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Native trees and shrubs for the productive rehabilitation of tropical cattle ranching lands

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ABSTRACT

Extensive cattle production currently occupies more than 27% of the rural landscapes in Latin America, and continues to expand. This activity, deeply rooted in the culture and rural economy of the region, requires an urgent transformation if it is to become both more efficient and environmentally friendly. Silvopastoral systems that incorporate native trees and shrubs are instrumental for the productive rehabilitation of cattle production and for biodiversity conservation in agricultural landscapes. We discuss research progress and adoption of intensive silvopastoral systems in Colombia and Mexico. Intensive silvopastoral systems (ISS) are a sustainable form of agroforestry for livestock production that combines fodder shrubs planted at high densities (more than 10,000 plants ha^{-1}), trees and palms, and improved pastures. High stocking and the natural production of milk and meat in these systems are achieved through rotational grazing with electric fencing and a permanent supply of water for the cattle. While milk and meat production and cattle reproduction are enhanced, production costs decline as external inputs are replaced by natural processes related to fertility and biological control. We also discuss the importance of the ISS with native trees for climate change adaptation and mitigation, the barriers for their adoption, and how these have been successfully addressed using payment for environmental services, special credits and technical assistance. Finally, we highlight the need for enhancing landscape connectivity by integrating SPS to conservation corridors with native species to promote biodiversity conservation and other environmental services demanded by society.

1. Introduction

Between 2000 and 2005, global deforestation proceeded at an alarming rate of about 13 million hectares per year. The estimated annual loss of forest cover during that period actually decreased to 7.3 million hectares, from 8.9 in the previous decade, partially counterbalanced by forest planting, restoration and natural re-growth (United Nations, 2009). In tropical regions, however, no progress was made in reversing the loss of forests during that period, and instead, deforestation rates increased by 8.5% to an impressive average of 10.4 million hectares per year (FAO, 2006a). Latin America and the Caribbean continue to account for the largest percentage of net forest losses, with 4.7% in 2000–2005 (United Nations, 2009).

Deforestation, particularly in the tropics, has often resulted in the large-scale conversion to unsustainable land uses—ecosystems so simplified and homogeneous that they can no longer support biodiversity and its complex ecological functions (Lamb et al., 2005). This degree of forest degradation has ultimately compromised the land's ability to provide the goods and environmental services required to support millions of livelihoods (ITTO, 2002; Lamb et al., 2005). Tropical deforestation has thus failed to deliver the anticipated benefits of economic development (Millennium Ecosystem Assessment, 2005), and therefore the model of forest-land conversion as a necessary step towards progress is no longer acceptable (Perfecto and Vandermeer, 2010).

Livestock production, frequently cited as a major driver of tropical deforestation, illustrates well the failure of this model. Indeed, in Latin America and the Caribbean the area occupied by pastures increased from 458.4 million ha in 1961 to 550.1 million ha in 2007 (Table 1), and today corresponds to roughly 27.1% of the land (FAO, 2009). Colombia is a representative example within the regional context, where between 1960 and 1995 pasturelands more than doubled from 14.6 to 35.5 million ha, while natural forests and agriculture declined from 94.6 to 72.4 million ha (IAvH et al., 1998). Today, the country has 40.6 million ha of permanent grazing lands

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Table 1
Land use change in Latin America and the Caribbean, 1961–2001.

Land use	Annual change		Total area in 2001 (%)
	1961–1991 (%)	1991–2000/1 (%)	
Agriculture	1.1	0.9	7.4
Pasturelands	0.6	0.3	30.5
Forests	−0.1	−0.3	47.0

Source: Adapted from Steinfeld et al. (2006).

and an annual deforestation rate of 300,000 ha, which doubled between 2004 and 2009 (Jarvis et al., 2010). At the continental scale, this expansion of pasture areas has aggressively transformed rural landscapes with enormous—and mostly negative— environmental and social impacts (Bennett and Hoffmann, 1992; McAlpine et al., 2009), while little improvement has been made in terms of land use efficiency. Meat and milk production show only modest productivity increments expressed in minimum animal loads, low per animal and per hectare production indexes, and meager contributions to rural employment. Despite a considerable total bovine population of 359 million heads in the region, the average annual per ha productivity and stocking rates remain low with 19.93 kg of beef, 89.7 l of milk and 0.59 animals respectively (FAO, 2006b).

Such unimpressive results probably explain why agriculture—livestock production in particular—has long been regarded as the antithesis of tropical forest conservation, and therefore a land use that conflicts directly with the provision of ecosystem services (Perfecto and Vandermeer, 2010). Consequently, conservation efforts over the past decades focused mainly on the protection of fragments of natural ecosystems with little human intervention, while the potential contribution of the prevalent agricultural landscapes to biodiversity conservation was grossly overlooked. But recently, a growing body of scientific work is showing that certain types of agricultural land uses and traditional practices can not only support important numbers of native plant and animal species (McNeely, 1995; Daily et al., 2003; Mayfield and Daily, 2005; Philpott et al., 2008), but may also contribute to enhance the conservation value of nearby tropical forest remnants (Gascon et al., 1999; Daily et al. 2003; Faria and Baumgarten, 2007; Harvey et al., 2008a). Thus, a new paradigm is emerging whereby the design and management of the agricultural matrix is becoming an instrumental tool for sustainable landscape level conservation (Fischer et al., 2005; Harvey et al., 2008a; Chazdon et al., 2009; Perfecto and Vandermeer, 2010).

This new approach to tropical agriculture from the ecosystem perspective has the added value of opening opportunities to address other key issues simultaneously, namely food production and sustainability. Agricultural systems worldwide continue to be challenged by the ongoing pressures of population growth and competition for natural resources (Herrero et al., 2010), but in tropical regions these are compounded by the increasing effects of severe land degradation and climate change. The high-input agricultural intensification model has not only driven tropical deforestation (Grau et al., 2005; Fitzherbert et al., 2008), but in the end has failed to deliver its basic promise of guaranteeing food security. Today we are beginning to recognize the productive, ecological, and social advantages of smaller-scale, less-intensive, sustainable farming systems, and their potential to provide future food security (Harvey et al., 2008a,b; Herrero et al., 2010; Perfecto and Vandermeer, 2010). And within this context, the most gains should be expected from further refining existing mixed crop-livestock (Herrero et al., 2010) and agroforestry systems, particularly in those tropical developing countries where moderately degraded lands are available and the potential for crop production has not yet been fully developed.

This article is not intended as a detailed review of the technical aspects of silvopastoral systems, which have been discussed at length elsewhere (Mosquera-Losada et al., 2004). Instead, it offers a perspective on how the much-needed change of paradigm in Latin American cattle ranching may offer important pay-offs at different levels. We briefly discuss the basic principles of tropical silvopastoral systems and provide real examples of their main benefits in terms of ecosystem services, climate change, sustainable productivity, and landscape-level restoration. We then explain how mainstreaming these systems into a larger scale land-use planning strategy can make substantial contributions to both forest and biodiversity conservation, as well as human livelihoods, all improvements that are critically needed in the region. Finally we address the main barriers to large-scale adoption of SPS and illustrate with examples how promotion strategies can be designed to achieve different goals. Thus, we offer the reader a wider perspective on how cattle ranching in Latin America can be made part of the solution rather than the problem.

2. The need for transforming conventional cattle ranching in Latin America

In Latin America, the origin and history of cattle ranching are closely linked to the dynamics of land use change. Ranching began five centuries ago in the natural savannas of the Caribbean, Orinoco and Pampa ecosystems, where the use of fire for controlling secondary succession and the introduction of aggressive African grass species resulted in the transformation of native forests into millions of hectares of pasturelands (Murgueitio, 2004). The myriad negative environmental effects of these conventional livestock production practices have been extensively discussed in Steinfeld et al. (2006), but in spite of those, cattle ranching is not likely to decline any time soon in Latin America. Not only is this activity deeply rooted in the Spanish and Portuguese ancestry of the region, but also it has often been a reaction to agricultural failures that result from biophysical constraints (Hernández, 2001; Murgueitio, 2004), and over time, it has become instrumental as a means to consolidate land control (Murgueitio and Ibrahim, 2008).

Because this activity is here to stay, the environmental transformation of livestock production is a priority for Latin America (Murgueitio, 2000). Underlying this transformation is the principle that cattle production needs to shift from its current path of ongoing degradation of the natural and social capitals, onto one which generates goods (milk, meat, and timber) while maintaining some ecosystem attributes and rendering ecosystem services. This change should therefore consist of four basic elements: (1) increasing plant biomass and diversity, (2) curbing soil degradation and promoting its recovery, (3) protecting water sources and using them rationally, and (4) increasing animal productivity on a per hectare basis. The first element is a prerequisite to achieve the other three, and therefore increasing vegetation cover in conventional grass monocultures will play a central role in the transformation. The resulting vegetation mixtures that combine grasses, legumes, trees, palms, shrubs and edible weeds, will contribute to increase photosynthesis, improve nutrient recycling, recover soil biota and fertility, and enhance biodiversity (Murgueitio and Calle, 1999).

3. Silvopastoral systems for the provision of environmental services

The recommended alternative to traditional cattle pastures are silvopastoral systems (SPS), a term comprising different agroforestry arrangements that combine fodder plants, such as grasses and leguminous herbs, with shrubs and trees for animal nutrition and complementary uses. Worldwide, the main SPS—some developed by farmers based on their practical experience and others designed though scientific research—include scattered trees in pasturelands, managed plant succession, live fences, windbreaks, fodder tree banks, cut-and-carry systems, tree plantations with livestock grazing, pastures between tree alleys, and intensive silvopastoral systems (ISS) (Murgueitio and Ibrahim, 2001; Calle, 2007). In temperate regions, where pristine forests were progressively transformed into multi-purpose landscapes through the selection of trees and livestock (Castro, 2009), SPS consisting of one layer of trees above one layer of grasses are still being successfully managed after 4500 years (Stevenson and Harrison, 1992).

At a landscape level, SPS provide more ecosystem services than open pasturelands (Buttler et al., 2009; Calle et al., 2009). They favor biodiversity by creating complex habitats that support diverse plants and animals (McAdam et al., 2007; Castro, 2009; Moreno and Pulido, 2009), harbor a richer soil biota, and increase connectivity between forest fragments (Rice and Greenberg, 2004; Ibrahim et al., 2006). In farmed landscapes, both tropical and temperate, SPS provide food and cover for birds serving as wildlife corridors where unique species assemblages can be found (McAdam et al. 2007). Throughout continental Europe and the British Isles the conservation or restoration of such systems is being promoted for biodiversity enhancement (McAdam and McEvoy, 2009). In humid regions, SPS can sequester more carbon than pastures and store it deeper and more permanently (Ibrahim et al., 2007; Nair et al., 2007a; Haile et al., 2010). The combination of grasses and trees also helps retain soil and water, protecting watersheds and soils from erosion (Ibrahim et al., 2006) and nutrient pollution (Michel and Nair, 2005; Michel et al., 2007). As trees mature, nutrient cycling speeds up and habitats become more wildlife-friendly (McAdam et al., 2007; Murgueitio et al., 2007). Ultimately, SPS can remain productive for longer periods than conventional pastures, thus reducing the pressure to clear more forests (Steinfeld et al., 2006).

From the farmers' point of view, trees planted in SPS also offer a variety of direct benefits. Trees and palms provide marketable wood products such as saw-timber, veneer logs, pulpwood, firewood, materials for tool handles, posts and poles, as well as non-timber products such as crafts and thatching materials, nuts, ornamental flowers and greenery, leaves, roots and bark for medicinal uses, green forage for livestock, resins, essential oils, honey, and even sap for preparing alcoholic beverages (Bellefontaine et al., 2002). They also produce fruits, seeds, and pods that feed humans, cattle, and wild animals (Rice and Greenberg, 2004), and flowers that provide nectar for crop and wild plant pollinators.

At the same time, trees in SPS also provide a range of indirect benefits that are often overlooked by farmers, because they originate from more complex mechanisms. Trees are key to maintain and improve soil fertility: they contribute to nitrogen fixation (Bryan, 2000; Dulormne et al., 2003; Teklehaimanot and Mmolotsi, 2007) and nutrient uptake from deep soil horizons (McPherson, 1997; Scholes and Archer, 1997; Nair et al., 2007b), while their litter helps replenish soil nutrients (Menezes et al., 2002), maintain organic matter, and support complex soil food webs (Young, 1997 and references therein; Montagnini et al., 2000). They also improve the physical conditions of the soil (Ayres et al., 2009) because their root systems counteract compaction, reduce surface runoff and erosion, and enhance water infiltration (Ilstedt et al., 2007). Trees even provide suitable habitat for dung beetles (Giraldo et al., 2010) and other decomposers that quickly recycle nutrients, and for predators and parasitoids that control harmful insects. They shelter epiphytes, climbers, and lianas that in turn support a variety of organisms, and favor biodiversity by serving as stepping stones for the movement of wildlife within the landscape (Bellefontaine et al., 2002; Manning et al., 2006; Uezu et al., 2008).

The real value and potential of SPS as a tool for tropical landscape-scale restoration stems from the fact that their productive and environmental advantages cannot be decoupled. In other words, the productive advantages that make SPS so attractive for landowners ultimately originate from the myriad environmental benefits they provide, even if it takes longer for these to be perceived as added value. Very traditional temperate SPS such as the Portuguese *montado* (Castro, 2009), the Spanish *dehesa* (Moreno and Pulido, 2009) and the wooded pastures of the Swiss Jura mountains (Buttler et al., 2009) have been recognized for their high cultural, socioeconomic, ecological and landscape values (Eichhorn et al., 2006), and are being preserved.

4. Intensive silvopastoral systems for sustainable productivity

Among the variety of SPS, those known as intensive silvopastoral systems (ISS) show particular promise for tropical regions due to their many benefits (Table 2). ISS are a form of agroforestry for animal production that integrates fodder shrubs planted at high densities (more than 10,000 plants ha^{-1}), intercropped with improved, highly-productive pastures and timber trees planted in east-west lines to minimize shading, all combined in a system that can be directly grazed by livestock (Murgueitio and Solorio, 2008). Their name may be misleading, because what is *intensive* about ISS is not the use of capital, labor, or chemical inputs, but rather the efficiency of biological processes such as photosynthesis, nitrogen fixation, solubilization of soil phosphorus, and the enhancement of soil biological activity. In this case, the “inputs” of the system are the natural processes themselves.

ISS are being successfully adopted in beef cattle, dual purpose, and tropical dairy farms in the Cauca and Cesar valleys, Tolima, and Eje Cafetero regions in Colombia, in the Tepalcatepec and Apatzingán valleys of Michoacán and the Huasteca region of San Luis Potosí in Mexico, and in the provinces of Chiriquí, Coclé and Darién in Panama. After their second year of establishment, ISS have shown significant advantages compared to other livestock production systems with high tree densities (Murgueitio and Solorio, 2008). In fact, the pioneer ISS in Colombia have recorded sustained high milk and meat production for two decades and still show no evidence of declining grazing potential (Molina et al., 2008).

The key to successful ISS is the adequate selection of the species, particularly the fodder shrub that is the backbone of the system. Of the different species tested, Mexican sunflower *Tithonia diversifolia* Hemsl and in particular leucaena *Leucaena leucocephala* (Lam.) de Wit show the best results so far.

Native to Mexico, leucaena was already being fed by Asian smallholders to their cattle in Eastern Indonesia in the 1930s, but Australian graziers were the first to plant commercial stands integrated to grasses in the 1970s. In Northern Australia, leucaena hedgerows are sown with grasses to form highly productive grass–legume grazing systems for cattle (Dalzell et al., 2006; Shelton, 2009). Approximately 150,000 ha of these sustainable leucaena pastures existed by 2006, some of which have remained productive over the past 30 years. In Latin America, several attempts have been made to apply similar models at a smaller scale. In Mexico, where leucaena seeds have been used for human consumption for thousands of years, its potential as a fodder species was being studied more than 40 years ago (National Academy of Sciences, 1977), but research and technology transfer were interrupted until recently (Murgueitio and Solorio, 2008).

In Colombia, the development of an equivalent to the Australian system began twenty years ago. First, the shrubs were associated with nitrogen-hungry, highly productive grasses, in an attempt to challenge the limits of biomass production. Later, third and fourth layers of timber trees, fruit trees, and palms, were added in an

Table 2
Observed productive and environmental benefits of ISS.

Direct benefits to farm productivity
• Tolerance to dry periods between three and five months
• Reduced vulnerability to dessicating winds
• Fast growth of shrubs and grasses with high biomass production of good quality forage
• Increased stocking rates: 200–500% higher (0.8–4 large animals in the dry Caribbean and Andean valleys in Colombia and the Pacific region in Mexico)
• Increased reproductive rates for cattle
• Significant reduction of heat stress for the animals
• Increased meat and milk production: 200–1500 kg meat ha^{-1} yr^{-1} and 800–>3000 L ha^{-1} yr^{-1} in the dry Caribbean in Colombia and Pacific region of Mexico
• Increased total solids and protein in milk, two key quality parameters rewarded by the dairy industry
• High financial returns for small, medium, and large producers (internal rates of return between 14% and 22%)
• Reduced need for weeding and herbicides for maintenance
• Elimination of dependence on nitrogen fertilizers
• Increased production of timber trees in windbreaks
• Creation of ideal conditions for achieving good farming practices and certification of organic production for new milk and meat markets
Indirect benefits to farm productivity resulting from benefits to the environment
• Disruption of the life cycles of internal parasites resulting from quick rotation and the effects of secondary metabolites from leucaena, Guazuma ulmifolia and other trees
• Decrease in external parasites such as the horn fly *Haematobia irritans* due to higher presence of dung beetles and earthworms (biological indicators of tropical soil health) that interrupt parasite's life cycle by quickly degrading cattle manure
• Enhanced biological control of ticks due to higher presence of predators (birds and ants) and parasitic fungi
Benefits to the environment
• Surface soil erosion minimized by permanent and complete ground cover
• Reduced soil compaction due to the presence of a deep and complex root system combined with brief grazing periods and long breaks
• Reduced wood consumption resulting from the use of electric and live fences to replace dead fence posts
• Enhanced protection of water sources, as a result of increased awareness by farmers that this resource demands careful management
• Enhanced hydrological regulation due to better water infiltration through the roots of the shrubs
• Increased connectivity between forest remnants
• Increased presence of beneficial biota in the system resulting from enhanced microclimate and vegetation cover

Source: CIPAV, unpublished data; Murgueitio and Solorio (2008).

attempt to mitigate the drying effect of winds, enhance biodiversity habitat, and provide fruits for the cattle (i.e. a dry weight of 400 kg ha^{-1} yr^{-1} of nutritious *Prosopis juliflora* fruits in the farming system described in Section 4.1). This new integrated timber-animal production system solved the two main problems of forest plantations: lack of cash flow and high cost of grass control during establishment. In addition to the vegetation layers, animal management techniques were also improved for an optimal grazing, where the cattle rotate quickly through the pastures consuming only fresh biomass, and have permanent on-site access to fresh water. High stocking rates during short periods of time under a dim shade environment allow the immediate harvest of biomass from both shrubs and grasses, followed by long recovery periods. This combination of animal management and spatial distribution of plants results in an even distribution of the manure on the ground, as well as the reduction of soil compaction due to the rapid root turnover of shrubs and grasses. Adequately managed, multi-strata ISS such as the one described in the following section, can out-

Table 3
Animal loads, milk production and lifespan of two conventional grazing systems and two SPS.

	Conventional systems without trees		Silvopastoral systems	
Region	Humid tropics (Colombian Amazon)	Humid tropics (Costa Rica)	Andean slopes (Colombia)	Dry tropics (Mexico and Colombia)
Altitude (m.a.s.l.)	500	600	1450–1800	200–1000
Rainfall (mm yr^{-1})	3000	2600	1500–1750	800–1200
Production system	Degraded pasture	Improved pasture with chemical fertilizer (>250 kg N_2 ha^{-1} yr^{-1})	Silvopastoral system with fodder bank and organic fertilizer.	Intensive silvopastoral system (no fertilizer)
Animal load (450 kg animals ha^{-1})	0.6	5	4.6	4
Milk production (ha^{-1} yr^{-1})	400	10,800	5320	>10,000
Grazing system lifespan or renewal period (yr)	4	6	>20	>20
Reference	Ramírez et al. (2008)	Pezo et al. (1999)	Ramírez et al. (2008)	Murgueitio and Solorio (2008)

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compete the conventional "intensive" livestock production systems (Table 3).

4.1. Case study: El Hatico nature reserve

El Hatico nature reserve is one of the farms that pioneered the use of SPS in Colombia in the 1970s. Located in the municipality of El Cerrito in the fertile flatlands of the Cauca river valley in Colombia, El Hatico lies at 1000 m.a.s.l. in a region with 24 °C of average temperature and 800 mm of average bimodal rainfall. Until 1970, the farm was managed with conventional ranching practices: pastures with low tree cover (10 trees ha^{-1}), application of herbicides for weed control, irrigation during dry periods, chemical fertilization, and animal loads below 3 cows ha^{-1}. But by end of the 1970s, the first attempts were made to promote natural regeneration in order to increase tree cover and today, the farm boasts 70 tree species in its silvopastures. In 1993, leucaena was planted at high density for browsing, and 3 years later this family enterprise was certified as ecologic. Since then, El Hatico has been contributing to the research and development of environmentally friendly agriculture and livestock production systems through the integration of diverse tree species, the continuous improvement of its technical, economic, social and environmental indicators, and a rigorous record keeping.

Today, five plant strata are clearly identifiable in the mature and fully productive ISS present in El Hatico: (1) creeping grass cover including star (*Cynodon plestostachys*), guinea (*Panicum maximum)*, Bermuda (*Cynodon dactylon)* and native (*Paspalum notatum*) grasses; (2) leucaena (*L. leucocephala)* at high density (10.000–15.000 shrubs ha^{-1}); (3) medium sized trees (*Prosopis juliflora*, *Senna spectabilis, Guazuma ulmifolia, Guarea guidonia)* at medium density (30–50 ha^{-1}); (4) a canopy of large trees (*Ceiba pentandra*, *Samanea saman*, *Enterolobium cyclocarpum*) at low density; and (5) a top layer of native and non-native palms (*Syagrus zancona*, *Attalea butyracea*, and *Roystonea regia)* and timber trees like mahogany, cedar, and others (*Swietenia macrophylla, Cedrela odorata, Zanthoxylum rhoifolium*). This tree-rich matrix hosts a diverse biota and facilitates connectivity between forest fragments, thereby strengthening the biodiversity benefits of the livestock grazing system.

In terms of productivity, El Hatico's figures speak for themselves. The ISS and rotational grazing systems used over the past 18 years have allowed to increase stocking rates to 4.3 dairy cows ha^{-1} and milk production by 130%, and to completely eliminate the use of chemical fertilizers. Today, El Hatico produces 2350 l of milk daily for an annual production of 16,000 liters ha^{-1}. The animal mortality rate is 5% for the young and 0.5% for adults, and the birth rate is estimated at 95% with a calving interval of 12.8 months and age at first birth of 30 months (Molina et al., 2008). Milk production figures in two conventional grazing systems (without trees) and two SPS are provided for comparison (Table 3).

Recent climatic events at different scales have disrupted the rainfall distribution in this region, making 2009 the driest in El Hatico's 40-year record, with precipitation having dropped by 44% compared to the historical average, to only 440 mm. Despite a reduction of 25% in pasture biomass, the fodder production of trees and shrubs remained constant throughout the year, neutralizing the negative effects of drought on the whole system. In response to the extreme weather, the farm had to adjust its stocking rates and increase energy supplementation. In spite of this, the farm's milk production for 2009 was the highest on record with a surprising 10% increase compared to the previous four years. Meanwhile, farmers in other parts of the country reported severe animal weight loss and high mortality rates due to starvation and thirst.

5. Silvopastoral systems for climate change adaptation

It has been anticipated that the sustainable intensification of production in some agroecosystems will be an important response to climate change. Provided that the necessary policies and incentives are put in place, intensification technologies are expected to promote and enable forms of production that are both economically and environmentally viable (Steinfeld et al., 2006). The productive performance of El Hatico during the exceptionally hot and dry period of El Niño Southern Oscillation illustrates the huge potential of SPS as a sustainable intensification strategy for climate change adaptation and mitigation. In this context, the combined benefits of water regulation, favorable microclimate, biodiversity, and carbon stocks in these ISS, not only provide environmental goods and services for livestock producers but also greater resilience to climate change.

Other examples of how SPS help farmers adapt to increasingly drier conditions come from the Regional Integrated Silvopastoral Approaches to Ecosystem Management Project (RISAEM Project), implemented in Colombia, Costa Rica, and Nicaragua between 2002 and 2007, (Pagiola et al., 2005). The project showed that drought-tolerant, non-deciduous tree species that provide high-quality fodder throughout the dry season, can safeguard the farmers' assets against the uncertainties of seasonality by sustaining a stable milk and beef production and protecting cattle from the effects of heat stress (Murgueitio and Ibrahim, 2008). SPS can also contribute to mitigation because they improve forage digestibility reducing methane emissions by 20%, increase carbon sequestration in both trees and soils (Ibrahim et al., 2007), and suppress the use of fire for pasture management (Murgueitio and Ibrahim, 2008).

More recent data from three farms located in the dry Caribbean flatlands of the Cesar river valley, in northern Colombia, also confirm the potential of SPS for climate change adaptation. In these farms, weather stations placed in three cattle grazing systems —ISS with mango trees, ISS without a canopy, and a treeless pasture— took measurements every 30 min during 2009, a record hot year. Compared to the treeless pasture, the mango ISS and ISS with no canopy had 20% and 10% higher average relative humidity and 2 °C and 3 °C lower average temperatures, respectively. Peak daytime temperatures during the hottest month, February, were on average 14 °C lower (44 °C vs. 30 °C) in the ISS with mango trees. Evapotranspiration in both ISS was 1.8 mm day^{-1} lower than in the treeless pasture (CIPAV, unpublished data).

6. Silvopastoral systems for landscape level biodiversity conservation

Outside of Europe, perhaps the least discussed benefit provided by SPS is their contribution to landscape level rehabilitation and conservation efforts. Tropical livestock systems are typically regarded as biodiversity deserts because they harbor low tree diversity, given that very few forest species are able to maintain viable populations when subject to the disturbance regime of active grazing (Esquivel et al., 2008). In addition, cattle farmers themselves have simplified the species composition of their surroundings by eliminating most trees that have no known or perceived direct benefits (Harvey et al., 2008a,b). On the other hand, research in the cattle sector has simplistically focused on identifying "miracle grasses" that promise to boost productivity when planted in improved monocultures, while ignoring the fact that most of the mechanisms that sustain high natural productivity in tropical ecosystems are linked to trees. Conventional cattle production management systems —whether the traditional extensive or the modern input-intensive— consisting of pasture monocultures with few or no trees, ultimately lead to ecosystem degradation.

On the contrary, SPS can have positive impacts and even play a significant role in the restoration of soils degraded by intensive agriculture. The use of ISS to rehabilitate the wastelands left by intensive cotton monocultures in Cesar, Colombia is a recent example. SPS have been shown to enhance biodiversity in agricultural landscapes, as revealed by an analysis of the changes perceived following the implementation of the RISAEM project in Quindío, Colombia. Participant farmers reported that they perceived a dramatic increase in bird abundance and diversity (71%), an increment in plant and animal diversity (54%), higher frequency of mammals in their pastures (36%), and more sightings of endangered or rare species (11%) (Calle et al., 2009). Bird abundance and species richness in the new SPS were found to be higher than in the original pastures and similar to those of the remnant forests. Of the 170 bird species recorded in these SPS, 54% are considered forest dependent (Murgueitio et al., 2007; Sáenz et al., 2007), and one endemic subspecies, *Ammodramus sabanarum caucae*, was sighted again after nearly three decades.

Such results suggest that SPS can be easily integrated with other landscape level strategies such as connectivity corridors in order conserve biodiversity and enhance other environmental services within agricultural landscapes. Many unprotected forest remnants of high conservation value are embedded within a matrix of cattle grazing areas formed by pasture monocultures with few trees. In such areas, SPS with complex vegetation structures can support important levels of biodiversity (Harvey et al., 2005, 2006; Sáenz et al., 2007) and provide ecosystem services such as natural pest management, carbon sequestration, water and soil conservation, nutrient cycling, hydrological protection, and crop pollination (Chazdon et al., 2009; Calle et al., 2010). Hence it is possible to enhance biodiversity by strategically placing elements such as live fences, scattered trees, riparian buffers, and connectivity corridors within the landscape. This model is based on the principle that the larger landscape can be more important for species survival than the size of particular patches of natural habitat (Perfecto and Vandermeer, 2010).

7. Strategies to scale-up silvopastoral system adoption

With so many proven on-farm and off-farm productive and ecological benefits, the limited adoption of SPS in countries like Colombia begs the question: If SPS are so profitable and efficient, why have they not been more widely adopted? The barriers to the adoption (Pattanayak et al., 2003) of these systems have been well studied and understood, and can be grouped in two main categories. (1) Financial capital barriers. The high initial costs required to establish many SPS defy the prevailing view of tropical cattle ranching as a low-investment activity, and neither technicians, producers, nor banks are prepared for them. (2) Knowledge barriers. The technical complexity of some SPS demands a kind of specialized knowledge that is not commonplace among farmers, professionals, conventional academia, or commercial firms in the field (Calle, 2008). Thus, specialized technical assistance is required to overcome implementation barriers, such as those arising from the complex ecological interactions between the components of the system, and to effectively diffuse this recently acquired scientific knowledge (Murgueitio, 2009).

From the perspective of individual landholders, many of the benefits provided by SPS, such as biodiversity conservation, carbon sequestration, and water services, are externalities and therefore do not really act as incentives for adoption (Pagiola et al., 2005, 2007). Some European countries use incentives to promote the adoption of agroforestry practices and subsidies to preserve their existing traditional SPS (EC, 2005; McAdam and McEvoy, 2009). In tropical regions, the scaling-up of ISS and other SPS—like any other transition to forested land uses—will require some form of incentive to address the two main adoption barriers. Such incentives should proceed in two ways: first, farmers must gain access to financial capital, and second, training and technical assistance must be provided to farmers, technicians, and field workers. These two basic lessons, confirmed by the results of the RISAEM Project, are now being applied in Colombia to promote the adoption of SPS at a wider scale. The following examples illustrate how the strategies to scale-up SPS can be designed with different priorities in mind.

7.1. Rural capitalization incentive (RCI)

In Colombia, 40% of the cattle, sheep and goats in the country are produced in extensive systems subject to strong seasonality in the Caribbean lowlands (FEDEGAN, 2006). Despite the key role of the sector in the regional economy, livestock farming systems remain highly vulnerable to the effects of extreme weather, particularly the dry season when aridity and fodder shortages lead to dramatic production declines. As a result of overgrazing and the nearly complete loss of plant cover, the soils have been seriously degraded. Under these conditions, the adoption and adaptation of ISS could play a critical role in supporting beef and dual purpose farms.

ISS were introduced to the Cesar department in 2006 through an alliance between the Ministry of Agriculture and Rural Development, the Colombian Federation of Cattle Producers (FEDEGAN), and CIPAV, with the establishment of 20.4 ha in El Porvenir farm. With the new system, the farm now supports stocking rates higher than those of the Andean region, and at four animals ha^{-1} in the rainy season has demonstrated the huge potential of ISS in the dry Caribbean. Nearby Rancho Alegre farm also implemented ISS and as a result was able to completely stop irrigating its 100 ha since 2007. Today, it supports at least 2.5 large animals (450 kg) ha^{-1} during the dry season with an average meat production of 1400 kg ha^{-1} (CIPAV, unpublished data). Through an outreach strategy designed to share these results and educate producers about the potential of SPS in the Cesar river valley, livestock producers throughout the region became interested and are now implementing nearly 2000 ha in over 100 farms. In 2009 a new land rehabilitation project set out to establish 2500 additional ha of ISS, which were designed specifically for the region's dry conditions and integrated a variety of timber trees in different arrangements. This initiative is driven by CIPAV and Fundalianza (NGO specializing in rural credit) and supported by FEDEGAN, and has been embraced by seven core partnerships of small and medium livestock producers.

This success in the adoption of ISS is partly the result of the new rural capitalization incentive (RCI), implemented in 2007 to promote the planting of fodder trees and improved pastures. The RCI gives farmers a 5–6 year loan to establish their ISS, an additional one-time 40% incentive after planting the first 100 ha, and 30% for additional areas. Based on the estimated establishment costs of one ha of ISS, the incentive is currently about US$1000 for ISS with over 7000 shrubs and no trees, and US$2000 for ISS with 5000 shrubs and 500 timber trees. Because it does not depend on the farm size or the farmer's capital, the ICR is available to all farmers (Murgueitio, 2009). Other public incentives that address the issue of high up-front costs are available to farmers in Nicaragua, Panama, and the states of Michoacán and San Luis Potosí in México, where the benefits of ISS have also been demonstrated (Murgueitio and Solorio, 2008).

7.2. Mainstreaming biodiversity in sustainable cattle ranching project (MBSCRP)

The Mainstreaming Biodiversity in Sustainable Cattle Ranching Project (MBSCRP) is based on the idea of incorporating the agricultural matrix as an integral component of conservation programs,

Table 4
Colombian cattle ranching regions covered by the Mainstreaming Biodiversity in Sustainable Cattle Ranching Project (MBSCRP).

Region	Total land area (ha)	Area covered by natural ecosystems (ha)	Altitude (m.a.s.l.)	Rainfall (mm^{-1} yr^{-1})	Average temperature (°C)
Cesar River Valley (Caribbean region)	387,047	92,025	20–250	810–2100	26–28
Lower Magdalena River Basin (Caribbean region)	146,087	35,944	100–300	900–1300	26–29
Oak forest corridor –Boyacá and Santander (Andean region)	163,675	104,590	1290–2800	726–3281	13–21
Coffee growing ecoregion (Andean region)	698,075	225,794	251–3000	966–2829	13–27
Eastern Andean foothills – Meta (Orinoco region)	324,012	88,989	220–600	2613–5200	24–27

proposed recently by Perfecto and Vandermeer (2010). The goal is to promote the adoption of SPS among Colombian cattle ranchers, as an alternative to improve natural resource management, enhance the provision of environmental services (biodiversity, land, carbon, and water), and raise the productivity in participating farms. The five cattle ranching regions targeted by the project (Table 4) were selected for their high levels of biodiversity and their proximity to strategic ecosystems and protected areas, and it is expected that increasing connectivity within them will safeguard globally important biodiversity. Two main components of the project aim at: (1) improving productivity in participating cattle farms by establishing SPS, and (2) increasing connectivity and reducing land degradation in participating cattle farms through differentiated payment for environmental services (PES) schemes.

Short-term PES will be given to those land uses with high levels of biodiversity that, once established, are profitable in the medium and long term (i.e. live fences, windbreaks, and isolated trees in pastures), and therefore will most likely be kept in place by the farmers. On the other hand, those land uses that foster high levels of biodiversity but are not profitable in the medium and long term (i.e. riparian forests, connectivity corridors, SPS with native trees, secondary forests, and wetlands) will receive short term payments by the project, and additional funding sources will be explored to guarantee that they receive long-term PES (Chará et al., 2009). The direct payment through the project is intended to stimulate the maintenance and restoration of native forests (mature, secondary, or riparian), which offer important environmental services (Rey-Benayas et al., 2010) but do not generate obvious revenue for most landowners, and sometimes are even subject to taxes.

Another goal of the project is to establish 15,750 ha of connectivity corridors through a combination of secondary succession and enrichment planting. The MBSCRP defines connectivity corridors as “stretches of tree or shrub vegetation connecting fragments of natural ecosystems through riparian strips, pastures with high tree density, and other elements of the landscape”. Each corridor consists of a 10 m wide core strip set aside for strict conservation, partially or completely including fragments of natural ecosystems, surrounded on both sides by 25 m wide buffer strips that may include secondary succession or SPS (scattered trees, ISS, live fences and windbreaks). Participation by landowners in this project is voluntarily and therefore, when their lands fall within the core areas of connectivity corridors, only those who commit to strict conservation will receive a payment. Those located in the buffer strips will be paid for some land uses, as long as they are sufficiently compatible with biodiversity. The profit and biodiversity trade-offs for different land uses are summarized in Fig. 1.

The MBSCRP also contemplates a premium payment for those landowners who incorporate focal tree and palm species into their connectivity corridors. Focal species (Lambeck, 1997) are the basis of a multi-species approach that helps to define the landscape attributes and management practices needed to meet the conservation requirements of the biota affected by fragmentation and habitat loss. This approach has been used in the context of animal species conservation (Freudenberger and Brooker, 2004), and

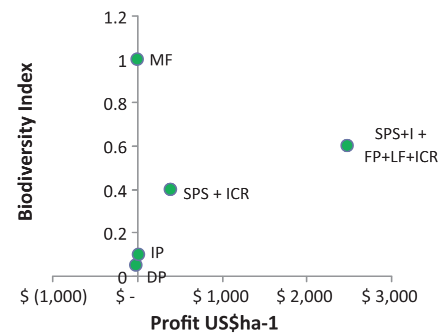

Fig. 1. Profit and biodiversity trade-offs for different land uses (Regional Integrated Silvopastoral Approaches to Ecosystem Management RISAEM Project) MF, mature forest; DP, degraded pasture; IP, improved pasture without trees; SPS + ICR, silvopastoral system with economic incentive; SPS + I + FP + LF + ICR, silvopastoral system with irrigation, forest plantation, live fences and economic incentive.

is being adapted by the MBSCR Project for the restoration of connectivity corridors. In this case, the focal species are a group of 50 native trees, palms, and cacti selected for their particular contributions to biodiversity. In the absence of the payment, farmers are not likely to plant such native species given their slower growth rates, higher establishment and management costs, and reduced (or no) market value (Calle and Piedrahita, 2007). The 50 focal species will be selected from a preliminary list of 130 species of native trees and palms of global conservation concern present in the areas of project intervention, based on specific criteria (Support online material).

8. Conclusions

Recently McAlpine et al. (2009) proposed some policy imperatives to mitigate the environmental impacts of cattle ranching: stop subsidizing beef production, stop promoting beef consumption, and restore forests in grazing lands. Here we propose a more realistic alternative based on the environmental transformation of meat and milk production through the use of SPS that can contribute to rehabilitate the lands degraded by conventional cattle production and agriculture. Cattle ranching does not have to be the cause of serious environmental problems. Instead, it may be part of their solution if properly managed at a landscape scale, applying the available practical knowledge on the uses and benefits of trees. To achieve this it is important to remember that:

1. Extensive cattle grazing systems continue to expand in Latin America, further aggravating the degradation of natural resources. Land rehabilitation and the environmental transformation of this activity are regional priorities that must combine research, technology transfer, and public policy.
2. Intensive silvopastoral systems are a form of science-based agroforestry that allows a rapid increase in productivity and the rehabilitation of degraded pasturelands, and are therefore a novel tool that would allow the spatial concentration of cattle

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production in the most appropriate areas while freeing other lands for ecological restoration and conservation.
3. Native trees and shrubs will certainly play a key role in enhancing ecosystem services in pastoral landscapes once the physical, cultural, technological, and financial barriers are removed. However, better land use planning, more applied research, additional incentives, and the incorporation of farmers' preferences are still required.
4. Native trees planted in corridors linking fragments of natural ecosystems through a silvopastoral matrix may contribute to enhance landscape-scale connectivity and biodiversity while mitigating the effects of climate change. The successful application of this strategy will require innovative payment for environmental services schemes.

Although this article focuses on experiences from Latin America, the same basic principles apply in other tropical regions with comparable land ownership, where complex SPS could be designed and implemented taking advantage of native species with potential for achieving similar results.

In summary, we propose that the mainstreaming of silvopastoral systems in tropical degraded landscapes can simultaneously address environmental and productive issues, making cattle ranching part of the solution rather than the problem.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.foreco.2010.09.027.

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