data multiplied by the retention/removal of biomass in Fig. 19.6 to estimate the Mg of Carbon retained/emitted with each different treatment simulation (Table 19.4).

SPS are currently one of the options for increasing cattle production in the region and are implemented to balance ecosystem services such as Carbon and production. However, there are some uncertainties over the trade-offs between production and carbon cycling in the system that needs further research. We already pointed out that

**Table 19.4** Amount of carbon retained and emitted (Mg C/year$^{-1}$) for implemented management plans for national law N° 26.331 for the 2010–2014 period (200,000 ha in this period)

| | T1 | T2 | T3 |
|---|---|---|---|
| Carbon emitted | $2.6 \times 10^6$ | $1.2 \times 10^6$ | $3.7 \times 10^6$ |
| Carbon retained | $8.1 \times 10^6$ | $9.5 \times 10^6$ | $7.0 \times 10^6$ |

Note: we simulated the removal of trees under three scenarios: (T1) in which we applied a silvicultural rule to conserve all trees with DBH >20 cm, and conserved shade for cattle, a common situation in cattle farms; (T2) in which we conserved all the trees with DBH >20 cm plus 30% of the undergrowth forest aboveground biomass (AGB) (10–15 cm DBH) in order to conserve species for regeneration; and (T3) in which we simulated the removal of all the individuals with a DBH < 20 cm and cut 30% of the large trees with DBH > 20 cm for forestry production

the long-term carbon stock depends largely on large tree species that are compromised by the lack of regeneration. On other hand, the relationship between tree coverage and forage production is still unclear. There is little information on this relationship along the aridity gradient. Furthermore, the tree cover-forage production relationship changes with the use of alternative species, such as gatton panic (*Megathyrsus maximus var maximus*) or buffel grass (*Cenchrus ciliaris*). Finally, the trade-off of carbon stock and cattle production could be affected by cattle management and decisions like silage, supplementary feeding, cattle grazing strategy, technology and animal genetic improvement. This determines the balance between carbon and cattle production in the SPS of the Dry Chaco.

## 4 Carbon Sequestration in Silvopastoral Systems of the Mesopotamia Region

Silvopastoral systems (SPS) in the Mesopotamian region of Argentina emerge as a proposal of greater sustainability, as compared with tree plantations, being productive systems suitable for both large and small farmers. While tree plantations store significant amounts of C in their biomass, the soil organic Carbon (SOC) content generally decreases in young plantations following plowing and seeding (Eclesia et al. 2012). SOC stocks may recover gradually thereafter, since C inputs into the soil, either from roots or litter, are initially accumulated in woody biomass and only after several years, important amounts of biomass C reach the soil. On the other hand, $C_4$ pastures increase SOC stocks mainly due to larger root production that generates high inputs of C to the soil. Recent measurement using stable $^{13}C$ isotopes have showed that new C derived from pastures was 65.4 Mg ha$^{-1}$, while the new C derived from tree plantations was only 9.4 Mg ha$^{-1}$ for the whole soil profile, after conversion from native forests and grasslands respectively (Eclesia et al. 2016). Therefore, SPS emerge as a promising alternative for SOC storage and wood production simultaneously. Because experiments referring to C cycling in the Mesopotamia region are scarce, we further describe here some findings obtained in our research in the northeast of the Corrientes province.

**Table 19.5** Soil organic carbon (SOC) and particulate organic carbon stocks (C-POC) at 1 m of soil depth, in different land uses studied in NE Corrientes, Argentina

| | Tree plantations | Grasslands | Silvopastoral systems |
|---|---|---|---|
| Depth (cm) | **SOC (Mg ha$^{-1}$)** | | |
| 0–20 | 56.56 ± 6.0 (ns) | 58.13 ± 5.5 | 53.584 ± 3.1 (ns) |
| 20–100 | 139.42 ± 4.3 (ns) | 135.52 ± 13 | 136.51 ± 8.3 (ns) |
| | **C-POC (Mg ha$^{-1}$)** | | |
| 0–20 | 4.94 ± 0.2 (ns) | 5.15 ± 0.4 | 4.75 ± 0.8 (ns) |
| 20–100 | 5.73 ± 2.0 (ns) | 4.74 ± 0.3 | 4.56 ± 0.5 (ns) |

## 4.1 Soil Organic Carbon Stocks and Dynamics

Eclesia et al. (2015) reported no significant differences in SOC and C-POC (Particulate Organic Carbon) between SPS, tree plantations, and grasslands of northeast Corrientes on a paired experiment (Table 19.5). However, SOC and C-POC values in tree plantations were higher than values reported in previous research at the same region (Eclesia et al. 2012). While previous research reported 169 Mg ha$^{-1}$ of SOC under tree plantations, SOC stocks were 217 Mg ha$^{-1}$ in Eclesia et al. (2015). These differences could be due to differential plowing and seeding without burning activities in the latter, because soils are similar.

Although SOC stocks showed no changes between land uses, important differences in SOC and POC dynamics were observed. SPS stabilized more new C than tree plantations did in the soil. The difference in the new C stabilized was 10 Mg ha$^{-1}$ ($p < 0.05$) in the top 20 cm of soil between SPS and tree plantations, representing ~18% of SOC stocks. In addition, SOC decomposition rates tended to be lower in tree plantations than SPS (data not shown). This evidence suggested a higher C turnover in SPS that could be due to different pasture species or different microclimate conditions, such as direct sunlight, temperature, or moisture generated by lower tree densities in the SPS than in the tree plantations.

## 4.2 Carbon Stocks in Plant Biomass

Aboveground biomass-C differences between plantations and SPS occurred only when comparing with young plantations (21.53 vs. 38.63 Mg of C ha$^{-1}$), due to differences in tree density and silvicultural management in SPS (Fig. 19.8). Small differences were observed between plantations and 12 year old SPS (40.43 vs. 43.84 Mg of C ha$^{-1}$). The lower density of trees in the SPS lead to higher rates of woody biomass accumulation per tree than in plantations, compensating overall biomass accumulation on a per ha basis. Differences between plantations and SPS were lower when litter and herbaceous stocks were taken into account. Although herbaceous vegetation accounted for only 0.41% and 5.87% of total above-ground

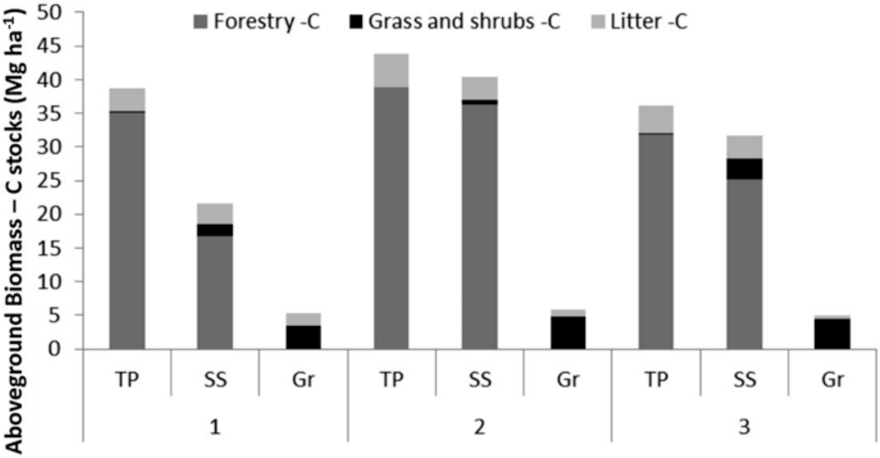


**Fig. 19.8** Carbon stocks in different aboveground biomass pools in grasslands, tree plantations and silvopastoral systems in plantations of different ages: site 1 (6–8 years old), site 2 (12–13 years old), site 3 (19–20 years old)

biomass in plantations and SPS respectively, this component is the most dynamic and allocates more C to roots than trees do. Therefore, litter C stocks were similar in plantations and SPS, but they were both higher than in grasslands (4.11 and 3.27 vs. 1.16 Mg of C $ha^{-1}$).

## 5 Carbon Sequestration in Silvopastoral Systems of the Patagonia Region

### *5.1 Native* Nothofagus antarctica *Forest*

In Southern Patagonia, mean annual temperature is predicted to increase by 2–3 °C by 2080 between 46 and 52° 30′ Southern Latitude (Kreps et al. 2012). If reached, such an increase will have significant effects on Patagonian ecosystems. In this context, native forests are considered efficient C sink ecosystems. Peri et al. (2010) and Peri (2011) showed that C storage in tree components (leaves, stems, branches, roots) and forest floor change as a result of different forest structures determined by the proportion of crown classes, development stages (age), and the site quality where trees grow. Above-ground and below-ground C sequestration for different components of plants, trees, understory, grasslands, and the C storage in soil horizons (0–0.6 m) in a *N. antarctica* silvopastoral system, a primary forest, and adjacent grassland grown in Southern Patagonia are shown in Fig. 19.1. In these systems, the total C stored ranged from 108.4 to 182.2 Mg C $ha^{-1}$ for grasslands and primary forest, respectively. The C stored in the silvopastoral system showed an intermediate value of 148.4 Mg C ha$^{-1}$ and it was distributed approximately with 85% in soil, 7% in below-ground biomass (understory and tree roots) and 8% in above-ground biomass.

Below-ground biomass represented an important C storage pool in the ecosystem. The importance of roots as a C sink in these forests has been reported as an adaptation to improve water and nutrient uptake in dry environments, and to provide better support in windy sites with shallow soils, compared to other *Nothofagus* species (Peri et al. 2010). It is important to emphasize that roots in these forest ecosystems can contribute up to two times more biomass and C storage than above-ground components in young growth phases (Peri et al. 2010). The C accumulation for trees followed the order coarse roots > heartwood > sapwood > bark > small branches/fine roots > rotten wood > leaves.

Mean total soil carbon concentration in the mineral horizon (3–30 cm depth) was significantly lower: 2.1% in the grassland compared to 3.2% in the silvopastoral system and 3.8% in the primary forest (Peri et al. 2010; Peri 2011). In addition, the C concentration decreased from 51% in floor litter to 0.5% at 0.6 m mineral soil depth in the SPS. Soil respiration rates in the SPS and primary forest were higher than in the grassland located in the adjacent open site (Fig. 19.9). The most likely reason for this is the presence of trees in the system (Peri et al. 2015). This has been demonstrated previously by Raich and Schlesinger (1992) who reported, from a review of several studies, that soil respiration from forested land compared to conventional agricultural land was up to three times higher. The trend of higher soil respiration in SPS compared with primary forest may be due to an improvement of microclimate (soil temperature, incoming radiation, and moisture regime) that enhanced organic matter decomposition (Peri et al. 2015). This has been confirmed by Bahamonde et al. (2012) who determined that the total transmitted radiation, and soil and air temperatures explained 61 and 40% of the variation of litter (grasses and tree leaves) decomposition in a *N. antarctica* forest in Patagonia under silvopastoral use. There was no C detected in leached soil solution from the evaluated systems over the summer period.

Silvopastoral systems are expected to store more C than pure grasslands systems through two main mechanisms: increased C storage in the biomass of trees, and increased soil organic carbon (SOC) storage through C inputs to the soil. The litterfall rate varied from 0.42 (silvopastoral system) to 0.89 Mg C ha$^{-1}$ year$^{-1}$ (primary forest). The higher C input in the form of litterfall in ecosystems with trees probably creates favorable conditions for soil microorganisms leading to enhanced microbial activity and $CO_2$ evolution, or higher tree root respiration (Matteucci et al. 2000).

Few studies of above- and below-ground pools of C storage in Patagonian *Nothofagus* forests and the consequences of different disturbance and management regimes have been conducted. In this context, forest management strongly affects forest ecosystem pools and fluxes of C.

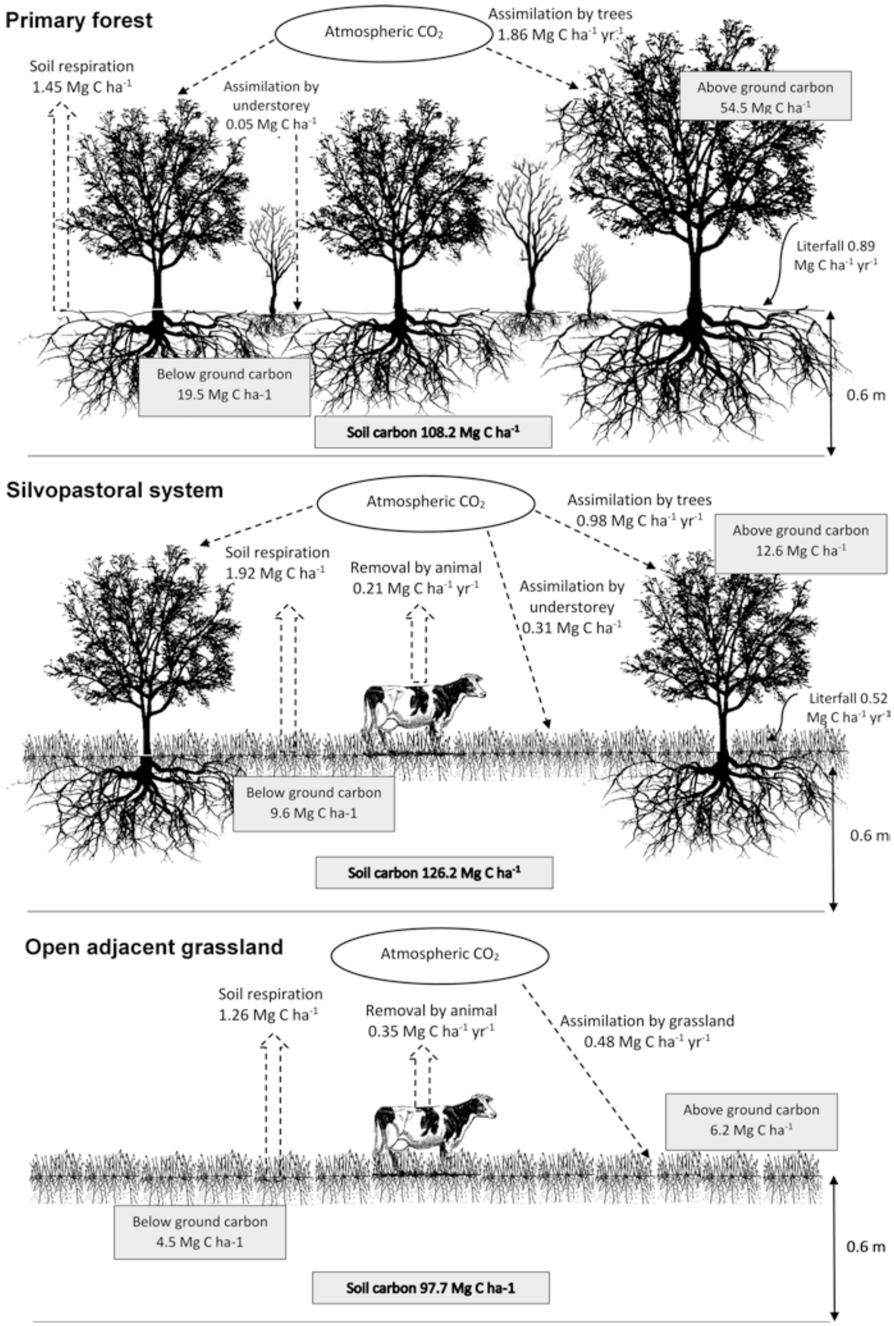


**Fig. 19.9** Main carbon (C) pools and C fluxes within (**a**) primary *Nothofagus antarctica* forest: mean stand density: 960 trees ha$^{-1}$ (21% dominant, 28% co-dominant, 22% intermediate, and 29% suppressed trees); Site Class V: stands where the mean total height of dominant mature tree (Hd) reach 5.8 m in mature development stage (195 ± 15 years); (**b**) *N. antarctica* silvopastoral systems: 175 trees ha$^{-1}$ (80% dominant and 20% co-dominant trees); Hd of 5.6 m in mature development stage (188 ± 21 years); and (**c**) an open adjacent grasslands in Southern Patagonia. Boxes indicate C pools and arrows indicate C flux

**Table 19.6** Mean and standard deviations of carbon storage (Mg C $ha^{-1}$) in biomass and soil of ponderosa pine plantations (between 8 and 20 years old; mean annual precipitation of 1053 mm) in northwest Patagonia

| Variable | Mean | S.D. |
|---|---|---|
| Total above ground | 44.0 | 26.1 |
| Coarse and tap roots | 8.3 | 4.6 |
| Root/shoot ratio (%) | 19.5 | 1.5 |
| Litter | 6.6 | 5.4 |
| Soil (0–50 cm) | 80.0 | 44.7 |
| **Total** | **139.1** | **64.7** |

Adapted from Laclau (2003)

## 5.2 *Pine Plantations*

The improvement of environmental and production efficiency of Patagonian land-use activities is critical, and one option is the use of SPS based on plantations established on natural grassland in the forest-steppe ecotone (Caballé et al. 2016). Additionally, this agroforestry system has clear environmental advantages over high-density timber plantations. In terms of biodiversity, it increases the richness and diversity of flora and avifauna (Rusch et al. 2004).

Based on individual above- and below-ground biomass models, Laclau (2003) estimated C storage at the stand level in a ponderosa pine plantation growing on native grasslands in northwest Patagonia (Table 19.6). In this work, a strong relationship between soil carbon and precipitation was found for pine plantations in the 8–20 years range. Total carbon varied from approximately 65 to 210 Mg C $ha^{-1}$ for <600 and >1500 mm $year^{-1}$, respectively. The mean estimated biomass carbon in *Festuca pallescens* grasslands of 2.6 Mg C $ha^{-1}$ (including dead foliage and litter) represents the baseline from which the forest land-use would add carbon to the ecosystem.

# 6 Conclusions

Silvopastoral systems practiced in Argentina provide multiple products (e.g., food, wood, fodder) and services, where erosion control and carbon sequestration represent an advantage compared with land-use changes from forests and monocultures (pastures or crops). Therefore, the proposition of feasible models for forest-livestock systems in contrast to the traditional cropping systems, the extensive cattle and sheep systems, and the specialization of plantations continues to be a target of research and extension services.

In this chapter, carbon sequestration information at stand level (including importance of soil, stand age, site quality) and landscape level were provided for different regions of Argentina. In the Chaco region, a mature forest of *Aspidosperma quebra-*

*cho blanco* stored 67.6 Mg C $ha^{-1}$ and managed under the new guidelines of Forest Management Incorporating Livestock (FMIL) it is estimated to store 17.1% less carbon due to the reductions in tree density and shrub cover in reference to the unmanaged forests. In the same region, after 6 years of evaluation, the soil organic C (100 cm depth) stored in a silvopastoral system (*Prosopis alba* and a tropical pasture *Chloris gayana*) was higher than in an adjacent grazing beef cattle pasture (84.7 vs. 64.6 Mg C $ha^{-1}$). Estimating the potential regional impact of implementing SPS on carbon stocks across the Dry Chaco, it was found that the positive response of SPS depends largely on the landowner's decisions and perceptions, and on the initial natural vegetation. In the Mesopotamia region, data of C dynamics highlighted that SPS emerge as a promising alternative for SOC storage and wood production simultaneously. In Patagonia, the total C stored ranged from 108.4 to 182.2 Mg C $ha^{-1}$ for grasslands and primary native forest, respectively. The C stored in SPS showed an intermediate value of 148.4 Mg C $ha^{-1}$ and it was distributed approximately with 85% in soil, 7% in below-ground biomass (understory and tree roots) and 8% in above-ground biomass. The estimated C storage in a ponderosa pine plantation growing on native grasslands in northwest Patagonia varied from 65 to 210 Mg C $ha^{-1}$ for areas with precipitation of <600 and >1500 mm $year^{-1}$, respectively being higher than in pure grasslands (2.6 Mg C $ha^{-1}$).

However, the quantification of the role of silvopastoralism on climate change adaptation and mitigation activities (carbon sequestration, Greenhouse Gases (GHG) emissions, soil conservation and improvement) should be developed. The implementation of clean development mechanism (CDM) offered by the Kyoto Protocol by extending payments to low-income farmers who provide C storage through sustainable land-use systems such as those SPS is one option. Well-managed SPS increase soil and biomass C storage, while directly improving the livelihoods of farmers through increased livestock production.

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# Chapter 20
# Conclusions: Lessons Learned and Pending Challenges

**Florencia Montagnini**

## 1 Introduction

What are the main lessons shared by the authors of this book? Here is a brief summary:

**Part I: Agroforestry Challenges and Alternatives** sets the stage with an Introduction that intends to summarize the major challenges for agroforestry in the new millennium, followed by a chapter describing how agroforestry can contribute to the achievement of Sustainable Development Goal 2: End hunger, attain food security and improved nutrition, and promote sustainable agriculture. This part also contains two more contributions, which offer regional (tropical dry forests, temperate) perspectives on the same issues presented in the previous chapters. They both provide detailed descriptions of AFS across landscapes in these contrasting parts of the world, focusing on their effects on biodiversity conservation and livelihoods, laying out their possibilities and research needs. This first part closes by proposing an approach to tackle landscape management issues, stressing that social-ecological factors need to be taken into consideration to achieve landscape-level resilience.

**Part II: From Subsistence to Market Oriented Systems** contains the largest number of contributions of the three parts of the book with a total of nine chapters that embrace the concept of sustainability in the context of AFS at both the farm and landscape levels. It starts by presenting innovative ways of approaching the sustainability issue with energy analysis exemplified with coffee AFS. The following chapters place emphasis on indigenous, successional AFS, pointing at the factors that make or have made these AFS successful for smallholders in several locations of the

F. Montagnini (✉)
School of Forestry and Environmental Studies, Yale University, New Haven, CT, USA
e-mail: florencia.montagnini@yale.edu



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world, as they mimic nature and can be in tune with natural management of forest landscapes. Economic value forms part of the sustainability equation, and this is addressed for both small scale (açaí forest farming, guayusa, yerba mate, cacao) and medium to large scale agroforestry (organic coffee, organic yerba mate, specialty crops), exploring the possibilities of accessing global markets and the potential implications on the livelihoods of farmers who have traditionally practiced these systems for their own sustenance.

Again the chapters in this part present experiences or case studies from Amazonian regions of Bolivia, Brazil and Ecuador, where indigenous management predominates, to contrasting regions of South, Central and North America where more modern approaches are prevalent. In many of these case studies the integration of ecological indigenous knowledge (EIK) and ecological scientific knowledge (ESK) is a key for pursuing sustainable development: the difficulties and challenges of this integration are described in a separate chapter, with case studies and recommendations for success. This part closes with a chapter dealing with alternatives for supplying fuel for cooking and heating in developing countries in an efficient, sustainable manner. Use of conventional devices can lead to serious environmental and health issues, and a call to action is made to alleviate this situation. Fuelwood produced in plantations and AFS can be a viable energy source, while biofuels using agricultural residues or animal wastes can alleviate fuel needs and generate employment opportunities at the local level.

**Part III: Environmental Services in Multifunctional Landscapes** is comprised of five chapters covering how different types and components of AFS contribute to the provision of environmental services such as conservation of biodiversity, carbon storage, and climate change adaptation and mitigation. It emphasizes how to manage AFS to preserve these important services at the AFS component, farm and landscape levels. Examples are provided from both tropical and temperate systems of the Americas. More innovative AFS are also described in this part, including Intensive Silvopastoral Systems, as well as often overlooked AFS such as Trees on Farms (TonF), their management and recommendations for national policies aimed at promoting these systems.

The nineteen chapters summarized here review many of the rational arguments as to why well designed and well managed AFS can enhance benefits at the household, ecosystem and landscape levels and fulfill an enormous purpose in facilitating rural development, promoting self-sufficiency among smallholders, increasing productivity and sustainability while conserving biodiversity, as well as providing for other important environmental services such as carbon sequestration. Thus, the dissemination and adoption of AFS should be a key landscape management strategy, contributing substantially to the achievement of the Sustainable Development Goals (SDGs). Widespread dissemination of AFS should also contribute to fulfilling the Aichi targets on biodiversity conservation,[1] especially the targets of Strategic Goal

[1]At the 10th meeting of the Conference of the Parties, held in October 2010, in Nagoya, Aichi, Japan, a revised and updated Strategic Plan for Biodiversity was adopted, including the Aichi Biodiversity Targets, for the 2011–2020 period. The 20 Aichi Biodiversity Targets are organized under five strategic goals. The goals and targets comprise both aspirations for achievement at the

B: Reduce the direct pressures on biodiversity and promote sustainable use, and Strategic Goal D: Enhance the benefits to all from biodiversity and ecosystem services. The chapters in this volume have presented convincing, well documented arguments.

However, several chapters also discuss the challenges and reasons as to why AFS are not more widely adopted. In this concluding chapter, the lessons learned are presented along with alternatives and suggestions for addressing some of the pending challenges in relation to agroforestry adoption, profitability of agroforestry products and services, and implementation of integrated landscape management approaches including AFS.

## 2 Pending Challenges

AFS implementation can face a number of barriers and challenges, including inhospitable or incompatible regulatory environments, difficulties in achieving economies of scale, and insufficient access to technical and financial support. These problems can be overcome when there is a willingness to support sustainable agriculture and sufficient financial resources to subsidize AFS implementation as needed.

### *2.1 Why Aren't AFS More Widely Adopted?*

It can be argued that maximizing sustainability at one hierarchical level precludes maximizing sustainability at other levels, and that maximizing sustainability at the national level comes at the cost of environmental deterioration at the local and farm levels (see Jordan 2017, Chap. 6, this volume). Conventional, high input agriculture can be more competitive than AFS as it relies on short-term exploitation of the environment. AFS depend more on human labor, while conventional agriculture replaces labor with high input technology. Governmental policies often favor conventional agriculture because it can bring immediate economic profits, as is the case with oil palm plantations in Indonesia and in several regions of Latin America. Nevertheless, this economic benefit comes at the expense of environmental damage that often is irreparable.

global level, and a flexible framework for the establishment of national or regional targets. Strategic Goal A: Address the underlying causes of biodiversity loss by mainstreaming biodiversity across government and society, B: Reduce the direct pressures on biodiversity and promote sustainable use, C: To improve the status of biodiversity by safeguarding ecosystems, species and genetic diversity, D: Enhance the benefits to all from biodiversity and ecosystem services, E: Enhance implementation through participatory planning, knowledge management and capacity building (http://www.biodiv.be/convention/strategic-plan-2011-2020, https://www.cbd.int/sp/targets/)

However, there are several cases in which AFS compete well with conventional agriculture from both the environmental and the financial points of view. For example, recent research has shown that organic production of coffee is an interesting alternative with similar productivity to conventional systems, when legume tree species are incorporated (Schnabel et al. 2017). Organic coffee production in AFS provides a similar level of productivity to moderate conventional management in terms of both yield and coffee morphology, and offers a price premium and the possibility of entering specialty markets. In a recent comparison of certified and non-certified organic coffee farms in Nicaragua, Haggar et al. (2017) found that certified farms had better environmental characteristics and generally received better prices than non-certified farms.

There are also good examples of profitable AFS in the case of the use of taungya models (i.e., intercropping agricultural crops with trees during the establishment phase of a tree plantation, as explained in the chapter by Montes-Londoño 2017, Chap. 3, this volume). For example, the use of taungya during the establishment of intensive oil palm plantations reduces establishment costs, generates early income, improves the initial development of the palms and in general favors overall financial performance (Somarriba, personal communication, August 2017). In addition, the proponents of certain types of intensive agriculture should acknowledge the fact that, as shown in the chapter by Somarriba et al. (2017), Chap. 15, this volume, often AFS exist in the landscape in the form of agricultural or cattle fields with relatively low tree densities that do not affect yields of the main crops and at the same time provide important environmental services and benefits that can improve financial performance.

Adoption of sustainable practices such as in AFS can be possible through subsidies or through certification garnered by organic, fair-trade, biodiversity friendly or low C-footprint commodities and products. The premium for AFS products contributes to their adoption and dissemination, as shown for cacao, guayusa, yerba mate and other crops grown in organic AFS, in case studies described in the chapters by Eibl et al. (2017), Chap. 11, Jarrett et al. (2017), Chap. 12, Montagnini and Metzel (2017), Chap. 2 and Rocha et al. (2017), Chap. 10, this volume. Ultimately, widespread adoption is undoubtedly hindered by poor local and regional infrastructure (such as processing and transportation), and by a lack of local, regional, and global market incentives.

## 3 Viable Alternatives

### *3.1 Increasing Value of AFS Products*

Markets are currently unable to support the high diversity of farm products that do not reach economy of scale, thus attention is needed to harness cooperative approaches to address these economic and infrastructure limitations. For many of these high-value AFS crops, producers still face many challenges as they often obtain a minimal share of profits gained by intermediaries and final selling points in local and foreign markets. Smallholder farmers grow 70% of the world's food, and as much as 90% of cocoa. However, they receive only a small percentage, generally less than 10% of the retail price (Jamnadass et al. 2014).

Local producer associations and cooperatives offer the potential for alternative points of sale that give a greater possibility for recognition of a higher quality product. This is the case of açaí berries: Pepper and De Freitas Navegantes Alves (2017) in Chap. 9 of this volume, conclude that the direct sale made possible by aggregating the harvest through producer cooperatives is effective in bargaining for and obtaining better prices. Again, certification is seen here as an instrument for guaranteeing higher quality and ecologically sound management that could facilitate the sale of AFS products to specialty export markets.

These are good examples of how indigenous ecological knowledge concerning sustainable practices used in growing the product can be aided by scientific knowledge on technical aspects related to chemistry of the preferred products, as well as the technicalities surrounding the issues of accessing preferred markets, as shown by Rocha et al. (2017), Chap. 10 and others in this volume. As pointed out by Bertsch (2017) and by Young (2017) in Chaps. 7 and 8 of this volume, respectively, in designing agricultural systems that support food sovereignty for smallholder farmers it is imperative that we understand the past and the present, and find ways to effectively integrate indigenous systems into modernity without losing their sustainability.

Many AFS systems are highly complex, and knowledge and labor-intensive—particularly during the first 5–10 years of establishment. Without quantitative evidence of the socio-economic and ecological benefits of implementing a more complex AFS at the farm level, adoption by local farmers will continue to be limited. Data on soil erosion, nutrient leaching, soil quality, crop yields, nutritional values of products and farmer income and well-being before and after agroforestry development, as compared to other local/regional data, would be an important first step along these lines, especially for large scale, commercial producers. Many smallholders use AFS as they have the knowledge and the availability of labor required, and prefer to practice low-input systems. The practice of AFS provides additional financial advantages to both the small and the medium to large scale producer, such as diversifying products and decreasing risks of crop failures and market instabilities.

### *3.2 Environmentally and Financially Sound AFS at the Medium to Large Scale*

There are several examples presented in the chapters by Montes-Londoño 2017, Chap. 3, Roberts, Chap. 4, Chará et al., Chap. 16, and Ormsby Mori et al., Chap. 14 of AFS that are environmentally and financially sound, and are practiced at the medium to large scale, including silvopastoral systems (SPS). In these chapters emphasis is placed on the technical aspects of choices of species and varieties as well as on the management and design that are required to make these systems feasible. More detailed financial analyses of SPS, including those called intensive SPS (ISPS) can be found in Colcombet et al. (2015), Murgueitio et al. (2015) and others. SPS and ISPS are highly technified and in some cases may be less diverse than more traditional multistrata AFS, but they represent a much more environmentally-sound alternative to large-scale cattle raising, monocultures of soybeans or pure pine plantations.

In SPS, sales of cattle products help offset initial costs until timber is mature and ready for marketing. As is often expressed by practitioners, the cattle provides cash flows, while the timber represents a "savings account." The same can be said of many AFS which combine annual crops with perennial or more long-term producing crops and trees (Somarriba et al. 2014). In AFS weeding costs are reduced, an important financial consideration given that weeding is a major cost in early establishment years of a tree plantation (Montagnini et al. 1995; Montagnini and Piotto 2011). As previously discussed, AFS are seen by both the smallholder and the medium to large-scale farmer as a way to diversify investments and decrease risk in an unpredictable, unstable economy. Finally farmers may not depend entirely on AFS as their main source of income, but AFS may be part of several land uses coexisting with forests, plantations and other activities across the landscape.

In any case even conventional agriculture needs initial capital. All types of agriculture need subsidies, not just AFS, and this is true for temperate regions of the USA as well as for tropical regions/developing countries of the world (see Roberts, Chap. 4 and Ormsby Mori et al., Chap. 14). In the case of smallholders in developing countries, who are the target population for many private and government aid agencies, the only way of attaining the goal of eliminating poverty is by placing the emphasis of development projects on improving their livelihoods by encouraging and disseminating systems leading to the production of high value goods and services. These include food/medicines/spices/other products and services directed to the international markets, as well as cattle, fish and agricultural foodstuffs to increase their food sovereignty. Alternative funds could be directed to improving livelihoods; for example, a significant portion of carbon taxes collected worldwide could be set aside and distributed to farmers and stakeholders who manage their landscapes and AFS to sequester and preserve carbon stocks. Funding could also be used to capitalize local financial vehicles which would provide interim funding/loans to cover some of the initial costs of AFS.

Conserving and sustaining biodiversity while promoting profitable agricultural production is a great challenge but several strategies advanced in this volume can be used effectively. Providing financial incentives toward biodiversity-friendly agriculture is a key strategy in this direction. Over the past decade a number of international projects have focused on the adoption of best management practices by farmers as a tool for biodiversity conservation in the tropics, and market transformation for sustainable agri-commodity supply chains. The Central American Markets for Biodiversity project (CAMBio, or Mercados Centroamericanos para la

Biodiversidad in Spanish) financed by the Global Environment Facility (GEF),[2] designed and implemented by the United Nations Development Programme (UNDP), and executed by the Central American Bank for Economic Integration (CABEI/BCIE)[3] from 2008 to 2014 is a good example (Gross et al. 2016).

An evaluation recently conducted by EcoAgriculture Partners[4] in Guatemala, El Salvador, Honduras and Nicaragua revealed that the CAMBio project was successful in improving the adoption of best management practices on farms, including increased tree cover (through agroforestry) and the reduction of agrochemical usage (through organic production). Organic agriculture together with AFS of coffee, cocoa and cardamom, and silvopastoral systems represented nearly 75% of the loans, with the producers stating that participating in the project allowed them to invest in their AFS by incorporating live fences and tree barriers, increasing the number of trees in existing coffee plantations and changing other land uses to AFS (Gross et al. 2016). By focusing on agroforestry-based commodity producing farming systems, CAMBio was able to effectively target areas in need of increased landscape connectivity or protection of high conservation values. Overall the project's public-private partnership structure demonstrates that facilitating loans through banking institutions can be an effective tool to increase tree planting or tree retention in farm land to protect biodiversity (Gross et al. 2016).

A recent document by FAO states that neither a world free of hunger, nor one free of poverty can be achieved by 2030 – as specified in the first two SDGs – without a substantial increase in capital flows in agriculture and food systems. Public and private, as well as domestic and foreign investment will have to increase to reach these goals, particularly for the small-scale producers, who are the major investors in agriculture (FAO 2017). Increased funding for agriculture needs to include financing energy alternatives, especially in those cases, as described in Berg's chapter (2017, Chap. 13 of this volume), when people's lives are in peril from health hazards caused by inefficient cooking and fuel devices. A relatively modest expenditure to promote the use of more efficient cook stoves and alternative fuels would have a major impact on reducing GHG emissions and save millions of lives.

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[2] The Global Environment Facility (GEF) was established on the eve of the 1992 Rio Earth Summit to help tackle our planet's most pressing environmental problems. Since then, the GEF has provided over $17 billion in grants and mobilized an additional $88 billion in financing for more than 4000 projects in 170 countries. Today, the GEF is an international partnership of 183 countries, international institutions, civil society organizations and the private sector that addresses global environmental issues (http://www.thegef.org)

[3] The Central American Bank for Economic Integration (CABEI/BCIE) was founded in 1960. It is an international institution aimed at promoting integration and development among its founding countries: Guatemala, Honduras, El Salvador, Nicaragua and Costa Rica. CABEI is a multilateral development bank whose mission is promoting economic integration and balanced social and economic development of Central American countries, which include founding and non-founding countries (https://www.bcie.org)

[4] EcoAgriculture Partners (ecoagriculture.org) is an internationally recognized center of expertise in integrated landscape management. Their experience supporting landscape initiatives and partnerships has provided them with a comparative understanding of landscape contexts around the world, available tools for conveners, and connections to diverse learning networks.

### 3.3 Enhancing Financial Returns of AFS: Payments for Environmental Services

Payments for Environmental Services (PES) using different mechanisms and procedures such as staggered payments, targeted financing, market and price incentives and subsidies as shown by Montagnini and Finney (2011), Jayachandran et al. (2017) and several others, should promote AFS by increasing profits. Several PES programs have proved to be effective at decreasing deforestation and protecting forests. They can also provide economic benefits, as the value of the delayed carbon dioxide emissions can exceed the program costs (Jayachandran et al. 2017). Toensmeier's chapter (2017, Chap. 18 of this volume) presents evidence of the high rates of carbon sequestration in biomass and soils of perennial staple AFS, which makes these AFS more desirable than conventional annual crop production with their associated loss of soil organic carbon. Perennial staple AFS have rates of C sequestration which are often 5–10 times higher than carbon-sequestering annual crop production practices like conservation agriculture, and they also provide numerous ecological and agroecological co-benefits.

Likewise, as shown in the chapters by Chará et al. (2017, Chap. 16 and Peri et al. (2017), Chap. 19, well-managed SPS increase soil and biomass C storage, while directly improving the livelihoods of farmers through increased livestock production. Due to their lower dependence on external inputs such as fertilizers and concentrates (in comparison with conventional cattle ranching), and to improved animal production, intensive SPS (ISPS) are a valid alternative to increase productivity and lower environmental burdens of livestock production. ISPS can also contribute to the SDGs, mainly those related to responsible production and consumption, climate action, life on earth, and zero hunger.

ISPS are an important tool in supplying beef and dairy products for local and global markets, while also increasing resilience to climate change. The role of trees and shrubs in ameliorating high temperatures and increasing animal and human comfort, so vital in view of the current climate change scenario, has been well documented (Murgueitio et al. 2015, among others). The double role of SPS and other AFS in adaptation and mitigation of climate change is a great advantage that can be utilized to promote collaboration and institutional arrangements leading to the scaling-up of these systems worldwide. The implementation of clean development mechanisms (CDM) offered by the Kyoto Protocol by extending payments to low-income farmers who provide C storage through sustainable land-use systems such as ISPS is a viable option.

Trees on farms (TonF), an often "invisible" resource as stated by Somarriba et al. (2017) in their Chap. 15, also serve an important role in providing livelihoods to smallholder farmers, conservation of tree diversity, and storage of carbon in aboveground biomass and in soils. Calle et al. (2017) also stress in their Chap. 17 that the need for reducing heat stress and adapting to climate change has provided a strong motivation for ranchers to plant or maintain more trees and palms on their lands. Economic incentives such as PES will continue to play a key role in promoting the introduction of native trees and palms of high conservation value in cattle dominated landscapes. In multifunctional landscapes where AFS are providing for improved livelihoods, biodiversity, with its associated services such as pollination, could be enhanced by placing "biodiversity islands" across the landscape (biodiversityislands.wordpress.com).

### *3.4 Public-Private Partnerships (PPPs) in Agroforestry*

There are several examples of value-chain business models already in use in several countries in developing regions of the world, including producer-driven and buyer-driven associations, and integrated models (Miller and Jones 2010). Development agencies can provide support to facilitate the integration of small farmers and agro-enterprises into commercial value chains.

The involvement of Public-Private Partnerships (PPPs) in agroforestry is relatively new. Private companies wishing to increase their market supply of a product, develop 'new' commodities to meet market demand, improve the functioning of supply chains and collaborate with public partners, such as international and national research organizations. The objectives of these collaborative arrangements are to protect the natural resource base of commercially important plant species and to develop improved varieties with increased quality/productivity. In addition, such partnerships embrace government departments engaged in formulating and enabling policies, as well as nongovernmental organizations (NGOs) working with farmers and product processors (Jamnadass et al. 2014; Heiner et al. 2017).

Jamnadass et al. (2014) described case studies of agroforestry PPPs from a range of countries (mostly in Africa and SE Asia), to provide examples of how different public and private sector stakeholders are contributing resources, expertise, skills, and financial investment to enhance market supply of agroforestry products and improve environmental sustainability. The role of PPPs in PES schemes is also discussed as a form of PPP that involves public and private sector actors as providers and buyers of services that include carbon sequestration, watershed protection, and biodiversity protection, many of which can be provided by AFS.

For example, a private company, Energy Africa, promotes the growing of Jatropha as a social business in Kenya. Energy Africa purchases the seed produced by the farmers at a fair price and processes it into oil for their buyers. It works in partnership with the Norwegian University of Life Sciences and the World Agroforestry Center, both of which are interested in the viability of Jatropha production. Other partners include the Global Environment Fund which provided technical collaboration, and the German Development Service interested in development of various Jatropha products. Factors that ensure partnership effectiveness include agreement on a common goal, effective governance, monitoring, and information sharing. The main challenges associated with agroforestry PPPs are issues of difference in culture between private and public sector partners, investment of time and effort, overcoming risks, obstacles associated with public policy, and failures in reporting and delivery. PPPs require contributions of knowledge from multiple actors across both time and space (Jamnadass et al. 2014).

EcoAgriculture Partners and IDH, and the Sustainable Trade Initiative[5] recently published "Public-private civic partnerships for sustainable landscapes, A Practical Guide for Conveners" to share experiences in developing multi-stakeholder initiatives with strong private sector engagement and effective governance systems that promote sustainable land and water management at the farm and landscape scales. Integrated landscape management (ILM) is a term used to describe multi-stakeholder approaches to landscape management. The level of cooperation within integrated landscape management varies from information sharing and consultation to more formal models, with shared decision-making and joint implementation. Integrated landscape management will attract business support, or at least alignment, when it results in clear risk mitigation, value creation and coordinated financial investments (Heiner et al. 2017).

# 4 The Context: Integrated Management of Multifunctional Landscapes

## *4.1 The Multifunctional Agricultural Landscape*

The landscape approach can be defined as "a long-term collaborative process bringing together diverse stakeholders aiming to achieve a balance between multiple and sometimes conflicting objectives in a landscape or seascape" (Sayer et al. 2017). Landscape approaches are commonly proposed for situations where there is ambiguity or disagreement over desirable outcomes. As expressed in Chap. 5 of this volume by López et al. (2017), the sustainable management of agroforestry landscapes is complex because they are socio-ecosystems that integrate biological and socio-productive diversity with spatial-temporal interactions. As decision-making at the farm scale may have indirect and unexpected effects at the landscape level, replacing a farm-scale perspective with a landscape-scale perspective could increase resilience of social-ecological systems, reducing their vulnerability to different drivers. The assumption behind landscape approaches is that by accounting for trade-offs and exploiting potential synergies, they will achieve a better balance

[5] IDH, the Sustainable Trade Initiative convenes companies, civil society organizations, governments and others in public-private partnerships to drive sustainable market transformation in 18 international trade sectors and 11 landscapes that are key sourcing areas for globally traded commodities. Together they drive the joint design, co-funding and prototyping of new economically viable approaches to realize green and inclusive growth at scale in commodity sectors and landscapes. IDH is supported by multiple European governments, and works together with over 500 companies, civil society organizations, financial institutions, producer organizations, and governments in over 50 countries worldwide.

between conflicting objectives compared with conventional spatial planning or sectoral approaches.

Around the world, agricultural landscapes are increasingly seen as "multifunctional" spaces, expected to deliver food supplies while improving rural livelihoods and protecting and restoring healthy ecosystems. Rural producers in many areas have embraced elements of multifunctional land management. Hart et al. (2015) examined case studies in six countries around the world where producer movements and advocates were engaged in field-level production practices that increased efficiency or farm incomes while also benefitting ecosystems and biodiversity. The practices included AFS, conservation tillage and permanent ground cover for soil conservation, agroecological systems, organic agriculture, diverse and traditional crop germplasm and increases in input efficiency. They ranged from traditional and modified traditional systems to new and technologically modern systems. Some of these newly adopted systems resulted in notable increases in crop productivity, and diversity in agroecological and traditional systems was an important contributor to food security and sovereignty. Producer movements and advocates are playing pivotal roles in supporting landscape multi-functionality, not only through agroecological farming practices but also through off-farm efforts to conserve ecosystems and support multi-stakeholder landscape planning (Hart et al. 2015).

Integrated landscape management (ILM) offers an action-oriented means to achieve multiple SDG targets simultaneously at local and subnational levels. Integrated landscape management has been implemented in a wide range of environments and cultures across the globe, providing practical examples of place-based implementation to enhance ecosystems and livelihoods (Thaxton et al. 2015). In a recent White Paper to discuss the benefits of using ILM as a key means of implementation of the SDGs, produced by the Landscapes for People, Food and Nature Initiative (LPFN),[6] Thaxton et al. (2015) discuss the role of landscape partnerships for sustainable development and draw recommendations for implementation of ILM at the national and international levels.

The ILM approach is increasingly being used worldwide (Shames et al. 2017). Once a diverse and inclusive stakeholder group has adopted locally appropriate objectives that recognize the full array of services provided by the landscape, farm and field practices must be designed to improve conditions for working toward multiple objectives. Examples of such practices include utilizing integrated pest

[6] The Landscapes for People, Food and Nature Initiative (www.peoplefoodandnature.org) is a global network of more than 70 conservation, development, and agriculture organizations who champion integrated landscape management at landscape, national and international levels. Founded in 2011, the Initiative is co-organized by Bioversity International, EcoAgriculture Partners, the Food and Agriculture Organization of the United Nations (FAO), Ministry of Economic Affairs of the Government of the Netherlands, the United Nations Environment Programme (UNEP), the World Agroforestry Centre (ICRAF), the World Bank, and the World Resources Institute. The Initiative links and adds value to the many landscape initiatives and networks already in place worldwide, and coordinates action to improve the enabling environment for integrated landscape management.

management (IPM), tillage regimes, crop rotations, and AFS, among others. Sustainable practices such as these protect wild habitats, sustain land quality, efficiently use water and energy, contribute to food and nutrition security, and minimize pollution from nutrients, pest control, and waste, thus positively affecting human health.

Integrated landscape initiatives need to strengthen landscape governance by developing and facilitating multi-stakeholder platforms that enable discussion, negotiation, and joint planning between stakeholders from various sectors in a given landscape. Participatory methods need to be used to aid planning, monitoring, and evaluation of such platforms for effective Integrated Landscape Solutions (ILS) (Kursters et al. 2017). Recent experiences from Ghana and Indonesia demonstrate that collaboration enables stakeholders to jointly identify options to optimize synergies between production practices, livelihoods and the conservation of biodiversity and environmental services, through the promotion of AFS, eco-labelling, and sustainable supply chain development. Likewise, through collaboration stakeholders can identify options to align conservation practices with the interests of other stakeholders in the landscape, e.g., through schemes for compensation, PES, developing ecotourism, etc. (Kursters et al. 2017). A recent document: "Public policy guidelines for integrated landscape management" provides insights and recommendations on the enabling policy environment for a variety of related topics, including sustainable land management, forest and landscape restoration, AFS, territorial development, watershed management, landscape governance, and 'green growth' in agri-commodity landscapes (Scherr et al. 2015), among others (Shames et al. 2017).

### *4.2 How to Assess Effectiveness of Integrated Landscape Management (ILM)?*

Landscapes should be the building blocks for development of socio-ecological resilience, as presented in the chapter by López et al. (2017), Chap. 5 of this volume, with case studies illustrating this approach at the local and regional levels. Landscape planning incorporates all voices, including those of the public, private, and civic sectors, including local stakeholders and serving as the fundamental starting point for building resilient communities and ecosystems. Governments will benefit from intentionally promoting knowledge sharing between sectors, institutions and agencies, drawing upon diverse local and international experiences to define and adopt best practices (Thaxton et al. 2015).

In the White Paper mentioned in the previous part, Thaxton et al. (2015) outline a set of Action Steps for National Governments, followed by guidelines for the international community, which play a key role in promoting ILM and supporting national governments in utilizing ILM. The international community should support these actions through increased and better coordinated financing, including the formation of locally organized finance entities, stronger coordination between international agencies, and support for global knowledge sharing. Effort should be made to encourage the participation of people in close proximity and with solid ties to the local economies.

In spite of the recognized advantages of integrated landscape management, its long-term effectiveness has not yet been adequately evaluated or documented (Sayer et al. 2017). The combination of multiple and potentially changing goals presents problems for the conventional measures of impact. A more critical use of theories of change and measures of process and progress to complement the conventional impact assessments may be needed. Theories of change make explicit the links between project deliverables, outputs, outcomes, and impacts, and allow a full exploration of the landscape context (Belcher and Palenberg in review).

Landscape approaches are long-term engagements, but short-term metrics are needed to confirm success in negotiation of goals, stakeholder engagement, connections to policies, and effectiveness of governance. Long-term impact metrics are also needed to assess progress on achieving landscapes that deliver multiple societal benefits, including conservation, production, and livelihood benefits (Sayer et al. 2017). Theories of change should use simple metrics that can provide practitioners with evidence to verify the effectiveness of landscape scale interventions. If we are to realize the full potential of landscape approaches to address major social and environmental challenges, we must apply rigorous theory of change methodologies, ensure effective processes, define clear goals, ensure continuity of funding, and deploy appropriate multi-disciplinary skills to measure metrics at all stages along the impact pathway (Sayer et al. 2017).

## 5 Concluding Remarks

The lessons learned from the chapters of this volume form a collection of experiences showing positive and promising results on how AFS can be implemented and managed for sustainable production as well as for provision of environmental services. In several cases there are technical issues that merit further attention, but perhaps the greatest challenges now concern issues of scaling-up successful experiences with broader adoption and implementation.

Large scale adoption of agroforestry does not need to come at the expense of profit to the practitioner, if the environmental services provided by the systems are given their proper monetary recognition. As shown in several examples described in this volume, many useful lessons of sustainable agricultural practices were developed by indigenous societies, and integration with more modern scientific approaches can work to bring them more in tune with current markets to result in better compensation for the producers. Producers' associations, proper financing mechanisms, as well as public-private partnerships are needed to ensure that successful local experiences are replicated and implemented at larger scales.

Increasingly, society has come to acknowledge that sustainability is a must for the survival of humans and the planet, and environmental concerns are taking increasing precedence. Tools described in this volume should be useful in planning and implementing AFS programs with an integrated landscape management perspective. There is still work to be done in assessing the effectiveness of AFS and other landscape management strategies. Theories of change used in this assessment should be explicit on the specific outputs and outcomes that need to be accomplished in the short and long term. National and international development programs and projects are favoring integrative approaches and need to be properly supported to reach their goals.

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