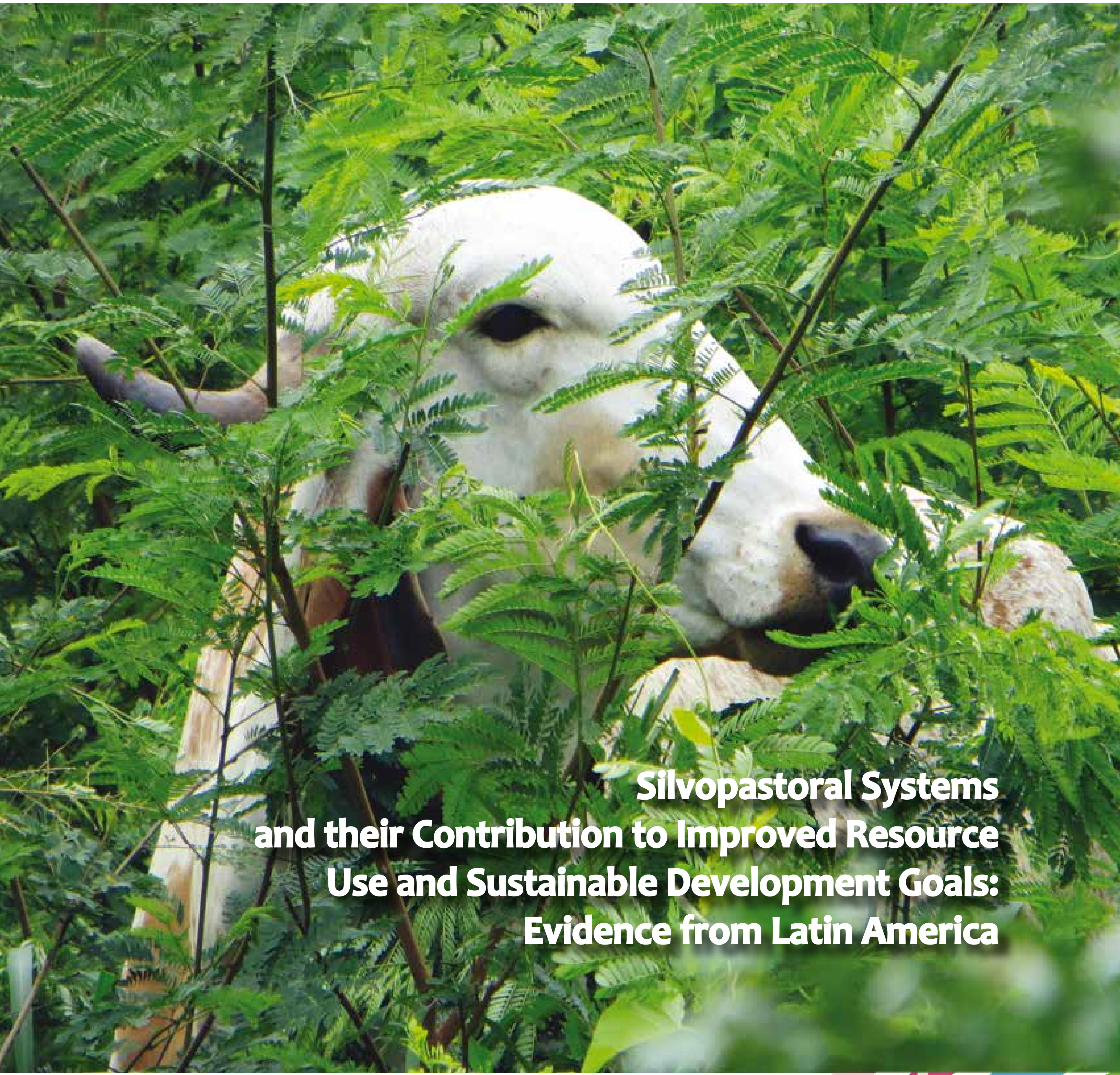
Food and Agriculture Organization of the United Nations

CIPAV

agri benchmark

Global Network on Silvopastoral Systems



Silvopastoral Systems and their Contribution to Improved Resource Use and Sustainable Development Goals: Evidence from Latin America

Global Agenda for Sustainable Livestock

Silvopastoral Systems and their Contribution to Improved Resource Use and Sustainable Development Goals: Evidence from Latin America

Advance copy

ISBN 978-958-9386-83-5
E-ISBN 978-958-9386-84-2

Global Agenda for Sustainable Livestock

Recommended citation

Chará J., Reyes E., Peri P., Otte J., Arce E., Schneider F. 2018. Silvopastoral Systems and their Contribution to Improved Resource Use and Sustainable Development Goals: Evidence from Latin America. FAO, CIPAV. Editorial CIPAV, Cali, 58p.

Disclaimer

This report is a co-publication of the Centre for Research on Sustainable Agriculture (CIPAV), *agri benchmark* and the Food and Agriculture Organization of the United Nations (FAO). The findings, interpretations, and conclusions expressed in the report do not necessarily reflect the views of FAO, its Board of Executive Directors, or the governments they represent.

The designations employed and the presentation of material in this information product do not imply the expression of any opinion whatsoever on the part of FAO concerning the legal or development status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. The mention of specific companies or products of manufacturers, whether or not these have been patented, does not imply that these have been endorsed or recommended by FAO in preference to others of a similar nature that are not mentioned.

The views expressed in this information product are those of the authors and do not necessarily reflect the views or policies of FAO, CIPAV or *agri benchmark*.

ISBN 978-958-9386-83-5
E-ISBN 978-958-9386-84-2

Cover Photo. Las Tinajas farm. Michoacan, Mexico. Photo: J. Chará

Contents

Petequi Farm. Valle del Cauca, Colombia. Photo M. Kohut-WAP.

Preface

Livestock are central to many of the Sustainable Development Goals (SDGs) and can directly or indirectly contribute to most of them. The main potential contributions of livestock to the SDGs pertain to three major domains: (i) food security and livelihoods, (ii) human health (communicable and non-communicable diseases), and (iii) ecosystem sustainability and climate change.

However, the sector's sustainability can only be improved effectively through concerted action by all stakeholder groups. Given the public-good nature of the sector's environmental, social and economic challenges and its increasing economic integration, collective global action is essential.

The Global Agenda for Sustainable Livestock, established in 2011, is a multi-stakeholder partnership mechanism with the aim to foster and guide the sustainable development of the global livestock sector in alignment with the SDG framework of the UN Agenda 2030. It provides a platform to address comprehensively the sector's multiple challenges towards sustainable development through facilitating global dialogue and encouraging local practice and policy change, focusing on innovation, capacity building, and incentive systems and enabling environments.

The achievements of the Global Agenda have proven that multi-stakeholder partnerships are a powerful cooperation approach to support the implementation of the SDGs on issues related to livestock and the four priorities agreed during the 2018 Global Forum for Food and Agriculture (GFFA): food and nutrition security, livelihoods and economic growth, health and animal welfare and climate and natural resource use.

Therefore, the strategic approach in the Global Agenda has evolved from a first phase where the seven stakeholder clusters were the main focus to consolidate the multi-stakeholder vision, to a situation where the action networks have been prioritized to foster knowledge production, pilots and practical impact at local level. The action networks are the specific technical initiatives the Global Agenda liaises with to foster concrete livestock sustainability aspects.

ISPS with *Tithonia diversifolia*. San José Farm. Valle del Cauca, Colombia Photo F. Uribe.

As part of the Global Agenda, the Global Network on Silvopastoral Systems (GNSPS) promotes the scaling-up of silvopastoral systems worldwide. At global level there are many examples of silvopastoral systems (SPS) contributing to sustainable livestock production by reducing impact on natural resources, increasing productive efficiency and profitability, improving food security and animal welfare and contributing to the mitigation and adaptation to climate change.

This document represents a joint effort between two action networks of the Global Agenda: (i) Closing the Efficiency Gap and (ii) the Global Network on Silvopastoral Systems. A framework for evaluating natural resource use efficiency is applied to a variety of silvopastoral production models to determine productivity and their socio-economic and environmental benefits. It presents an overview of SPS, their main characteristics and advantages regarding production and benefits for the environment and climate, and their contribution to the SDGs, describing the results of ten case studies of adoption of SPS in diverse contexts in Colombia, Mexico, and Argentina, with a focus on land productivity, meat and milk production, and economic performance at the farm level. Based on the findings, a number of policy recommendations are made with a view to scaling-up and promoting SPS in Latin America and other regions.

Since all success stories include strong policy development components, only with conducive public policies which allow to link small scale producers to inputs, markets and capacity building measures the programmes have been successful.

I congratulate the leaders of this initiative for showcasing the important role of silvopastoral systems towards achieving the SDGs.

Fritz Schneider
Chair
Global Agenda for Sustainable Livestock

Acknowledgments

This publication is the result of collaboration between two Action Networks of the Global Agenda for Sustainable Livestock: Closing the Efficiency Gap and the Global Network on Silvopastoral Systems (GNSPS).

The report was prepared by Julián Chará (CIPAV), Ernesto Reyes (*agri benchmark*), Pablo Peri (INTA), Joachim Otte (BEAR), Fritz Schneider (GASL) and Eduardo Arce (GASL).

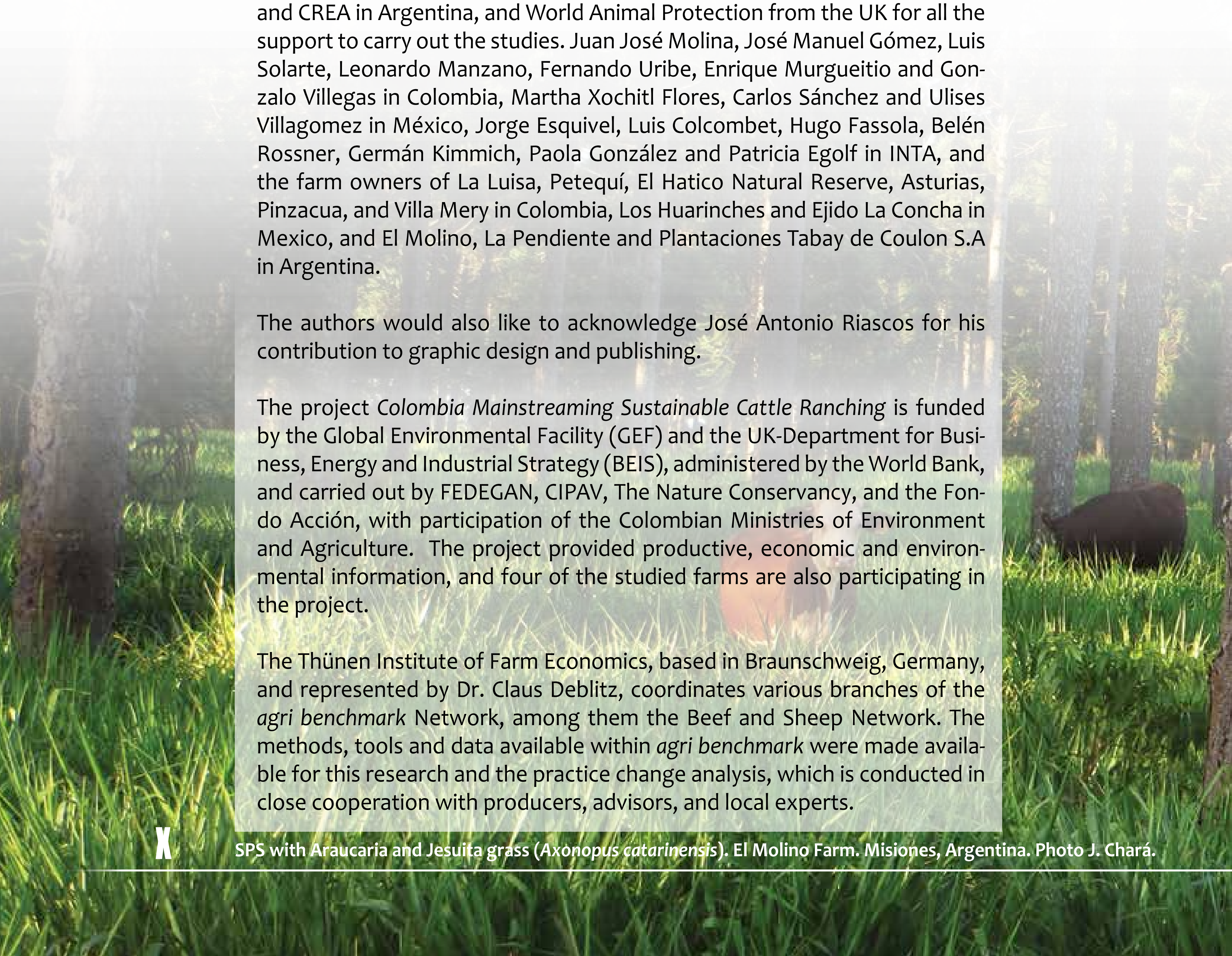
The report greatly benefited from the comments of two members of the Academic Cluster of GASL: Liz Wedderburn (AgResearch) and Rogerio Martins Mauricio (UFSJ).

The authors would like to acknowledge the support of the project *Mainstreaming Sustainable Cattle Ranching*, FEDEGAN, the Comité de Ganaderos del Caquetá in Colombia, Fundación Produce Michoacán in Mexico, the INTA and CREA in Argentina, and World Animal Protection from the UK for all the support to carry out the studies. Juan José Molina, José Manuel Gómez, Luis Solarte, Leonardo Manzano, Fernando Uribe, Enrique Murgueitio and Gonzalo Villegas in Colombia, Martha Xochitl Flores, Carlos Sánchez and Ulises Villagomez in México, Jorge Esquivel, Luis Colcombet, Hugo Fassola, Belén Rossner, Germán Kimmich, Paola González and Patricia Egolf in INTA, and the farm owners of La Luisa, Petequí, El Hatico Natural Reserve, Asturias, Pinzacua, and Villa Mery in Colombia, Los Huarinches and Ejido La Concha in Mexico, and El Molino, La Pendiente and Plantaciones Tabay de Coulon S.A in Argentina.

The authors would also like to acknowledge José Antonio Riascos for his contribution to graphic design and publishing.

The project *Colombia Mainstreaming Sustainable Cattle Ranching* is funded by the Global Environmental Facility (GEF) and the UK-Department for Business, Energy and Industrial Strategy (BEIS), administered by the World Bank, and carried out by FEDEGAN, CIPAV, The Nature Conservancy, and the Fondo Acción, with participation of the Colombian Ministries of Environment and Agriculture. The project provided productive, economic and environmental information, and four of the studied farms are also participating in the project.

The Thünen Institute of Farm Economics, based in Braunschweig, Germany, and represented by Dr. Claus Deblitz, coordinates various branches of the *agri benchmark* Network, among them the Beef and Sheep Network. The methods, tools and data available within *agri benchmark* were made available for this research and the practice change analysis, which is conducted in close cooperation with producers, advisors, and local experts.



SPS with Araucaria and Jesuita grass (*Axonopus catarinensis*). El Molino Farm. Misiones, Argentina. Photo J. Chará.

Acronyms

ADF	Acid Detergent Fibre
CH_4	Methane
CIAT	International Center for Tropical Agriculture
CIPAV	Centre for Research on Sustainable Agricultural Production Systems
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
CREA	Regional Consortium of Agricultural Experimentation
DM	Dry Matter
ECDBC	Colombian strategy for low carbon development
ECM	Energy Corrected Milk
FAO	Food and Agricultural Organization of the United Nations
FEDEGAN	Colombian Cattle ranchers Federation
FPCM	Fat and Protein Corrected Milk
GASL	Global Agenda for Sustainable Livestock
GEF	Global Environment Facility
GFFA	Global Forum for Food and Agriculture
GHG	Greenhouse gases
GNSPS	Global Network on Silvopastoral Systems
HA	Hectare
INTA	National Institute for Agricultural Technology, Argentina
ISPS	Intensive Silvopastoral Systems
LW	Live weight
Mg	Mega gram
N_2	Nitrogen
N_2O	Nitrous Oxide
NDF	Neutral Detergent Fibre
PES	Payment of Environmental Services
SDG	Sustainable Development Goal
SPS	Silvopastoral Systems
UN	United Nations

Executive Summary

In 2015 the 193 Member States of the United Nations adopted the Sustainable Development Goals (SDGs), a set of 17 aspirational objectives expected to guide development actions of governments, international agencies, civil society and other institutions over the next 15 years (2016-2030). They integrate the three dimensions of sustainable development – economic, social and environmental – mutually depend on each other and form an 'indivisible whole'.

Livestock are central to many of the SDGs and can directly or indirectly contribute to most of them. The Global Agenda for Sustainable Livestock is a partnership of livestock sector stakeholders committed to fostering the sustainable development of the sector and aligning livestock sector development with the SDG framework. As part of the Global Agenda, the *Global Network on Silvopastoral Systems* promotes the scaling-up of silvopastoral systems worldwide to support sustainable livestock production.

Silvopastoral systems (SPS) are agroforestry arrangements that purposely combine fodder plants, such as grasses and leguminous herbs, with shrubs and trees for animal nutrition and complementary uses. They allow the intensification of cattle production based on natural processes and are recognized as an integrated approach to sustainable land use. SPS promote beneficial ecological interactions that manifest themselves as increased yield per unit area, improved resource use efficiency and enhanced provision of environmental services.

Latin America has extensively experimented with SPS as an option for sustainable cattle production and most Latin American countries have accumulated important experience in adopting and adapting SPS to local circumstances.

An analytical framework for evaluating natural resource use efficiency was applied to a variety of silvopastoral production models to determine their productivity, as well as their socio-economic and environmental benefits. Results from ten case studies from Argentina, Colombia, and Mexico, covering periods of ten years or longer, are presented to demonstrate the impacts of SPS adoption. The case studies have been purposefully selected to illustrate the adoption of different types of SPS under a variety of agro-ecological conditions, diverse production systems, and aiming to address different sustainability challenges.

Cattle fattening in a SPS with Pinus and Jesuita grass. Plantaciones Tabay. Misiones, Argentina. Photo J. Chará.

Over the study period, four of the ten farms converted all their land to SPS while the remaining six farms converted between 40% and 70%. Forage production per ha increased on nine of the ten farms with increases ranging from 12 to 733%, depending on the initial condition of the pastures and on the proportion of land converted. On one farm, forage production per ha decreased due to the total discontinuation of fertilizer use, which had been exceptionally high prior to the adoption of SPS. Production of milk/meat per ha increased considerably on all ten farms due to combined effects of higher stocking densities and improved individual production. As a result, GHG emissions per 100 kg of milk or live weight added declined on all farms as SPS were established. Animal welfare was higher than on comparison farms. One farm, on which impacts of SPS on biodiversity was tracked, had a three-fold increase in birds, a 60% higher ant count and a doubling of the number of dung beetles compared to baseline values.

In all cases, at the end of the analysis period, farm returns were higher than costs, and six of the eight farms in which cattle were not a complement to forestry made an annual profit per hectare of USD1 500 or more. From the cash flow point of view, the first period of investment, however, frequently resulted in a negative cash flow, which requires consideration with regards to the financing of the SPS investment.

The case studies provide sound evidence that SPS simultaneously deliver gains in productivity and profitability, environmental improvements, and animal welfare benefits and thereby support a number of SDGs. Despite these benefits, SPS have not been widely implemented due to a variety of technical, financial and cultural barriers. These include the lack of technical assistance to farmers to adapt the system to specific local conditions, the technical complexity of SPS management and the high initial investment requirements.

National policies should support SPS adoption by the provision of dedicated credit lines and incentives such as payment for environmental services. Furthermore, policies that promote specialized training for extension workers and technicians on all aspects of SPS are required to increase their adoption. Public-private alliances, driven by strong farmers' organizations, have proven crucial in overcoming technical complexities allowing a substantial number of farmers to successfully adopt SPS. Finally, it is essential to assess the economic, environmental, and animal welfare implications of SPS adoption for more arrangements, scales, and agro-ecological conditions to formulate SPS strategies tailored to local specificities.

ISPS with *L. Leucaena* and *Megathyrsus maximus* grass. La Luisa Farm. Cesar, Colombia. Photo J. Chará.

Introduction

In 2015 the 193 Member States of the United Nations adopted the Sustainable Development Goals (SDGs), a set of 17 aspirational objectives (Figure 1) with 169 targets expected to guide development actions of governments, international agencies, civil society and other institutions over the next 15 years (2016-2030). Replacing the Millennium Development Goals, the SDGs of the UN's 2030 Agenda for Sustainable Development have become the universally endorsed development objectives accepted by and applicable to all countries. They integrate the three dimensions of sustainable development – economic, social and environmental – mutually depend on each other and form an 'indivisible whole'.

Figure 1 United Nations Sustainable Development Goals

Plantaciones Tabay. Misiones, Argentina. Photo J. Chará.

Livestock are central to many of the SDGs and can directly or indirectly contribute to most of them. For many of the Goals, livestock can make both positive and negative contributions and synergies and trade-offs exist between Goals. For instance, the strong growth in demand for livestock products in developing countries, driven by population growth, higher incomes, and urbanization, represents a huge opportunity for reducing poverty (SDG 1) by enabling hundreds of millions of poor smallholder livestock farmers, processors and market agents to tap into that market demand. On the other hand, some forms of livestock production draw heavily on natural resources and a growing livestock sector could significantly accelerate resource depletion and environmental pollution, thereby undermining SDGs 14 and 15.

The main potential contributions of livestock, positive as well as negative, to the achievement of the SDGs pertain to the following three major domains: (i) food security and livelihoods (ii) human health (communicable and non-communicable diseases), and (iii) ecosystem sustainability and climate change. Different forms of livestock production are practiced around the globe, each with its specific impact profile across the three domains.

The Global Agenda for Sustainable Livestock is a partnership of livestock sector stakeholders committed to fostering the sustainable development of the sector and aligning livestock sector development with the SDG framework. With global population projected to reach 9.6 billion in 2050, the role of the livestock sector in the sustainability of food and agriculture will continue to increase. To be sustainable, livestock sector growth needs to simultaneously address key environmental, social and economic challenges: increasing scarcity and competition for natural resources, climate change, widespread poverty and food insecurity, and persistent as well as emerging threats to animal and human health.

As part of the Global Agenda, the Global Network on Silvopastoral Systems promotes the scaling-up of silvopastoral systems worldwide to support sustainable livestock, through the generation, exchange and dissemination of knowledge, the documentation of public policies, and the facilitation of dialogue.

There is a wide variety of silvopastoral systems (SPS) worldwide contributing to the sustainable development of livestock production and rural livelihoods. Silvopastoral systems provide technological, economic, environmental, and cultural options for supporting livelihoods and commercial activities through sustainable livestock farming. All these are coincident with the objectives of the Global Agenda and with its support of the SDGs.

This report provides an overview of the main characteristics of SPS, their benefits with respect to production, the environment and climate, and their contribution to the SDGs. It also describes their geographical distribution and the most important SPS arrangements in Latin America. Subsequently, the report presents the results of ten case studies of adoption of SPS in diverse contexts in Colombia, Mexico, and Argentina, with a focus on land productivity, meat and milk production, and economic performance at the farm level. Finally, based on the findings, a number of recommendations are made with a view to scaling-up and promoting SPS in Latin America and other regions.

SPS with scattered fruit trees. El Volga Farm. Caquetá, Colombia. Photo J. Chará.

Overview of SPS

Silvopastoral systems (SPS) are agroforestry arrangements that purposely combine fodder plants, such as grasses and leguminous herbs, with shrubs and trees for animal nutrition and complementary uses (Murgueitio *et al.* 2011). They allow the intensification of cattle production based on natural processes and are recognized as an integrated approach to sustainable land use (Nair *et al.* 2009). SPS promote beneficial ecological interactions that may manifest themselves as increased yield per unit area, improved resource use efficiency and enhanced provision of environmental services. As a result, farm income can be raised or diversified, both directly through increased sales of timber, animals and animal products, and indirectly through beneficial effects of soil conservation, the provision of shelter for livestock and improved animal welfare. Thus, these systems can be more productive, profitable and sustainable than specialized forestry or animal production on their own (Jose 2009, Peri *et al.* 2016).

The main SPS comprise: i) scattered trees in pasturelands, ii) timber plantations with livestock grazing areas, iii) pastures between tree alleys, windbreaks, live fences, fodder banks with shrubs and iv) intensive silvopastoral systems (Murgueitio *et al.* 2015, Chará *et al.* 2017). Intensive silvopastoral systems (ISPS) combine high-density cultivation of fodder shrubs (4 000–40 000 plants ha^{-1}) with improved grasses; and tree or palm species at densities of 100–600 trees ha^{-1}. These systems are managed under rotational grazing with occupation periods of 12 to 24 hours and 40 to 50-day rest periods, including *ad libitum* provision of clean water and mineralized salt in each paddock (Calle *et al.* 2012, Murgueitio *et al.* 2016).

Geographic distribution

SPS are found worldwide, either intentionally implemented by farmers in different arrangements or as a result of an adaptation and management of natural ecosystems to provide shelter and services as, for example, in the Dehesa and Montado ecosystems on the Iberian Peninsula, El Chaco in South America and several areas of Africa and Asia (Ferraz-de-Oliveira 2016, Kunst *et al.* 2016, Le Houerou 1987, Soni *et al.* 2016). In Europe and North America there is increasing interest in the introduction of the tree and shrub components either in integrated systems to produce wood, fruits or nuts in alley cropping systems, as windbreaks or to provide extra nutrients to livestock by direct browsing or after pruning or coppicing trees (Orefice *et al.* 2017, McAdam 2005, Vandermeulen *et al.* 2018, Papanastasis *et al.* 2009). In Australia, farmers have developed a system where Leucaena is cultivated at high density integrated with grasses (Shelton and Dalzell 2007).

In Latin America, farmers practice a wide variety of SPS ranging from small-scale fodder banks for cut and carry (through live fences in Mesoamerica and the Andean mountains or natural regeneration of native trees throughout the region) to large commercial areas with ISPS in Mexico and Colombia, timber-beef production in Argentina, Paraguay and Uruguay or integrated crop-livestock-forestry systems in Brazil, among many others (Murgueitio *et al.* 2016, Somarriba *et al.* 2018, Peri *et al.* 2016, Nunes *et al.* 2010).

In Colombia, the project *Mainstreaming biodiversity into sustainable cattle ranching*, along with other initiatives has promoted the establishment of SPS in five regions of the country. The systems include live fences, scattered trees in pastures, fodder banks and intensive silvopastoral systems with *Leucaena leucocephala* and *Tithonia diversifolia* (Murgueitio *et al.* 2015). ISPS with L. leucocephala have also been promoted in Mexico where more than 10 thousand hectares have been planted in the last decade involving 1 800 farms (beef and milk) under the technical supervision of Fundación Produce Michoacan (Solorio *et al.* 2012).

SPS have also become an economical, ecological and productive alternative in Argentina where exotic tree species or managed native forests are incorporated into farming systems allowing the production of trees and livestock from the same unit of land (Peri et al, 2016). The difference in conditions in the southern part of South America (geography, climate, culture, and markets) has stimulated the development of different SPS in the region. For example, in the Argentinean provinces of Corrientes and Misiones (Mesopotamia region), SPS with highly productive pine trees and C4 grasses have mainly been adopted by cattle farmers as an alternative to diversify production and increase the profitability as compared with traditional farming and forestry systems (Colcombet *et al.* 2015).

SPS benefits

The main benefits of SPS, when compared to treeless pastures are:

i) increased production of higher quality forages, which reduces the need of supplementation from external sources (Mojardino *et al.* 2010, Barahona *et al.* 2014);

ii) increased (up to 4-fold) cattle production per ha (Thornton and Herrero 2010);

iii) higher storage of carbon in both aboveground and belowground compartments of the system (Nair *et al.* 2010, Montagnini *et al.* 2013);

iv) improvement of soil properties due to greater uptake of nutrients from deeper soil layers, enhanced availability of nutrients from leaf-litter and increased nitrogen input by N2-fixing trees (Nair *et al.* 2007, Vallejo *et al.* 2010, Cubillos *et al.* 2016);

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 water holding and infiltration capacity of the soil which contributes to the regulation of the hydrological cycle by reducing runoff intensity (Jose 2009, Rios *et al.* 2007);

vii) habitats of higher biodiversity (Nair *et al.* 2010, Sáenz *et al.* 2007, Giraldo *et al.* 2011, Montoya-Molina *et al.* 2016); and

viii) improved animal welfare (Broom *et al.* 2013).

ISPS in El Hatico Natural Reserve, Valle del Cauca, Colombia. Photo M. Kohut-WAP.

Biomass and livestock production: SPS produce more dry matter, digestible energy, and crude protein per hectare than purely grass-based systems and thus can increase milk and/or meat production while reducing the need for external inputs such as chemical fertilizers and concentrate feeds (Murgueitio *et al.* 2011, Ribeiro *et al.* 2016). 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} $year^{-1}$ (Chará *et al.* 2017). In the same region DM production in degraded pastures averages 7.0 Mg ha^{-1} $year^{-1}$ (Cajas-Girón *et al.* 2011). In Mexico, DM yield on three farms adopting ISPS with Leucaena varied between 3.62 and 4.79 Mg ha^{-1} per rotation, more than three times higher than in an adjacent farm with a monoculture of star grass (*Cynodon plectostachyus*) (Solorio-Sánchez *et al.* 2011). In the Northeast of Argentina, SPS with Grevillea (timber tree) and Urochloa grass allowed a three-fold increment in the stocking rate when compared to adjacent open pastures (Lacorte and Esquivel 2009, Colcombet *et al.* 2015). In the same region, the grass *Axonopus catarinensis* used in SPS produced 41% more biomass and had higher protein content under shade (38% reduction in photosynthetically active radiation) than in open pastures (Pachas 2010). In Patagonia (Argentina), SPS increased the productivity of pastures by ~20-35% in relation to mixed improved pastures without trees (Peri *et al.* 2005). 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 SPS contain almost three times as much protein as tropical grasses (18-30% in shrubs vs 4-12% in grass) and have a lower fiber content with values under 41% of neutral detergent fiber (NDF) and 30% of acid detergent fiber (ADF) (Murgueitio *et al.* 2015).

Due to the above traits, in ISPS, production of beef or milk per animal and per ha is increased. In an ISPS in Colombia with Leucaena, star grass and timber trees the amount of meat produced increased from 74 kg (live weight) ha^{-1} $year^{-1}$ to 1 060 kg ha^{-1} $year^{-1}$ (Mahecha *et al.* 2011). Similar results were obtained in Mexico where production of meat increased from 456 kg ha^{-1} $year^{-1}$ on improved pastures to 1 971 kg in an ISPS with *L. leucocephala* (Solorio-Sánchez *et al.* 2011). Similarly, 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.

In an ISPS with *T. diversifolia* in the Amazons region of Colombia, Rivera *et al.* (2015) found an increment of 44% in total fodder biomass and 58% in milk production per ha as a result of a higher carrying capacity and individual milk yield when compared to treeless Urochloa-Brachiaria pastures. Milk quality was also improved as the production of protein, fat, and total solids were 29, 33 and 36% higher respectively in the ISPS.

ISPS with *T. diversifolia* and Brachiaria. La Santa María Farm. Caquetá, Colombia. Photo F. Uribe.

Carbon storage and GHG emissions: Tree incorporation in croplands and pastures results in greater net C storage above- and belowground (Montagnini and Nair 2004). Estimates of carbon sequestration potential of agroforestry systems range from 0.29 to 15.21 Mg ha^{-1} yr^{-1} aboveground and from 30 to 300 Mg C ha^{-1} up to 1 m depth in the soil (Nair *et al.* 2009, Nair 2011). For SPS, the estimated aboveground carbon sequestration potential ranges from 1.5 Mg ha^{-1} yr^{-1} (Ibrahim *et al.* 2010) to 6.55 Mg ha^{-1} yr^{-1} (Kumar *et al.* 1998). In Queensland, Australia, Radrizzani *et al.* (2011) found that Leucaena SPS accumulated between 79 and 267 kg ha^{-1} yr^{-1} more than adjacent pure grass plots. In the Patagonia region of Argentina, 148.4 Mg C ha^{-1} were stored in SPS, of which approximately 85% was stored in the soil, 7% in belowground biomass (understory and tree roots) and 8% in aboveground biomass. Belowground biomass thus represented an important C storage pool in the ecosystem (Peri *et at.* 2017a).

GHG emissions per unit of animal product are reduced in SPS as a result of higher production efficiency (lower age at first calving, shorter calving intervals, higher weight gains, increased milk yields) and improved dietary composition. As a result of higher nutrient quality in SPS diets, the amount of CH4 emitted per kg of dry matter consumed (and per kg of product) is reduced (Barahona *et al.* 2014). Thornton and Herrero (2010) when modelling potential measures to reduce GHG emissions in the tropics, estimated that the emissions per unit of milk and meat produced could be reduced by 57% and 73% respectively when concentrates and part of the basal diet were replaced by leaves of *L. leucocephala*.

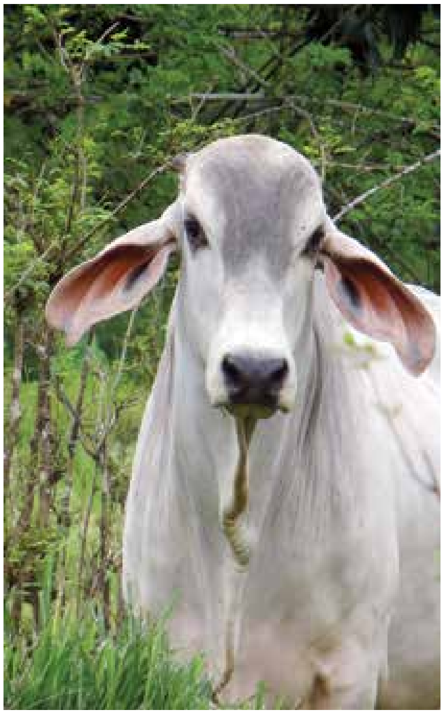
Biodiversity and soil quality: The presence of shrubs and trees in SPS have demonstrated effects on biodiversity by creating complex habitats for wild animals and plants (Harvey *et al.* 2006, Moreno and Pulido 2009), harbouring a richer soil biota (Rivera *et al.* 2013, Montoya-Molina *et al.* 2016), and increasing connectivity between forest fragments (Rice and Greenberg, 2004). In farmed landscapes, SPS provide food and cover for birds, serving as wildlife corridors where unique species assemblages can be found (McAdam *et al.* 2005, Murgueitio *et al.* 2011, Broom *et al.* 2013). In the Quindío region of Colombia, the areas with SPS were found to have three times as many bird species as pasture areas without trees (Fajardo *et al.* 2010). In the Argentinean Patagonia, it was found that the relative abundance and richness of birds, insects, and understory vascular plants was increased in SPS due to the enrichment of the habitat with trees of different ages, and structures such as dead trees and fallen logs (Peri *et al.* 2017b).

Higher biodiversity in the production areas and their surroundings also helps providing important environmental services for the farm such as pollination, pest control and water regulation. Regarding pest control, Giraldo *et al.* (2011) found reduced numbers of horn fly larvae in areas with SPS due to the increased activity of dung beetles. In Brazil fungal strains isolated from SPS were very effective in controlling immature stages of spittlebug (*Mahanarva spectabilis*) one of the major insect pests of forage grasses across tropical America (Campagnani 2017).

Several studies have demonstrated effects of SPS on the physical, chemical and microbiological properties of the soil. The shrubs and trees in the SPS add layers of vegetation capable of transforming solar energy into biomass, which includes the formation of roots that penetrate to deeper soil layers, from where they extract nutrients and water (Nair 2011, Chará *et al.* 2015). The greater number of strata also generates more abundant and heterogeneous biomass that is deposited on the soil in the form of leaves, branches, fruits, resins and exudates with important effects on nutrients, organic matter and biota (Vallejo *et al.* 2012). These benefits are complemented by the effect of nitrogen-fixing trees and shrubs and other associations between trees and microorganisms that increase the availability of vital nutrients for the production of biomass (Malchair *et al.* 2010).

In southwestern Colombia, Vallejo *et al.* (2010) found that soils under SPS had a higher percentage of macro- and micro-pores, less bulk density (<1.4 vs. 1.52 g-cc-3) and less penetration resistance (<3.3 vs. 3.98 MPa) than soils under pasture monocultures. These traits are associated with improved water retention and reduced runoff. In studies carried out in Costa Rica and Nicaragua, in pastures without trees water runoff was equivalent to 28-48% of the precipitation while it was less than 10% in SPS (Ríos *et al.* 2007).

Animal welfare: In SPS, animal welfare is improved as a result of higher availability of nutrients than in pasture-only systems, reduced heat stress due to the provision of shade, the possibility of concealment which reduces fear and anxiety, and a reduction of ectoparasites (Giraldo *et al.* 2011, Broom *et al.* 2013).



San Diego Farm. Quindío, Colombia.
Photo J. Chará.

<u>Farm economics:</u> A number of studies have demonstrated that the introduction of ISPS increased yield and improved farm profitability (Murgueitio *et al.* 2015). For example, Rivera *et al.* (2015) found that the income from milk sales was 42.1% higher in SPS compared to conventional pastures. When adopting SPS, after the initial establishment and associated cost and a stabilization period, the higher productivity per hectare generates returns that ensure the economic viability of ISPS. From a mid-term perspective, the implementation cost is more than compensated by the increase in farm returns due to higher productivity (Chará *et al.* 2017).

The contribution of SPS to SDGs

Most of the aspects and mechanisms by which SPS can make important contributions to the SDGs have been mentioned in the previous section (SPS benefits). In small and medium-scale farming, the inclusion of trees and shrubs improves and diversifies food production, reduces the dependence on external inputs, and reduces climatic and economic vulnerability and thereby contributes to improved livelihoods (SDG 1) and food security (SDG 2) in rural areas.

SPS make an important contribution to SDG 13, related to climate action, since they increase carbon sequestration, reduce GHG emissions per unit of product, and reduce the vulnerability of livestock production to climate change as they stabilize forage availability throughout the year by favouring water infiltration and soil conservation. By improving habitat biodiversity, enhancing connectivity and reducing land degradation in rural landscapes SPS also contribute to SDG 15, related to terrestrial biodiversity.

They can also contribute to responsible production (SDG 12) by making more efficient use of natural resources (producing more with less), improving animal welfare and reducing morbidity and mortality, and by enhancing nutrient cycling and other natural processes, which reduce the need for chemical fertilizers and pesticides.

SPS can also increase economic benefits by improving profitability as a result of higher gains in land and animal productivity and thereby contribute to SDG 8 (decent work and economic growth).

Brangus cattle in a SPS with Hybrid Pine. Estancia La Victoria. Corrientes, Argentina. Photo D Sempe.

ISPS with *T. diversifolia* and star grass. La Joya Farm. Valle del Cauca, Colombia. Photo. J. Chará.

Case Studies of the Adoption of SPS in Latin America

Global demand for beef and milk is expected to grow over the next decades, which, to be satisfied, will require a significant amount of additional natural resource use. Past and current beef and milk production have already occurred at the expense of natural ecosystems and have made significant contributions to the emissions of greenhouse gases (GHG) fuelling climate change (Steinfeld *et al.* 2006). These impacts have important implications for Latin America, as cattle production largely relies on extensive ranching systems, with low stocking rates and high GHG emissions per kg of product (O'Mara 2011, González *et al.* 2015).

Against this background, recent studies on SPS have demonstrated the possibility of sustainable intensification of cattle ranching, producing more meat and milk of higher quality, reducing GHG emissions (per kg of product) and restoring degraded ecosystems. Latin America has extensively experimented with SPS as an option for sustainable cattle production and most Latin American countries have accumulated important experience in adopting and adapting SPS to local circumstances.

Ten case studies from Argentina, Colombia, and Mexico have been selected to illustrate the adoption of SPS. Colombia is currently implementing a large-scale SPS project (See box 1), aiming to achieve an important regional coverage of SPS for cattle production. In the Michoacán region of Mexico public-private alliances, led by producers, have converted more than 10 000 ha of pasture monoculture to SPS. Finally, in Argentina, in the region of Misiones and Corrientes, large-scale timber industries have introduced beef production, alongside timber production, by implementing SPS.

ISPS with Leucaena and Megathyrsus.
El Hatico Natural Reserve. Valle del Cauca, Colombia. Photo M. Kohut-WAP.

Box 1 Project:
Mainstreaming Sustainable Cattle Ranching in Colombia

The project is funded by the UK Government and the Global Environment Fund (GEF) under administration of the World Bank, and is carried out by the Colombian Cattle Ranchers Federation (FEDEGAN), the Centre for Research on Sustainable Agricultural Production Systems (CIPAV), The Nature Conservancy (TNC) and Fondo Acción with participation of the Ministries of Environment and Agriculture. Its main objective is to promote the adoption of environment-friendly silvopastoral cattle ranching systems, with the aim of improving natural resource management, enhancing the provision of environmental services (biodiversity, land, carbon, and water), and raising farm productivity.

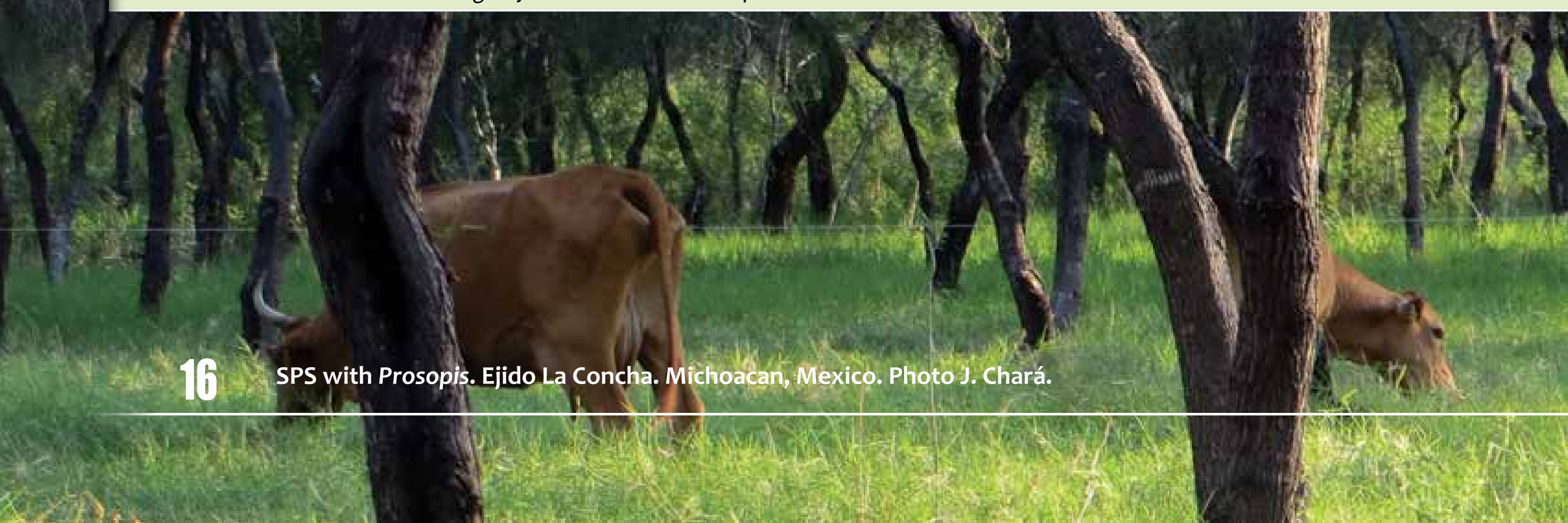
The project covers more than 2 500 farms in five regions of the country and has to date: i) introduced environmentally-friendly cattle production on close to 50 000 ha (31 000 ha of SPS with low-density trees, 2 650 ha of intensive SPS, 15 000 ha of forest preserved on farm), ii) placed 51 900 ha under a Payment for Environmental Services (PES) scheme, iii) improved stocking rates and productivity per animal by 15%, iv) enhanced biodiversity and incorporated/protected 50 globally endangered plant species on the farms and v) sequestered 1.9 million Mg of CO_2eq above and belowground in the implemented SPS areas. In addition, the project has significantly contributed to the development of public policies, the training of technicians and farmers, and the development of a network of demonstration farms and service providers.

The case studies have been purposefully selected to illustrate the adoption of different types of SPS, implemented under diverse agro-ecological conditions, different production systems, and trying to address specific sustainability challenges. Six of the SPS case studies cover the introduction of ISPS while four case studies refer to other silvopastoral arrangements. Table 1 provides an overview of the main characteristics of each of the case studies.

Table 1 Main characteristics of the selected case study farms

Case study	1	2	3	4
Country	**Colombia**	**Colombia**	**Colombia**	**Colombia**
Climatic conditions	*Dry Tropical*	*Semi-humid Tropical*	*Dry Tropical*	*Semi-humid Tropical*
Avg. temp. (°C)	28	23	24	22
Rainfall (mm/yr)	1 560	1 700	971	1 860
Altitude (masl)[1]	72	984	1 010	1 160
Production system	Beef finishing	Dual purpose	Tropical dairy	Tropical dairy
Sustainability goal	Restoring degraded natural resources	Sustainable intensive production	Sustainable intensive production	Sustainable intensive production
Baseline vs. SPS	From degraded soils to sustainable intensive production	From intensive production with high dependence on external inputs to sustainable intensive production	From intensive production with high dependence on external inputs to sustainable intensive production	From intensive production with high dependence on external inputs to sustainable intensive production
SPS strategy	ISPS	ISPS	ISPS	ISPS
	Leucaena + Panicum[2] + Eucalyptus	Leucaena + star grass / Panicum	Leucaena + star grass / Panicum	Leucaena + star grass

[1] meters above sea level. [2] *Megathyrsus maximus.* [3] *Axonopus catarinensis*



SPS with *Prosopis*. Ejido La Concha. Michoacan, Mexico. Photo J. Chará.

5	6	7	8	9	10
Colombia	**Colombia**	**Mexico**	**Mexico**	**Argentina**	**Argentina**
Semi-humid Tropical	*Humid Tropical*	*Dry Sub-tropical*	*Dry Sub-tropical*	*Humid Sub-tropical*	*Humid Sub-tropical*
22	25.8	22	22	20	21
1 872	3 500	2 600	2 600	1 585	1 650
1 232	260	380	271	210	80
Cattle breeding	Dual purpose	Tropical dairy	Beef finishing	Forestry + beef finishing	Forestry + beef finishing
Restoring degraded natural resources	Reducing deforestation and ecosystem recovery	Sustainable intensive production	Sustainable intensive production	Sustainable diversification of land use	Sustainable diversification of land use
From degraded soils to sustainable production	From deforested areas for extensive production to sustainable intensive production, releasing land for ecosystem recovery	From intensive production with high dependence on external inputs to sustainable intensive production	From extensive land use to sustainable intensive production	From monoculture (forestry) to diversi-fied land use	From extensive land use to sustainable intensive production
SPS	SPS	ISPS	ISPS	SPS	SPS
Trees in rows + star grass	Scattered trees + *Tithonia diversifolia*	*Leucaena + Panicum*	*Leucaena + Panicum*	*Hybrid Pine + Jesuita grass*[3]	*Hybrid Pine + Jesuita grass*

Methods and metrics

For each of the case studies, as the first step, the reference situation (baseline, 'year 0'), representing the status of the farm before the intervention was assessed. Historical data from farm records were used to define the baseline scenario. Then, assisted by advisors, farmers and researchers, information about the area converted per year and the implications on forage production, animal yields and farm economics was collected, discussed and recorded.

For each farm, two scenarios were defined: conventional grazing (before the adoption of SPS, i.e. baseline) and the SPS scenario. For modelling the adoption of SPS, farm records, as well as applied research findings, were used. Additionally, a panel formed by local and regional experts from different disciplines contributed to the analysis and discussion. *Agri benchmark* models and comparable methodologies were used for modelling the scenarios (see Annex 1). A set of variables was selected to assess different aspects of sustainability and modelled over a ten-year period. Table 2 presents the key variables used to evaluate selected aspects of sustainability.

Table 2 Key variables used to assess selected aspects of sustainability.

Area	Variable / Criteria	Unit of measurement
Productivity	Forage productivity	Tonnes of dry matter per ha
	'Land' productivity	Kg of meat or milk per ha
Economy	Whole farm costs	'000 USD
	Whole farm returns	'000 USD
Environment	CO_2 emissions	Kg/100 Kg LW* (or ECM**) added
	CH_4, N_2O emissions	Kg/100 Kg LW (or ECM) added
Animal welfare	Feeding	Water and feed availability
	Health	Absence of injuries, disease, and pain
	Housing	Thermal comfort, access to pasture and resting
	Behaviour	Absence of fear and aggression

* LW = Live Weight, ** ECM = Energy Corrected Milk

For each case study farm, data on the selected variables was collected over a period of at least ten years. The data was crosschecked with national and regional research institutions and an external quality protocol was applied. Interim and final results were validated by advisors, researchers, and farmers.

In order to standardize the economic analysis of SPS, the establishment costs across farms were assumed to have been financed through commercial credit with all services (fencing, planting, weed control, fertilizers, water pumping, pipelines, advice, etc.) being outsourced. To isolate the effects of the introduction of SPS on farm revenues from those due to economic fluctuations, prices of inputs and products (milk, beef and various classes of live animals) were kept constant over the period of analysis.

Results

Land area converted to SPS and forage production: At the end of year 9, four farms had converted all their land to SPS while the remaining six farms had converted between 40% (farm 10) and 70% (farm 3) of their land to SPS (Table 3). In year 9, farms that dedicated all their land to SPS, produced between 22 and 28 Mg DM ha^{-1}. In three cases, farms 1, 7 and 8, this represented an increase in forage production per hectare in the range of 175 to 733%. In the case of farm 4, production of forage declined by 29% after introducing SPS because the very high baseline production (40 Mg ha^{-1}) had been due to intensive use of chemical fertilizers (>600 kg ha^{-1} year^{-1}), which was totally discontinued after the introduction of SPS.

Table 3 Land area converted to SPS and change in forage production

	Productive land area (ha)		Forage production (Mg DM/ha)		
Case	**Total**	**SPS Y9 (%)**	**Baseline**	**Year 9**	**% diff.**
1	140	140 (100)	3	25	733
2	30	14 (47)	14	16	12
3	135	94 (69)	24	28	18
4	50	50 (100)	40	28	-29
5	37	25 (68)	2	11	450
6	170	100 (59)	5	25	400
7	50	50 (100)	10	28	180
8	60	60 (100)	8	22	175
9	240	195 (81)	3[1]	7	133
10	950	378 (40)	3	4	33

[1] at year of introduction of cattle, i.e. year 4 after start of conversion to SPS

SPS with forestry arrangements (cases 9 and 10) produced much lower amounts of forage DM per hectare, as forestry occupied most of the intervention area, but increases were nevertheless notable (33% and 133%). For more details see Annex 2.

Meat and milk production: On farms 4 and 7, which produced milk and converted their entire area to ISPS, milk production per hectare increased by 74% and 314% respectively (Table 4). Taking into account the smaller proportion of area converted to ISPS (46% and 69%), increases of a similar order of magnitude were seen on farms 2 and 3. Farm 6 had the highest increment in milk production per hectare, however from an exceptionally low baseline.

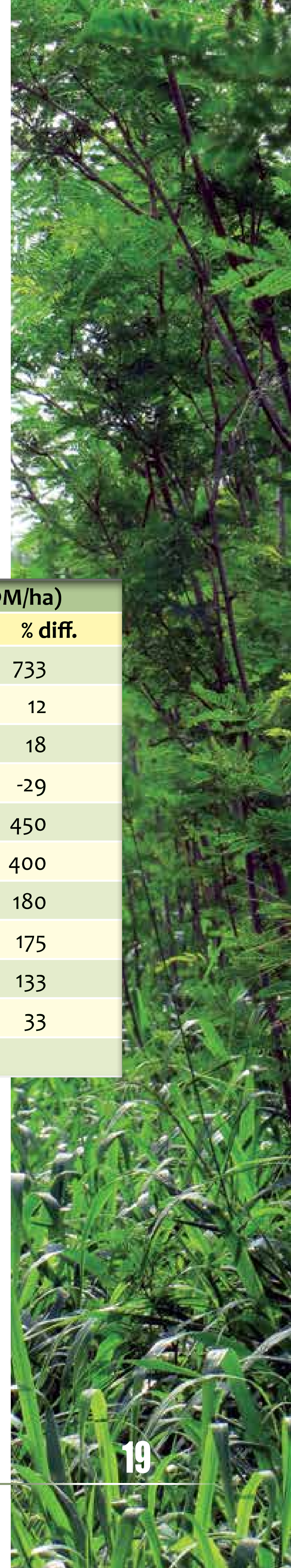


Table 4 Meat and milk production per hectare in years 0 and 9

	Milk (Mg ECM/ha)			Meat (Kg LW/ha)		
Case	Baseline	Year 9	% diff.	Baseline	Year 9	% diff.
1				126	1 187	842
2	7.2	11.5	60			
3	11.3	13.4	19			
4	14.0	24.4	74			
5				85	1 034	1 116
6	0.4	9.2	2 200			
7	2.9	12.0	314			
8				341	2 670	683
9				48[1]	274	471
10				86	150	74

[1] in year cattle were first introduced

Meat production per year, measured as total live weight gain, increased by 683, 842, and 1 116% on the three beef ranches (farms 1, 5, and 8) that did not have a forestry component, reaching 2 670 kg ha^{-1} on farm 8 (Table 4). On the two farms, which introduced beef as a complement to forestry (farms 9 and 10), meat production per hectare was much lower but also substantially increased over time.

The increases in milk and meat production per area resulted from the combined effects of higher stocking densities and improved individual production.

GHG emissions: GHG emissions per 100 kg of milk or live weight added were highly correlated with milk or meat production per hectare (r=-0.84 and -0.66 for milk and meat respectively) and thus declined on all farms following the production increase after SPS were introduced (Table 5).

Table 5 GHG emissions per 100kg milk/meat in years 0 and 9

	Kg CO_2eq/100kg ECM			Kg CO_2eq/100kg LW added		
Case	Baseline	Year 9	% diff	Baseline	Year 9	% diff
1				947	859	-9
2	181	179	-1			
3	192	179	-7			
4	178	92	-48			
5				1 029	977	-5
6	1 208	253	-79			
7	287	180	-37			
8				1 241	401	-68
9				–[1]	927	
10				1 264	945	-25

[1] no baseline emissions as initially no cattle were kept on the farm

The farms with highest increases in milk production per hectare relative to the baseline also achieved the greatest reductions in GHG emissions per unit of milk produced. However, this relationship was not as clear for beef production, where in some farms large gains in animal productivity (per hectare) did not result in major reductions in GHG emissions per kg of beef. For instance, farms 1 and 5 made large gains in live weight production per hectare (>800%), while emission reductions in CO_2-eq per 100 kg LW gain were below 10%. This was caused by the fact that in both farms the increase in live weight gain per hectare was mainly the result of a major increase in stocking rate rather than an increase in individual animal performance.

Additionally, specific studies on GHG emissions carried out on farm 3 showed that: i) ISPS areas with Leucaena generated 30% less CO_2, 98% less CH_4, and 89% less N_2O soil emissions per ha and month when compared with an adjacent farm with irrigation and high fertilizer input (Rivera *et al.* 2018); ii) heifers fed a silvopastoral diet (26% Leucaena and 74% Star grass on DM basis) produced 33% less CH_4 per kg of weight gain than heifers fed grass only (Molina *et al.* 2016); and iii) the emission of CO_2eq. per kg of fat and protein corrected milk (FPCM) and per kg of energy corrected milk (ECM) was 13.4% and 12.5% lower than in a conventional high-input system similar to that of the farm baseline (Rivera *et al.* 2016). Since in ISPS chemical fertilizers are not applied and concentrate feed requirements are greatly reduced, ISPS use 55% to 62% less non-renewable energy to produce a kg of ECM and FPCM than a conventional system. In addition to these reductions in GHG emissions, the carbon stock on the farm was estimated to be 45.3 Mg ha^{-1} aboveground in the ISPS areas vs. 11.7 Mg ha-1 in the areas with pasture monoculture (Arias *et al.* 2009).

Biodiversity: On farm 5, additional research carried out by CIPAV showed a three-fold increase in birds, a 60% higher ant count and a doubling of the number of dung beetles compared to baseline values.

Animal welfare: SPS offer optimal conditions for ensuring animal welfare. They provide a large amount of green fodder that meets nutritional needs while trees and shrubs provide shade during the day. Poor body condition and heat stress, seen on comparison farms practicing extensive cattle ranching, were not observed on the case study farms. The animals had the freedom to move and a diverse environment to express a wide range of natural behaviours. In comparison with neighboring non-SPS farms, very short flight distances and calm reactions, e.g. during movement between paddocks, indicated cattle had no fear of humans.

Farm economics: The period selected for the analysis of the farm economics of SPS introduction comprised the following stages: (i) initial interventions (1-2 years for selection and establishment – SPS areas start to produce at 6-8 months after establishment), (ii) scaling up of interventions (3-5 years for increasing SPS areas and consolidating farm management – some areas in full production, others partially established) and (iii) full implementation (4-6 years – all SPS areas in full production). In the two cases where SPS were implemented in conjunction with forestry, the period of economic analysis was longer (up to 27 years) so as to include timber sales.

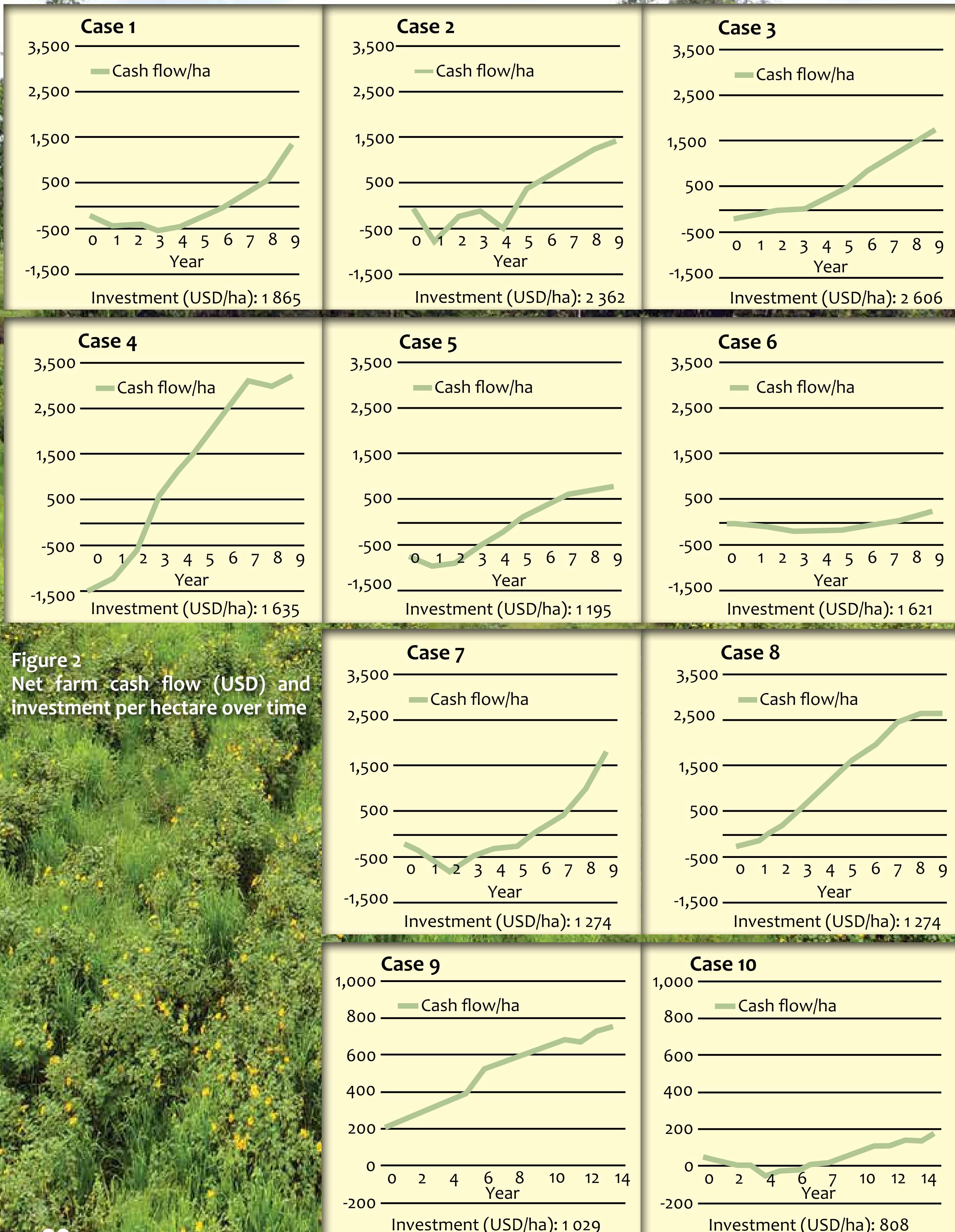


Figure 2
Net farm cash flow (USD) and investment per hectare over time

Investments per hectare converted to SPS ranged from USD808 (farm 10) to USD2 606 (farm 3) with an average of USD1 543. (As the exchange rate at the year of SPS introduction was used over the time frame of each case study, comparisons between farms in USD are affected by differences in exchange rate between years.) SPS strategies using scattered trees and/or live fences rather than high densities of shrubs and trees incurred lower investment costs (e.g. farm 5 with USD1 195/ha). Lower costs were also incurred in the forestry-beef combination (farms 9 and 10), in which some of the required SPS investments had already been assumed by the forestry operation (e.g. fencing).

In a number of cases, three periods of cash flow can be identified (Fig. 2). An initial period of negative cash flow due to a negative baseline situation and/or to a period of initial investments, in which animal production was not yet benefiting from increments in land productivity. A period of cash flow stabilization characterized by a gradual increase in farm returns due to increments in land and cattle productivity. And finally, a highly positive cash flow compared to the baseline.

In all cases, at the end of the analysis period, farm returns were higher than costs, and six of the eight farms, in which cattle were not a complement to forestry, made a profit per hectare of USD1 500 or more (Fig. 2). The positive development of farm profits over time, in many cases from a negative baseline, clearly demonstrates that investments in SPS are not only environmentally beneficial but also economically sound. From the cash flow point of view, the first period of investment can, however, result in a negative cash flow, which requires consideration with regards to the financing of the SPS investment.

ISPS with Eucalyptus, Leucaena and Megathyrsus. La Luisa farm. Cesar, Colombia. Photo J. Chará.

La Luisa Farm. Cesar , Colombia. Photo C. García.

Conclusions and Recommendations

The case studies provide evidence for the ability of SPS to generate a 'triple-win' by combining gains in productivity and profitability with environmental improvements and animal welfare benefits. However, the type of SPS selected, the amount of land converted, the financial requirements as well as the impacts of adopting SPS varied across farms. Thus, to be successful, efforts of expanding SPS require a sound understanding of the biological, economic and political factors determining its adoption.

Factors affecting the impact and adoption of SPS

The baseline conditions of the case study farms determined the objective of the adoption of SPS, the SPS model selected, its 'biological' impact, and the financial outcome.

For instance, in farms 1, 5, 6 and 8, the productive and economic baseline situation was very poor. These farms practiced extensive cattle raising on degraded land resulting in very low productivity. To introduce SPS, farm 1 (beef finishing), for example, had to make major changes in all domains of farm management (e.g. management of land and water, animal genetics and health, etc.). In such cases, the initial investments are high due to the complete change required when adopting SPS, leading to negative cash flows. In addition, farm 1 had to purchase animals every year to take advantage of the increased feed production, requiring yet more capital over a prolonged period.

A different situation presented itself in farms 2, 3, 4 and 7, where the baseline situation was characterised by a high dependence on external inputs such as fertilizers and concentrates. In these farms, the cash flow declined for about 2-3 years as the newly planted areas had to be taken out of production during preparation and establishment of SPS and only reached full production one year later. During that period, and depending on the area of intervention, total forage production (conventional pasture plus new SPS areas) may have decreased, which could have resulted in negative cash flows in the initial period.

The level of farm management prior to the adoption of SPS played an important role in the economic performance of the farm. Farms, which had a relatively high management level (in terms of record keeping, accounting, planning, and resource management,) before the introduction of SPS, quickly reached a positive cash flow situation during the period of adoption. Farms with lower management levels had to implement major changes, leading to more dramatic financial consequences during the period of adoption (longer negative cash flow periods and therefore higher credit requirements).

In the case of forestry production complemented by beef finishing (farms 9 and 10), the initial SPS costs were lower than in other cases, mainly due to the fact that major investments had been assumed by the forestry component (fencing, irrigation, planting). Economies of scale (mainly in relation to labour) also played an important role in reducing the cost of SPS adoption. In these two cases, the major income was derived from timber sales and the beef finishing enterprise provided additional short and midterm cash flows.

Although in the long term the economic benefits of investing in the establishment of SPS outweighs its costs, the overall uptake may be constrained by the required level of investment and associated risk, limitations in access to capital and deficits in farm management capacity.

SPS with Inga trees and stargrass. Pinzacua farm. Valle del Cauca, Colombia. Photo J. Chará.

ISPS with Leucaena and star grass. Asturias Farm. Quindío, Colombia. Photo J. Chará.

Scope of SPS adoption in Latin America

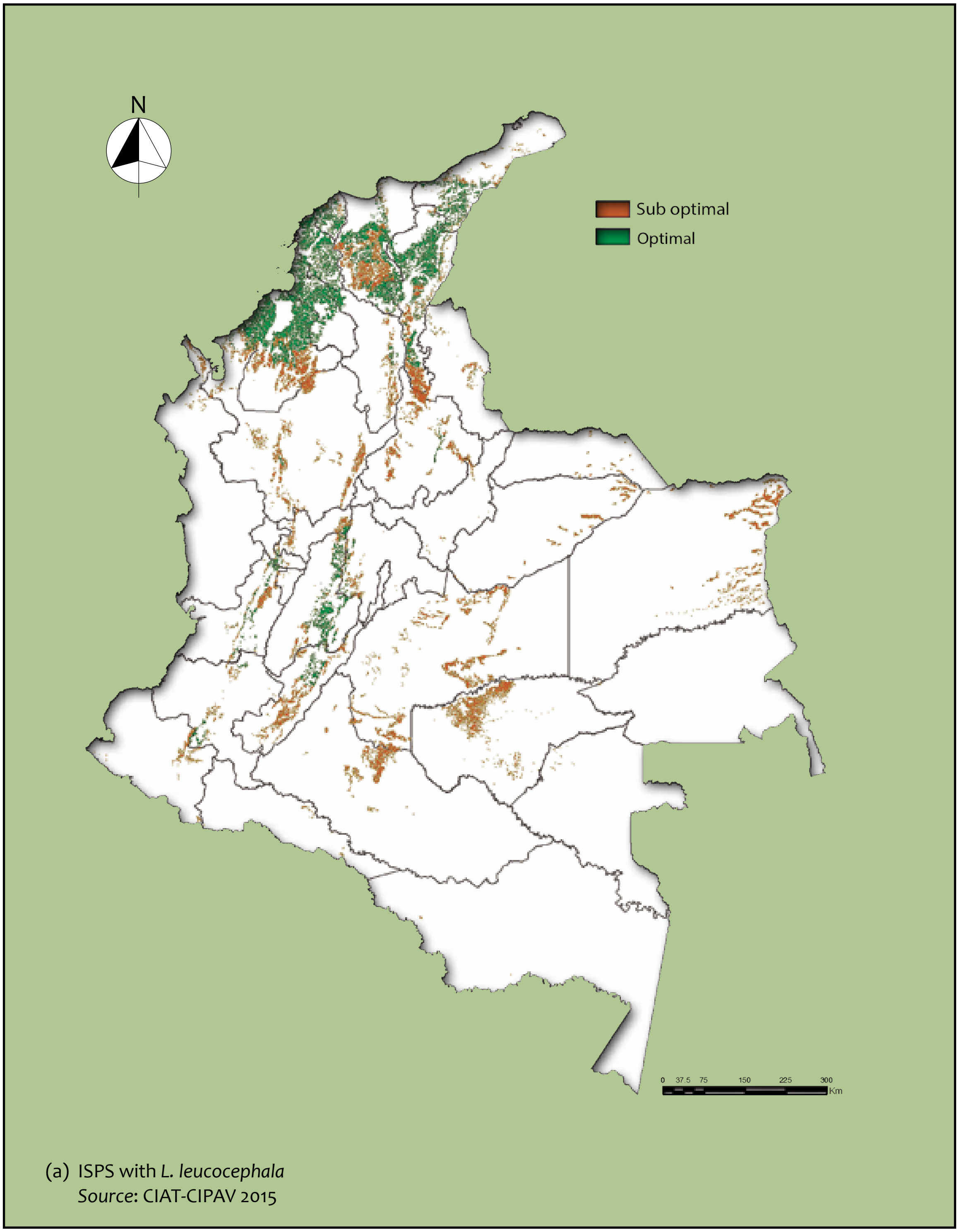
In Latin America, silvopastoral arrangements have the potential to be established in most of the locations where cattle ranching is practiced. Apart from the arrangements analyzed in the study cases, there are many others that have been developed and adapted to specific environmental conditions using native tree species and grasses or adopting new ones suitable for each condition. For each situation or type of arrangement, there are species of grasses, shrubs or trees that can be selected according to the soil type, altitude, temperature, precipitation, etc. The following table shows the range of conditions suited for the establishment of intensive SPS with *Leucaena leucocephala* or *Tithonia diversifolia* in the tropics.

Table 6 Optimal conditions for the establishment of three ISPS arrangements in Colombia

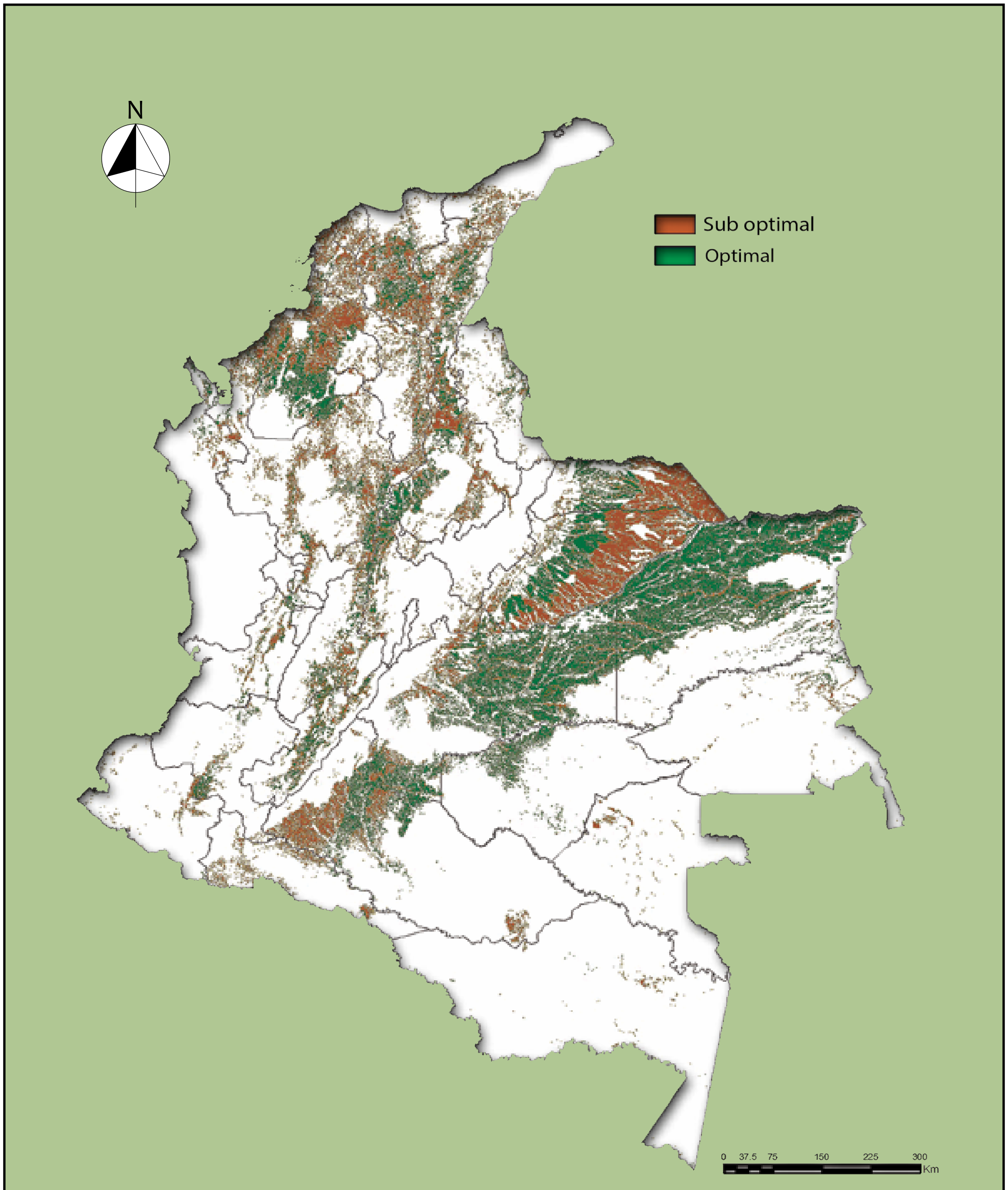
Soil and environment	***L. Leucaena*** – Stargrass/Megathyrsus	***Tithonia*** – ***Urochloa***/***Brachiaria*** grass	***Tithonia*** – Kikuyu grass
Soil characteristics			
pH	6.0 – 8.0 Without Aluminium toxicity	4.5 – 7.0	5.5 – 7.0
Texture	Sandy loam – clay loam Silty soils	Sandy loam – clay loam	Sandy loam – clay loam
Fertility	High to medium	High to medium	High
Drainage	Well-drained soils	Well-drained soils	Tolerates short flooding
Environmental conditions			
Rainfall (mm/year)	1 000 – 1 700	1 200 – 3 000	1 000 – 2 500
Temperature (°C)	24 – 30	22 – 28	14 – 18
Altitude (masl)	0 – 1 300	0 – 1 600	1 800 – 2 400
Luminosity (hours/yr)	1 000 – 1 500	1 000 – 1 500	900 – 1 200

According to a study carried out by CIPAV and CIAT in Colombia, taking into account the characteristics presented in Table 6, there is a potential to establish approximately 2.5 million ha of ISPS with *L. leucocephala*, 7.7 million ha of ISPS with *Tithonia* and *Urochloa/Brachiaria* grass (Figs. 3a & b), and 0.2 million ha of the SPS with *Tithonia* and Kikuyu grass (*Cenchrus clandestinus*). These 10.4 million hectares only consider optimal conditions for each the systems based on pasture areas already used for livestock rearing (ECDBC 2015).

Figure 3 Areas in Colombia suitable for the establishment of ISPS with (a) *L. leucocephala* and (b) *Tithonia* and *Urochloa/Brachiaria* grass



(a) ISPS with *L. leucocephala*
Source: CIAT-CIPAV 2015



(b) ISPS with *Tithonia* and *Urochloa/Brachiaria* grass
Source: CIAT-CIPAV 2015

Recommendations to support SPS adoption

The case studies provide sound evidence that SPS simultaneously deliver gains in productivity and profitability, environmental improvements, and animal welfare benefits and thereby support a number of SDGs. Despite these benefits, SPS have not been widely implemented due to a variety of technical, financial and cultural barriers. These include the lack of technical assistance to farmers to adapt the system to specific local conditions, the technical complexity of SPS management and the high initial investment requirements (Chará *et al.* 2017). Many farmers are not keen to implement the necessary changes since they view cattle ranching as a low-investment and low-management activity. Additionally, for ISPS, the technical complexity demands specialized knowledge that is not always available among farmers, professionals, academia, or commercial rural extension service providers (Calle *et al.* 2012).

At farm level, financial considerations are among the main drivers for adopting SPS. Any programme to introduce SPS must be underpinned by a detailed financing plan, which matches anticipated cash flows with the farmer's cash conditions over the adoption process. It is important to foresee critical periods in cash flow and define strategies to fill the financial gaps during the implementation process. This could be done by adapting the rhythm of SPS establishment to cash flows or by obtaining strategic loans that could be repaid once the negative cash flow period is overcome. A thorough financial risk assessment is required in this planning phase. National policies should support SPS adoption by the provision of dedicated credit lines and incentives such as payment for environmental services.

As SPS are more complex to manage than pasture monocultures, encouraging adoption of SPS also requires improving farmers' access to technical support. Livestock service providers play an important role in assisting farmers in the implementation of silvopastoral arrangements adapted to their needs. Technical assistance programmes require special attention during the first periods of adoption when the risk of failure is highest and cash flow may be negative. Also, in order to take full advantage of the benefits of SPS adoption, other key aspects of production such as herd management, strategic supplementation and genetics must also be improved. Thus, policies that promote specialized training for extension workers and technicians on all aspects of SPS adoption play an important role in increasing its uptake (Chará *et al.* 2017).

Another aspect related to services includes the adequate provision of inputs and supplies (for planting and seeding) and the availability of machinery contracting services. An adequate regional scale of implementation is crucial in facilitating the access to advisory services, supplies, and markets.

The results of the case studies highlight the large potential of information exchange between farmers and countries. At local level, information exchange and cross-learning between farmers have been among the most important elements for scaling-up of SPS programmes. Public-private alliances, driven by strong farmer's organizations, have been crucial in overcoming technical complexities allowing a substantial number of farmers to successfully adopt SPS. This was observed in Mexico with 'Fundación Produce' and in Argentina with the CREA (Regional Consortium of Agricultural Experimentation). These programmes spent considerable resources on capacity building schemes under the leadership of strong farmers' organizations with the support of regional/national governmental entities (producers as leaders and agents of change forming private-public alliances).

Information exchange across countries can accelerate SPS adoption as issues that are considered barriers in one country may have already been solved in another, as it is the case of timber production in SPS, which is well developed in Argentina but still incipient in Colombia and Mexico.

Research needs

In order to develop tailored strategies that can be used to promote SPS at (sub-)regional and local level, it is essential to assess the economic, environmental, and animal welfare implications of SPS adoption for more arrangements, scales, and agro-ecological conditions.

In regions, in which SPS have been shown to be viable options for sustainable cattle ranching, it is important to quantify their capacity to decrease deforestation, their reduction of the carbon footprint of cattle farming, and their potential to contribute to the SDGs related to climate change.

More knowledge of native trees, pastures, and their interactions needs to be generated. With respect to the tree component of SPS, technology for the introduction of forest species in rangelands is scarce, especially in tropical countries with relatively little experience in forestry. In these countries, the development of silvicultural practices, markets, and wood-processing techniques for timber from silvopastoral systems is in its infancy (Calle et al. 2012). Progress in current practices is required to improve the profitability of the system and to persuade farmers to introduce trees for timber into regions where the market for forestry products is not yet developed.

Finally, it is important to develop insurance schemes for the critical implementation periods of SPS so as to reduce the financial risks of SPS programmes.

SPS with Araucaria and Jesuita grass. El Molino farm. Misiones, Argentina. Photo J. Chará.

ISPS. La Luisa farm. Codazzi, Colombia. Photo J. Chará.

References

Arias LM, Camargo JC, Dossman MA, Echeverry MA, Rodríguez JA, Molina CH, Molina EJ, Melo ID (2009) Estimación de biomasa aérea y desarrollo de modelos alométricos para *Leucaena leucocephala* en sistemas silvopastoriles de alta densidad en el Valle del Cauca, Colombia. Recursos Naturales y Ambiente 58: 32-39.

Assurewel Project (2017) Advancing Animal Welfare Assurance. www.assurewel.org.

Barahona R, Sánchez MS, Murgueitio E, Chará J (2014) Contribución de la *Leucaena leucocephala* Lam (de Wit) a la oferta y digestibilidad de nutrientes y las emisiones de metano entérico en bovinos pastoreando en sistemas silvopastoriles intensivos. En: Premio Nacional de Ganadería José Raimundo Sojo Zambrano, modalidad Investigación Científica. Bogotá, Colombia. Revista Carta Fedegán 140:66-69.

Botreau R, Veissier I, Perny P (2009) Overall assessment of animal welfare: Strategy adopted in Welfare Quality. Animal Welfare 18:363–370.

Broom DM, FM Galindo, Murgueitio E (2013) Sustainable, efficient livestock production with high biodiversity and good welfare for animals. Proceedings of the Royal Society Biological Sciences 280:2013–2025.

Cajas-Girón YS, Cuesta PA, Arreaza-Tavera LC, Barahona-Rosales R (2011) Implementación de estrategias tecnológicas para mejorar la productividad y sostenibilidad de sistemas de doble propósito en las sabanas de la región Caribe colombiana. Revista Colombiana de Ciencias Pecuarias 24:495–201.

Calle Z, Murgueitio E, Chará J (2012) Integrating forestry, sustainable cattle-ranching and landscape restoration. Unasylva 63:31–40.

Campagnani M, Campos W, Amorim S, Rosa LH, Auad A, Cangussú M, Mauricio R (2017) Prospection and Fungal Virulence Associated with *Mahanarva spectabilis* (Hemiptera: Cercopidae) in an Amazon Silvopastoral System. Florida Entomologist 100: 426-432.

Chará J, Camargo JC, Calle Z, Bueno L, Murgueitio E, Arias L, Dossman M, Molina E (2015) Servicios ambientales de Sistemas Silvopastoriles Intensivos: mejoramiento del suelo y restauración ecológica. *In:* Montagnini F, Somarriba E, Murgueitio E, Fassola H, Eibl B (Eds) Sistemas Agroforestales. Funciones productivas, socioeconómicas y ambientales. Serie Técnica Informe Técnico 402, CATIE, Turrialba, Fundación CIPAV, Cali, pp 331–347.

Chará J, Rivera JE, Barahona R, Murgueitio E, Deblitz C, Reyes E, Mauricio R, Molina J, Flores M, Zuluaga A (2017) Intensive silvopastoral systems: economics and contribution to climate change mitigation and public policies. *In:* Montagnini F (Ed) Integrating Landscapes: Agroforestry for Biodiversity Conservation and Food Sovereignty. Advances in Agroforestry 12. Springer, Dordrecht.

CIAT-CIPAV 2015. Determinación del potencial de reducciones de gases de efecto invernadero en sistemas silvopastoriles en el proyecto "análisis de sistemas productivos en colombia para la adaptación al cambio climático". Final Report. Cali.

Colcombet L, Esquivel J, Fassola H, Goldfarb MC, Lacorte S, Pachas N, Rossner B, Winck R (2015) Los sistemas silvopastoriles en las provincias de Misiones y Corrientes, Argentina. *In:* Montagnini F, Somarriba E, Murgueitio E, Fassola H, Eibl B (Eds) Sistemas Agroforestales. Funciones productivas, socioeconómicas y ambientales. Serie Técnica Informe Técnico 402, CATIE, Turrialba, Fundación CIPAV, Cali, pp 105–129.

Cubillos AM, Vallejo V, Arbeli Z, Teran W, Dick R, Molina CH, Molina E, Roldan F (2016) Effect of the conversion of conventional pasture to intensive silvopastoral systems on edaphic bacterial and ammonia oxidizer communities in Colombia. European Journal of Soil Biology 72:42–50.

ECDBC (2015) Nota de información de la NAMA Ganadería Bovina Sostenible. Estrategia Colombiana de Desarrollo Bajo en Carbono, ECDBC. Bogotá.

Fajardo D, Johnston R, Neira L, Chará J, Murgueitio E (2010) Influencia de los sistemas silvopastoriles en la diversidad de aves en la cuenca del río La Vieja, Colombia. Recursos Naturales y Ambiente 58:9–16.

Ferraz-de-Oliveira MI, Azeda C, Pinto-Correia T (2016) Management of Montados and Dehesas for high nature value: an interdisciplinary pathway. Agrofor Syst 90:1–6.

Giraldo C, Escobar F, Chará J, Calle Z (2011) The adoption of silvopastoral systems promotes recovery of ecological processes regulated by dung beetles in the Colombian Andes. Insect Conservation and Diversity 4:115–122.

González R, Sánchez MS, Chirinda N, Arango J, Bolívar DM, Escobar D, Tapasco J, Barahona R (2015) Limitaciones para la implementación de acciones de mitigación de emisiones de gases de efecto de invernadero (GEI) en sistemas ganaderos en Latinoamérica. Livestock Research for Rural Development Volume 27, Article #249. http://www.lrrd.org/lrrd27/12/gonz27249.html. Accessed 21 Jan 2018.

Harvey C, Medina A, Sánchez D, Vílchez S, Hernández B, Saenz J, Maes JM, Casanoves F, Ssinclair F (2006) Patterns of animal diversity in different forms of tree cover in agricultural landscapes. Ecological Applications 16:1986–1999.

Harvey C, Chacón M, Donatti C, Garen E, Hannah L, Andrade LA, Bede L, Brown D, Calle A, Chará JD, Clement C, Gray E, Hoang M, Minang P, Rodríguez A, Seeberg-Elverfeldt C, Semroc B, Shames S, Smukler S, Somarriba E, Torquebiau E, van Etten J, Wollenberg E (2013) Climate-smart Landscapes: Opportunities and Challenges for Integrating Adaptation and Mitigation in Tropical Agriculture. Conservation Letters 7:77–90.

Ibrahim M, Guerra L, Casasola F, Neely N (2010) Importance of silvopastoral systems for mitigation of climate change and harnessing of environmental benefits. *In:* Abberton M, Conant R, Batello C (Eds) Grassland carbon sequestration: management, policy and economics. Proceedings of the workshop on the role of grassland carbon sequestration in the mitigation of climate change. Integrated Crop Management, Vol. 11. FAO, Rome, Italy. http://www.fao.org/docrep/013/i1880e/i1880e09.pdf .

Jose S (2009) Agroforestry for ecosystem services and environmental benefits: an overview. Agroforest Syst 76 (1):1–10.

Kumar BM, George SJ, Jamaludheen V, Suresh TK (1998) Comparison of biomass production, tree allometry and nutrient use efficiency of multipurpose trees grown in woodlot and silvopastoral experiments in Kerala, India. For. Ecol. Manage. 112:145–163.

Kunst C, Navall M, Ledesma R, Silberman J, Anríquez A, Coria D, Bravo S, Gómez A, Albanesi A, Grasso D, Dominguez Nuñez J, González A, Tomsic P, Godoy J (2016) Silvopastoral Systems in the Western Chaco Region, Argentina. *In:* Peri PL, Dube F, Varella A (Eds) Advances in Agroforestry Chapter 1, pp. 1–8, Springer International Publishing, Switzerland.

Lacorte S, Esquivel J (2009) Sistemas silvopastoriles en la Mesopotamia Argentina. Reseña del conocimiento, desarrollo y grado de adopción. 1° Congreso nacional de sistemas silvopastoriles. Posadas, Misiones, Argentina, 14–16/Mayo/2009, pp 70–82.

Le Heoureu H (1987) Indigenous shrubs and trees in the silvopastoral systems of Africa. *In:* Stepler H., Nair R. (Eds) Agroforestry: A decade of development. ICRAF, 1987.

Mahecha L, Murgueitio M, Angulo J, Olivera M, Zapata A, Cuartas CA, Naranjo JF, Murgueitio E (2011) Desempeño animal y características de la canal de dos grupos raciales de bovinos doble propósito pastoreando en sistemas silvopastoriles intensivos. Revista Colombiana de Ciencias Pecuarias 24:470.

Mc Adam J (2005) Silvopastoral systems in North-West Europe. *In:* Mosquera-Losada M, McAdam J, Rigueiro-Rodriguez A (Eds) Silvopastoralism and sustainable management. Proceedings of the international congress on silvoapastoralism and sustainable land management. Lugo, Spain, 2005.

Mojardino M, Revell D, Pannell DJ (2010) The potential contribution of forage shrubs to economic returns and environmental management in Australian dryland agricultural systems. Agricultural Systems 103:187–197.

Molina IC, Angarita E, Mayorga OL, Chará J, Barahona R (2016) Effect of *Leucaena leucoceophala* on methane production of Lucerna heifers fed a diet based on *Cynodon plectostachyus*. Livestock Science 185: 24-29.

Montagnini F, Nair PKR (2004) Carbon sequestration: An under-exploited environmental benefit of agroforestry systems. Agroforestry Systems 61 & 62:281–298.

Montagnini F, Ibrahim M, Murgueitio E (2013) Silvopastoral systems and climate change mitigation in Latin America. Bois et Forêts des Tropiques 316(2):3–16.

Montoya-Molina S, Giraldo-Echeverri C, Montoya-Lerma J, Chará J, Escobar F, Calle Z (2016) Land sharing vs. land sparing in the dry Caribbean lowlands: A dung beetles' perspective. Applied Soil Ecology 98:204–212.

Moreno G, Pulido F (2009) The functioning, management and persistence of the Dehesas. *In:* Rigueiro-Rodríguez A *et al.* (Eds) Agroforestry in Europe: 127 Current Status and Future Prospects. Springer Science & Business Media B.V: p127–160.

Murgueitio E, Calle Z, Uribe F, Calle A, Solorio B (2011) Native trees and shrubs for the productive rehabilitation of tropical cattle ranching lands. Forest Ecology and Management 261:1654–1663

Murgueitio E, Chará J, Solarte A, Uribe F, Zapata C, Rivera JE (2013) Agroforestería Pecuaria y Sistemas Silvopastoriles Intensivos (SSPi) para la adaptación ganadera al cambio climático con sostenibilidad. Revista Colombiana de Ciencias Pecuarias 26:313–316.

Murgueitio E, Flores M, Calle Z, Chará J, Barahona R, Molina CH, Uribe F (2015) Productividad en sistemas silvopastoriles intensivos en América Latina. *In:* Montagnini F, Somarriba E, Murgueitio E, Fassola H, Eibl B (Eds) Sistemas Agroforestales. Funciones productivas, socioeconómicas y ambientales. Serie Técnica Informe Técnico 402, CATIE, Turrialba, Fundación CIPAV, Cali, pp 59–101.

Murgueitio E, Uribe F, Molina C, Molina E, Galindo W, Chará J, Flores M, Giraldo C, Cuartas C, Naranjo J, Solarte L, González J (2016) Establecimiento y manejo de sistemas silvopastoriles intensivos con leucaena. *In:* Murgueitio E, Galindo W, Chará J, Uribe F (Eds) Editorial CIPAV. Cali, Colombia. 220pp.

Nair PKR (2011) Agroforestry systems and environmental quality: Introduction. Journal of Environmental Quality 40:784–790.

Nair PKR, Kumar BM, Nair VD (2009) Agroforestry as a strategy for carbon sequestration. Journal of Plant Nutrition and Soil Science 172:10–23.

Nair PKR, Nair VD, Kumar BM, Showalter J (2010) Carbon sequestration in agroforestry systems. Adv. Agron. 108:237–307Nair PKR (2011) Agroforestry systems and environmental quality: Introduction. Journal of Environmental Quality 40:784-790.

Nair VD, Haile SG, Michel GA, Nair R (2007) Environmental quality improvement of agricultural lands through silvopasture in southeastern United States. Scientia Agricola 64:513–519.

Nunes J, Siva G, Cerri CE, Bernoux M, Feigl BJ, Wruck FJ, Cerri CC (2010) Impact of pasture, agriculture and crop-livestock systems on soil C stocks in Brazil. Soil and Tillage Research 110:175–186.

O'Mara FP (2011) The significance of livestock as a contributor to global greenhouse gas emissions today and in the near future. Animal Feed Science & Technology 166–167:7–15

Orefice J, Carroll J, Conroy D, Ketner L (2017) Silvopastoral practices and perspective in the Northeastern United States. Agroforestry Systems 91:149–160.

Pachas A (2010) *Axonopus catarinensis* y *Arachis pintoi*: alternativas forrajeras en sistemas silvopastoriles de la provincia de Misiones, Argentina. Tesis MS. Escuela para graduados Ingeniero Agrónomo Alberto Soriano, Facultad de Agronomía, Universidad de Buenos Aires, 99pp.

Papanastasis VP, Mantzanas K, Dini-Papanastasi O, Ispikoudis I (2009) Traditional agroforestry systems and their evolution in Greece. *In:* Rigueiro-Rodríguez A, McAdam J, Mosquera-Losada MR (Eds) Agroforestry in Europe: current status and future prospects, pp. 89–109. Springer: Dordrecht.

Peri PL, Sturzenbaum MV, Monelos L, Livraghi E, Christiansen R, Moretto A. Mayo JP (2005) Productividad de sistemas silvopastoriles en bosques nativos de ñire (*Nothofagus antarctica*) de Patagonia Austral. *In:* Proceedings III Congreso Forestal Argentino y Latinoamericano. Corrientes, Argentina, 10 pp.

Peri PL, Dube F, Varella A (2016) Silvopastoral systems in the subtropical and temperate zones of South America: An overview. *In:* Peri PL, Dube F, Varella A (Eds) Silvopastoral Systems in Southern South America, Chapter 1, pp 1–8 Advances in Agroforestry, Springer International Publishing, Switzerland.

Peri PL, Banegas N, Gasparri I, Carranza C, Rossner B, Martínez Pastur G, Cavallero L, López DR, Loto D, Fernández P, Powel P, Ledesma M, Pedraza R, Albanesi A, Bahamonde H, Eclesia RP, Piñeiro G (2017a) Carbon Sequestration in Temperate Silvopastoral Systems, Argentina. *In:* Montagnini F (Ed) Integrating Landscapes: Agroforestry for Biodiversity Conservation and Food Sovereignty, Chapter 19, pp 453–478. Advances in Agroforestry 12, Springer International Publishing.

Peri PL, Caballe G, Hansen NE, Bahamonde HA, Lencinas MV, von Müller AR, Ormaechea S, Gargaglione V, Soler R, Sarasola M, Rusch V, Borrelli L, Fernandez ME, Gyenge J, Tejera LE, Lloyd CE, Martínez Pastur G (2017b) Silvopastoral systems in Patagonia, Argentina. *In:* Gordon AM, Newman SM, Coleman BRW (Eds) Temperate Agroforestry Systems, Chapter 11, pp. 252–273. CAB International, Wallingford, UK.

Radrizzani A, Shelton HM, Dalzell SA, Kirchhof G (2011) Soil organic carbon and total nitrogen under *Leucaena leucocephala* pastures in Queensland. Crop and Pasture Science 62:337–345.

Ribeiro RS, Terry SA, Sacramento JP, Rocha e Silveira S, Bento CB, Silva EF, Montovani HC, Gama MAS, Pereira LG, Tomich TR, Mauricio RM, Chaves A (2016) *Tithonia diversifolia* as a supplementary feed for dairy cows. PLoS One 11: e0165751.

Rice RA, Greenberg R (2004) Silvopastoral systems: ecological and socioeconomic benefits and migratory bird conservation. *In:* Schroth G, Fonseca GAB, Harvey CA, Gascon C, Vasconcelos HL, Izac A-MN (Eds) Agroforestry and Biodiversity Conservation in Tropical Landscapes. Island Press, Washington, DC: 453–472.

Ríos N, Cárdenas A, Andrade H, Ibrahim M, Jiménez F, Sancho F, Ramírez E, Reyes B, Woo A (2007) Escorrentía superficial e infiltración en sistemas ganaderos convencionales y silvopastoriles en el trópico sub-húmedo de Nicaragua y Costa Rica. Agroforestería en las Américas 45:66–71.

Rivera J, Cuartas CA, Naranjo JF, Tafur O, Hurtado EA, Arenas FA, Chará J, Murgueitio E (2015) Efecto de la oferta y el consumo de *Tithonia diversifolia* en un sistema silvopastoril intensivo (SSPi), en la calidad y productividad de leche bovina en el piedemonte Amazónico colombiano. Livestock Research for Rural Development. Volume 27, Article #189. http://www.lrrd.org/lrrd27/10/rive27189.html. Accessed 21 Jan 2018.

Rivera J, Chará J, Barahona R (2016) Análisis de ciclo de vida para la producción de leche bovina en un sistema silvopastoril intensivo y un sistema convencional en Colombia. Tropical and Subtropical Agroecosystems 19:237–251.

Rivera J, Chará J, Barahona R (2018) CH4, CO2 and N2O emissions from grasslands and bovine excreta in two intensive tropical dairy production systems. Agroforestry Systems https://doi.org/10.1007/s10457-018-0187-9.

Rivera L, Armbrecht I, Calle Z (2013) Silvopastoral systems and ant diversity conservation in a cattle-dominated landscape of the Colombian Andes. Agriculture, Ecosystems and Environment 181:188–194.

Sáenz JC, Villatoro F, Ibrahim M, Fajardo D, Pérez M (2007) Relación entre las comunidades de aves y la vegetación en agropaisajes dominados por la ganadería en Costa Rica, Nicaragua y Colombia. Agroforestería en las Américas, 45:37–48.

Shelton M, Dalzell S (2007). Production, economic and environmental benefits of leucaena pasture. Tropical Grasslands 41:174–190.

Solorio-Sánchez FJ, Bacab-Pérez HM, Ramírez-Avilés L (2011) Sistemas Silvopastoriles Intensivos: Investigación en el Valle de Tepalcatepec, Michoacán. *In:* Xóchitl-Flores M, Solorio-Sánchez B (Eds) Establecimiento de Sistemas Silvopastoriles Intensivos para la producción de leche y carne en el trópico de México. Primera etapa del proyecto estratégico de prioridad nacional. SAGARPA, Fundación Produce Michoacán, COFUPRO, UADY, Morelia, México, 15 pp.

Solorio-Sánchez FJ, Solorio-Sánchez B, Casanova-Lugo F, Ramírez-Avilés L, Ayala-Burgos A, Ku-Vera J, Aguilar-Pérez C (2012) Situación actual global de la investigación y desarrollo tecnológico en el establecimiento, manejo y aprovechamiento de los sistemas silvopastoriles intensivos. *In:* IV Congreso Internacional sobre Sistemas Silvopastoriles Intensivos. Fundación Produce Michoacán, Universidad Autónoma de Yucatán, Morelia, México, 21 -23 mar, pp 33–57.

Somarriba E, Carreño-Rocabado G, Amores F, Caicedo W, Gillés S, Cerda R, Ordóñez J (2018) Trees of farms for livelihoods, conservation of biodiversity and carbón storage. Evidence from Nicaragua on this Invisible resource. *In:* Montagnini F (Ed) Integrating landscapes: Agroforestry for biodiversity conservation and food sovereignty. Advances in Agroforestry 12, Springer International Publishing, Switzerland.

Soni M, Subbulakshmi V, Yadava V,Tewari J, Dagar J (2016) Silvopastoral agroforestry systems: Lifeline for dry regions. *In:* Dagar J, Tewari J (Eds) Agroforestry research developments. Nova Science Publishers, New York.

Steinfeld H, Gerber P, Wassenaar T, Castel V, Rosales M, De Haan C (2006) Livestock's long shadow: environmental issues and options. FAO, Rome.

Thornton PK, Herrero M (2010) Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics. Proceedings of the National Academy of Science 107(47):19667–19672.

Vallejo VE, Roldán F, Dick RP (2010) Soil enzymatic activities and microbial biomass in an integrated agroforestry chronosequence compared to monoculture and a native forest of Colombia. Biology and Fertility of Soils 46(6):577–587.

Vandermeulen S, Ramírez-Restrepo C, Beckers I, Claessens H, Bindelle J (2018) Agroforestry for ruminants: a review of trees and shrubs as fodder in silvopastoral temperate and tropical production systems. Animal Production Science 58:767–777.

 La Pendiente Farm. Misiones, Argentina. Photo J. Chará.

Annexes

Annex 1: Methods and metrics

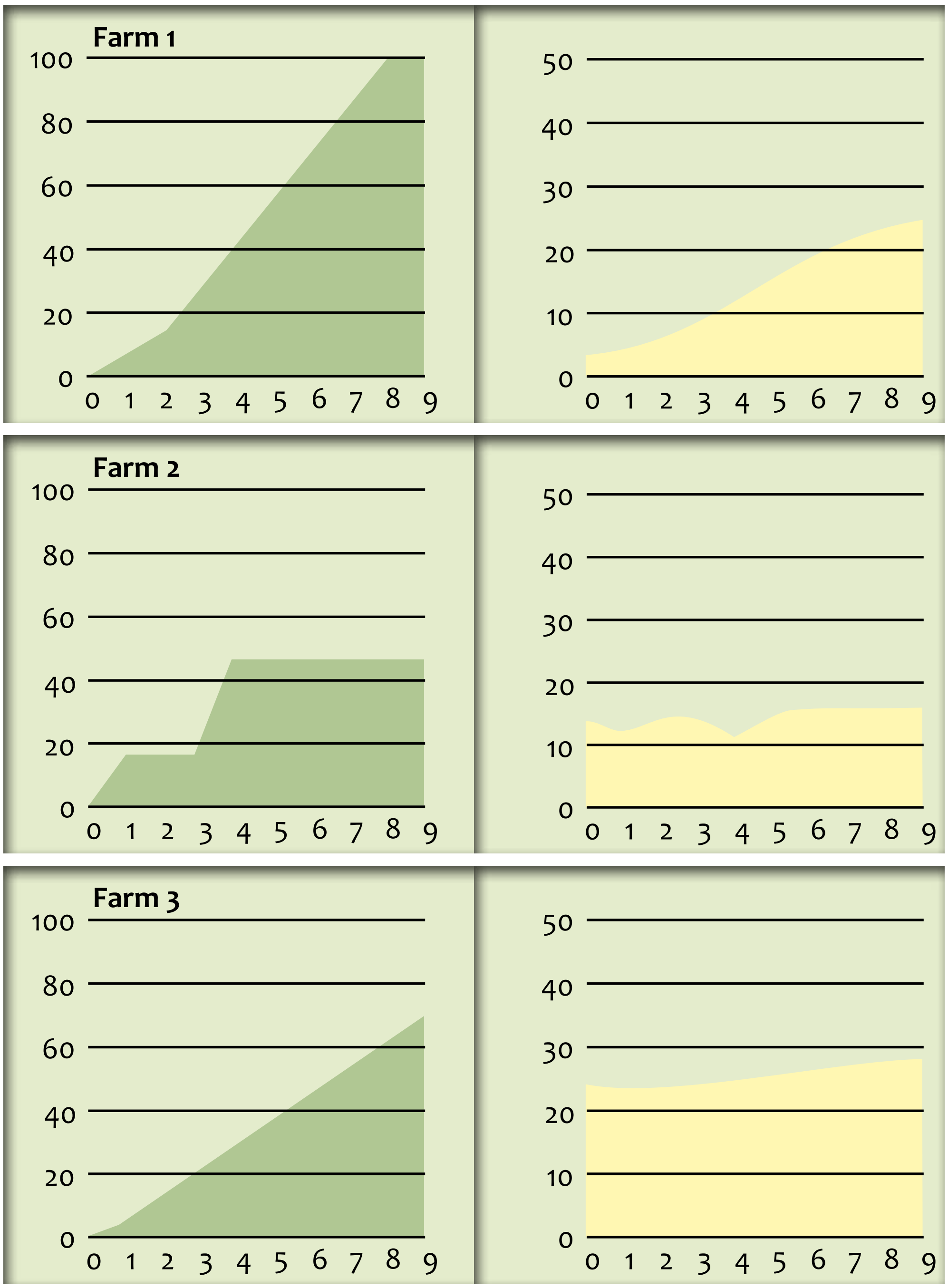
The TIPI-CAL model from the agri benchmark Network was used for the simulation of the 10-year periods of SPS introduction. TIPI-CAL is a production and accounting model and assessment tool. It has a 10-year dynamic-recursive structure and produces a profit and loss account, a balance sheet, a cash flow for the whole farm and all enterprises considered for each of the 10 years of simulation. It further provides very detailed information on activity levels, performance and productivity of the enterprises such as herd size, lactation yield, weight of animals, feed rations, mortality, weight gains etc.. For this project and in contrast with the standard operating procedure, actual case study farms instead of 'typical' farms were modelled to ensure accurate and consistent information as well as securing the link to the environmental and animal welfare related data. In some of the cases due to the requirements of the project the analysis periods were modified from 10 to 20 years.

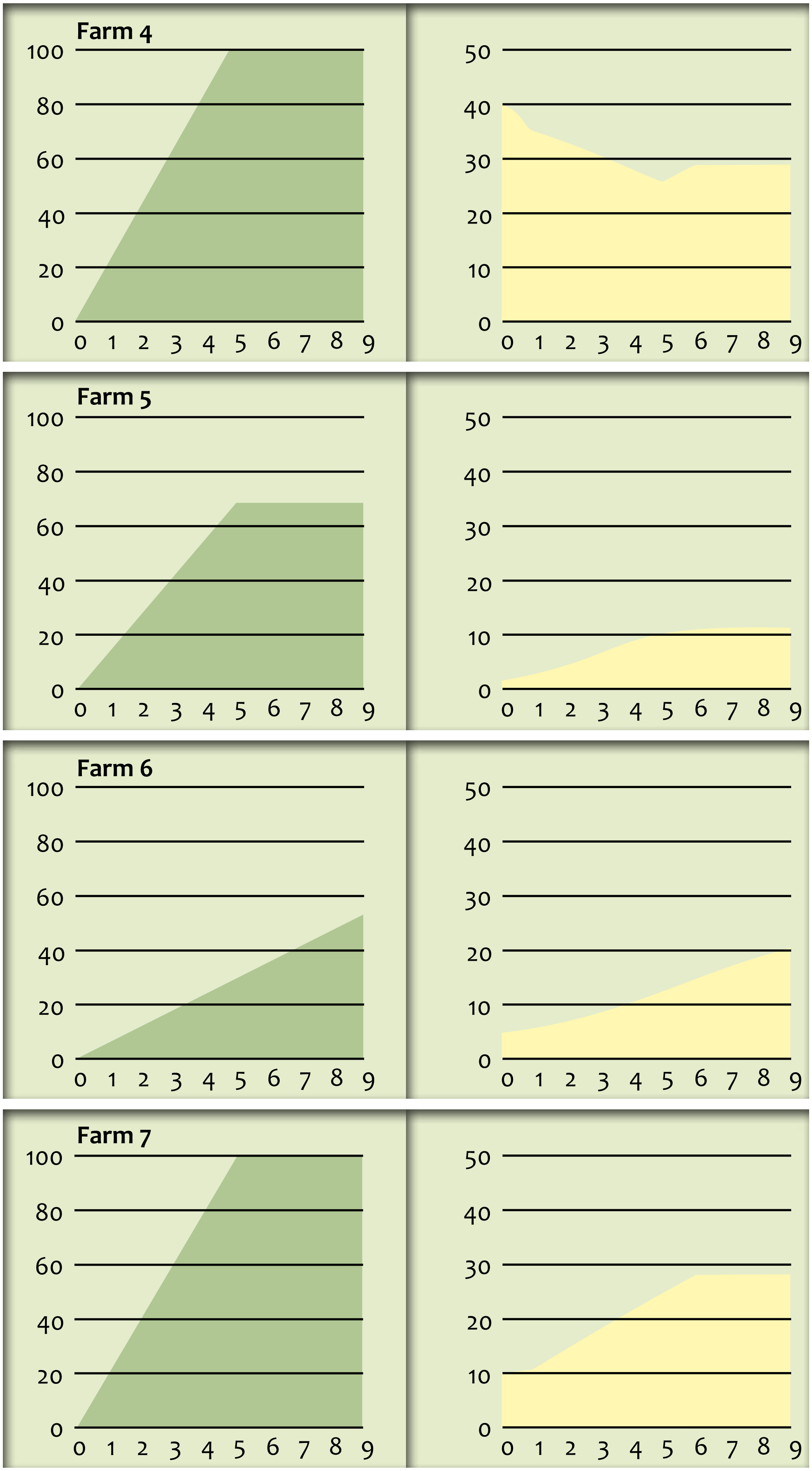
Environmental data for each of the farms analyzed was provided by CIPAV. This institution has been studying sustainable agricultural production systems for the tropical region. CIPAV has gathered historical information and measured the effects of SPS adoption on different productive and environmental variables. The information from CIPAV was confirmed by calculations on greenhouse gas emissions using the add-in of the TIPI-CAL model.

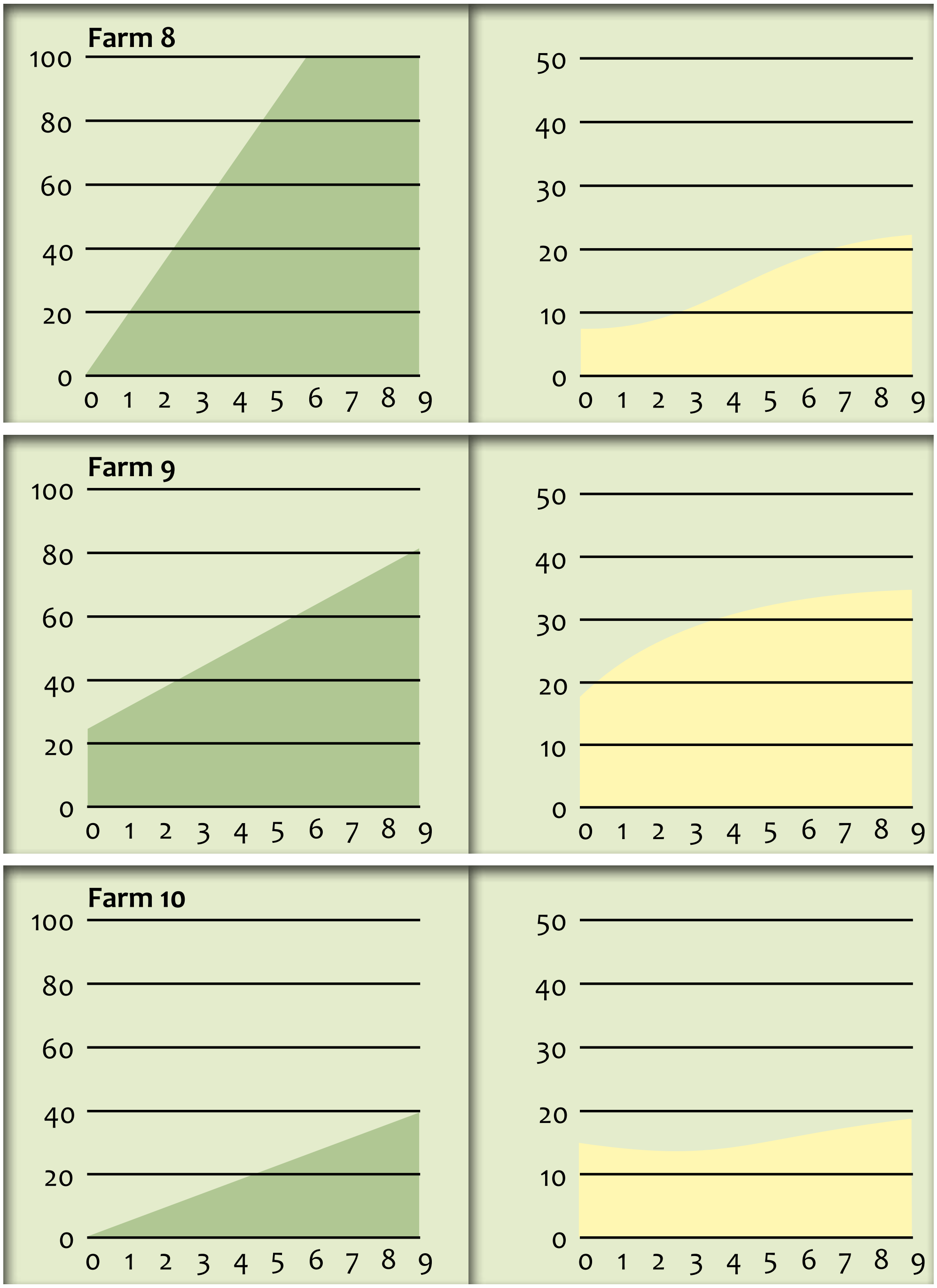
Animal welfare assessments were initially developed by animal welfare scientists at World Animal Protection in collaboration with independent external expert Prof. Donald Broom. An independent sustainability consultant from Good Food Futures Ltd completed further welfare assessments using these protocols. The method used in the field gave a concise and comprehensive overview of animal welfare. Objective measures of welfare, both outcomes-based such as body condition, and environmental such as water provision and shade, were used. Behavioural measures were adapted and simplified from globally recognised methods developed by Welfare Quality (Botreau *et al.* 2009) and Assurewel (Assurewel Project 2017), reflecting good feeding, good housing, good health and good behaviour.

Annex 2: Changes in main indicators over time

Figure A2.1 Change over time in proportion (%) of farm area converted to SPS (left) and DM (Mg) production per hectare of total farm area




Farm 4
100
80
60
40
20
0
0 1 2 3 4 5 6 7 8 9
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9
Farm 5
100
80
60
40
20
0
0 1 2 3 4 5 6 7 8 9
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9
Farm 6
100
80
60
40
20
0
0 1 2 3 4 5 6 7 8 9
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9
Farm 7
100
80
60
40
20
0
0 1 2 3 4 5 6 7 8 9
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9



Year 0 is the year cattle are introduced

El Hatico Natural Reserve. Valle del Cauca, Colombia. Photo M. Kohut-WAP.

Figure A2.3 Evolution of forage production, land productivity and profitability relative to baseline values

Farm 1	Colombia, Cesar / Prod. System: beef finishing / Area: 200 ha									
	Base line	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9
Forage production DM/Ha	100	129	177	254	349	445	540	636	696	731
Land Productivity Milk/Meat/Ha	100	100	149	218	331	468	599	732	813	943
Profitability Incomes-costs	100	-18	-19	-81	-31	84	218	356	560	969

Farm 2	Colombia, Valle del Cauca / Prod. System: dual purpose / Area: 39 ha									
	Base line	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9
Forage production DM/Ha	100	87	100	104	80	104	112	112	112	112
Land Productivity Milk/Meat/Ha	100	107	110	124	136	152	173	182	204	218
Profitability Incomes-costs	100	-2 336	-416	84	-1 247	1 778	2 688	3 648	4 798	5 491

Farm 3	Colombia, Valle del Cauca / Prod. System: Dairy / Area: 135 ha									
	Base line	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9
Forage production DM/Ha	100	99	99	101	104	107	109	112	115	117
Land Productivity Milk/Meat/Ha	100	103	109	113	123	130	135	138	145	152
Profitability Incomes-costs	100	173	199	204	281	360	477	558	677	773

Farm 4	Colombia, Quindio / Prod. System: Dairy / Area: 76 ha									
	Base line	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9
Forage production DM/Ha	100	87	81	75	69	64	71	71	71	71
Land Productivity Milk/Meat/Ha	100	121	141	163	180	195	212	212	212	212
Profitability Incomes-costs	100	114	152	231	275	306	355	398	393	404

Farm 5	Colombia, Armenia / Prod. System: Cattle breeding / Area: 45 ha									
	Base line	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9
Forage production DM/Ha	100	158	288	419	549	680	753	753	753	753
Land Productivity Milk/Meat/Ha	100	100	200	414	657	886	1 100	1 214	1 214	1 214
Profitability Incomes-costs	100	73	78	129	154	192	221	239	245	252

Farm 6	Colombia, Caqueta / Prod. System: Dual purpose / Area: 200 ha									
	Base line	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9
Forage production DM/Ha	100	111	138	181	225	269	313	356	400	444
Land Productivity Milk/Meat/Ha	100	108	144	191	263	355	517	605	741	947
Profitability Incomes-costs	100	-35	-132	-298	-269	-245	-75	61	271	609

Farm 7	México, Michoacán / Prod. System: Tropical dairy / Area: 50 ha									
	Base line	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9
Forage production DM/Ha	100	110	143	179	214	250	278	278	278	278
Land Productivity Milk/Meat/Ha	100	117	166	219	267	334	394	393	413	413
Profitability Incomes-costs	100	-228	-424	-258	-162	-126	69	218	492	949

El Hatico Natural Reserve. Valle del Cauca, Colombia. Photo M. Kohut-WAP.

Farm 8	México, Michoacán / Prod. System: Beef finishing / Area: 60 ha									
	Base line	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9
Forage production DM/Ha	100	99	115	146	177	208	240	271	287	287
Land Productivity Milk/Meat/Ha	100	144	212	321	433	547	659	742	784	784
Profitability Incomes-costs	100	-27	136	352	568	822	970	1 219	1 316	1 316

Farm 9	Argentina, Misiones / Prod. System: Forestry + beef finishing / Area: 240 ha									
	Base line	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9
Forage production DM/Ha	100	133	156	171	183	193	197	200	203	205
Land Productivity Milk/Meat/Ha	100	235	321	386	431	469	495	523	552	565
Profitability Incomes-costs	100	118	134	154	173	189	248	267	283	299

Farm 10	Argentina, Corrientes / Prod. System: Forestry + beef finishing / Area: 950 ha									
	Base line	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9
Forage production DM/Ha	100	96	93	89	95	102	108	114	121	127
Land Productivity Milk/Meat/Ha	100	100	95	92	87	108	121	140	154	174
Profitability Incomes-costs	100	65	42	36	-60	-18	-14	36	50	102

La Pendiente Farm. Misiones, Argentina. Photo J. Chará.

ISBN: 978-958-9386-83-5