Exploiting synergies between silvopastoral system components for carbon sequestration and an increase in cattle productivity: experience from Costa Rica and Nicaragua

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In Central America extension of grazing land for extensive cattle ranching has been a driving force behind deforestation, releasing considerable amounts of carbon dioxide (CO2) to the atmosphere. This trend is going to continue since about 60 percent of the regions pastureland has already been classified as degraded and a fast rising demand for livestock products aggravates the pressure on remaining forests. In search of possibilities to reduce livestock related deforestation, technology alternatives to extensive cattle grazing are rediscovered which verifiably have a less detrimental impact on the integrity of natural resources - those alternatives include silvopastoral technologies like dispersed trees in pasture. This study analyses the profitability of incorporating trees through natural regeneration into paddocks with Brachiaria brizantha on dual-purpose farms in Northern Nicaragua and the Central Pacific region of Costa Rica. We further determine the carbon (C) sequestration potential of the tree-pasture systems and calculate prices per tCO2 which would have to be offered to farmers as a compensation for the costs incurred in adopting the new land-use. The results of this research help to determine the point of equilibrium between C sequestration and livestock production per unit of land since the competition between silvopastoral system components can cause the degradation of natural resources and income losses for farmers. The change from treeless Hyparrhenia rufa to Brachiaria brizantha with a tree canopy cover of 20 percent is profitable in both countries without payments for carbon sequestration services. In Costa Rica, the average annual net income per hectare increases from US$ 122 generated by naturalized grassland without trees to US$ 290 in case of a canopy coverage of 20 percent. Cattle producers in Matiguás obtain similar income changes which are the result of additional income from timber sale and an increase of animal productivity due to the beneficial impact of shade. A comparison of the costs and benefits of establishing silvopastoral systems, plantations of Cordia alliodora and secondary forest indicate that C sequestration through silvopastoral systems is cheaper than through the respective forest alternatives. Prices per tCO2 range from US$ 0.8 to US$ 4.5 in case of land-use changes from naturalized pasture to improved pasture-tree systems and from US$ 11.4 to US$ 25.5 for forestry systems.

Keywords: Payments for Environmental Services; Land-use change; Cost-efficiency analysis; Natural regeneration

Introduction

The livestock sector generates 18% of global greenhouse gas emissions measured in carbon dioxide equivalent (CO2e) – exceeding the emissions of transport. About 2.4 billion of the estimated 4.5 to 6.5 billion tons of annual net additions of carbon (C) to the atmosphere derive from livestockrelated land-use

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changes like the conversion of forests into arable land for feed crop production and pasture. This trend is expected to continue particularly due to fast population growth in developing countries combined with urbanization, growing per capita income and changing diet habits which result in an increasing demand for livestock products (Steinfeld et al., 2006). In Central America, native forests have been reduced by almost 40% over the past 40 years (FAO, 2006). Extension of grazing land for extensive cattle ranching has been a driving force behind deforestation.

Approximately 69% of the deforested area will be used for pasture by 2010 (FAO, 2005) and at present, about 60% of pasture land are already classified as degraded which is an indicator for further deforestation. In search of possibilities to reduce CO2 emissions from livestock related deforestation and soil degradation, technology alternatives to extensive cattle grazing are rediscovered which verifiably have a less detrimental impact on the integrity of natural resources and human health - those alternatives include silvopastoral practices like dispersed trees in pasture.

A number of studies document that cattle farmers in Central America tend to leave isolated trees on pastureland at low densities (Harvey and Haber, 1999; Camargo et al., 2000; Esquivel et al., 2003; Villanueva et al., 2003). Farmers often have a good knowledge of the use of trees (Muñoz et al., 2003) but they are mostly a product of natural regeneration and are rarely managed with the aim to maximize environmental and economic benefits. Low densities of trees on grassland and the often insignificant contribution of timber sales to farm income (Souza et al. 2004, Camargo et al., 2005) indicate that the full potential of trees has not yet been exploited.

In this paper we adopt a holistic approach to get a better understanding of silvopastoral component interactions and their economic and environmental outcome. We analyze the profitability of switching land-use from treeless naturalized pasture (*Hyparrhenia rufa*) and improved pasture (*Brachiaria brizantha*) to improved pasture with different tree densities on dualpurpose (beef and dairy) cattle farms in Costa Rica and Nicaragua. Trees are incorporated into pastureland through natural regeneration, and we simulate the development of the tree canopy over a 30-year period. The dry matter availability of pasture under canopy cover levels ranging from 0 to 45% is determined and respective milk and meat yields are calculated. We estimate the C sequestration potential of the tree-pasture systems and determine a payment per tCO2 that would be necessary to compensate farmers for adopting silvopastoral systems for carbon sequestration.

Results are compared to the costs of C sequestration through laurel plantations and secondary forest regrowth on naturalized pasture.

Methodology

Study area

We select dual-purpose cattle farms for our research in Esparza, located in the province of Puntarenas in the Central Pacific zone of Costa Rica and in Matiguás, located in the department of Matagalpa in Northern Nicaragua. The selected farms participated in the Regional Integrated Silvopastoral Ecosystem Management Project (Silvopastoral Project) which has been financed by the Global Environmental Facility (GEF) to test the use of payments for environmental services (PES) as an incentive for the adoption of silvopastoral systems (Pagiola et al., 2004). Both regions present similar biophysical and agroecological conditions but differ significantly with regard to their infrastructure and socioeconomic characteristics of farm households. The ecological life zone of Esparza is classified as tropical sub-humid forest, and Matiguás is located in a zone in transition between tropical dry and humid forest. Average annual temperature is 27 °C, and the precipitation ranges from 1600-2000 mm in Matiguás and from 1800-2300 mm in Esparza, with a pronounced dry season from January to April. Parts of the project area comprise hilly terrain with slopes up to 50% where soils show signs of severe erosion caused by cattle grazing (Levard et al., 2002). Before the implementation of the Silvopastoral Project, the predominant land-uses in both project regions were degraded and naturalized pasture covering 40% and 60 % of the area in Esparza and Matiguás, respectively, followed by different types of forests including *tacotales* (local term for early stages of secondary forest succession), secondary and riparian forests, covering 22 and 28% in Nicaragua and Costa Rica, respectively (Ibrahim et. al., 2003).

The costs of converting naturalized pasture into silvopastoral and forestry systems

We construct income-expenditure profiles for representative one-hectare plots of treepasture systems, plantations of *Cordia alliodora* (laurel) and secondary forest regrowth to calculate the annual net income of each activity during a 30-year simulation period. In case of silvopastoral systems, treeless naturalized and improved pasture are converted into improved pasture with tree canopy covers from 15 to 45% at the end of the simulation period. Tree-naturalized pasture systems are not taken into account since we try to identify silvopastoral systems which present cost-effective opportunities to sequester carbon. A negative linear relationship between tree canopy coverage and the productivity of *Hyparrhenia rufa* even at low coverage reduces overall system productivity, whereas *Brachiaria brizantha* performs better under shade, shows a higher drought tolerance and a three times higher production of dry matter (Andrade et al., 2008). We use a growth model for laurel, a valuable timber species which reaches harvestable maturity in 25-30 years in the region, and we simulate its incorporation into pasture through natural generation which is a common practice among cattle farmers in Esparza and Matiguás. An evaluation of the effects of pasture management practices on natural regeneration of trees in project sites in Nicaragua identified laurel as the most abundant tree species in grazed pasture paddocks (Esquivel et al., 2008). Villanueva et al. (2007) found similar results in Esparza. Due to its abundance in the research region, the availability of extensive data on growth rates and crown diameters and a lack of data for other abundant tree species with similar growth patterns like *Tabebuia rosea* and *Cedrela odorata*, we use laurel as a cohort to simulate the natural regeneration of timber species in pasture under grazing.

To determine the costs and benefits of land-use changes, data from 80 farmers is used who participated in the Silvopastoral Project. The project conducted a quarterly monitoring during 3 years on 40 farms in both Costa Rica and Nicaragua to evaluate the socioeconomic performance and productivity of silvopastoral systems. Farmers' sources of revenues from tree-pasture system are sales of meat, milk and timber products including thinnings which can be sold as fence posts.

Costs include establishment costs of improved grassland and trees; cattle, tree and pasture management costs, administration costs and livestock opportunity costs. Opportunity costs occur (1) when a paddock has to be closed to establish the improved pasture and to permit natural regeneration; (2) at canopy cover percentages which reduce pasture availability to an extent that milk and meat yields fall below levels of naturalized and improved pasture without trees; (3) if inadequate management practices of improved pasture result in a productivity decline below the level of naturalized pasture. In case of the conventional pasture systems, farmers obtain revenues from cattle product sales and costs result from administration, pasture and cattle management. Point of departure for the establishment of forest plantations and secondary forest are naturalized pastures. Costs of the laurel plantation accrue for site preparation, planting and tree maintenance. Secondary forests are managed to facilitate the growth of valuable timber species and to obtain higher timber quality. Both forest alternatives derive revenues from the sale of timber products.

Net present values (NPV) are calculated and used as a criterion to compare the profitability of land-use alternatives. Although experience has shown that farmers' decisions regarding silvopastoral and forestry system adoption are much more complex, the financial viability of the investment in the new land-use is regarded as a decisive factor for both land-users and implementers of payment schemes for carbon sequestration. Hypothetical landowners who aim at maximizing farm profits are expected to adopt the land-use alternative if its net present value (NPVA) is higher than the one of the conventional pasture system (NPVC). In cases where the NPVA is lower than NPVC, payments for carbon sequestration have to be offered so that:

$$\sum_{t=0}^{T} \beta^t I + \sum_{t=0}^{T} \beta^t P - \sum_{t=0}^{T} \beta^t E - \sum_{t=0}^{T} \beta^t M > \sum_{t=0}^{T} \beta^t O \qquad [1]$$

where t is an index over time, E is the establishment cost for trees and improved pasture, M is the management cost for trees, cattle and improved pasture, O is the livestock opportunity cost, I are revenues from cattle and timber product sale, β is a discount factor, T is the project-investment period in years. We apply a discount rate of 10% but also test the impact of different rates on model outputs through a sensitivity analysis; the sensitivity analysis is also applied to vary the values of other parameters like milk, meat and timber prices in a range of 5% to 40%.

A regression analysis is developed to determine forage dry matter yields under varying shade levels and the carrying capacity and milk and meat production are adjusted accordingly. In locations with medium site qualities, laurel reaches harvestable maturity after 30 years, whereas the productive life of the improved pasture is estimated at 10 years. Thus we simulate 3 establishments of improved pasture resulting in a 30-year time horizon for our analysis. We simulate the impact of pasture degradation on animal productivity which is expected to start in the fourth year after pasture establishment and reduces meat and milk production by 5% annually.

Cost of carbon sequestration in selected land-use systems

Well managed silvopastoral systems have a higher annual biomass production than pasture ecosystems and combine pasture and forest nutrient cycles what often results in an overall higher C storage potential. Since aboveground forage biomass is periodically removed by grazing and no significant differences in belowground C in biomass of *H. rufa* and *B. brizantha* (Andrade, 2007) and in soil organic carbon (SOC) (Ruiz et al., 2004) have been determined, we presume in the case of silvopastoral systems that annual increments in the stock of total organic carbon (TOC) are the result of the incorporation of laurel into pasture. To determine the aboveground C storage in laurel, we use an equation [2] on the basis of the stem diameter at breast height (dbh) which has been developed for local sites. The equation is used for Esparza and Matiguás since both sites present similar biophysical and climatic conditions;

$$Ba = 10^{(-0,51+2,08*Log\ (dbh))} \qquad [2]$$

where *Ba* is the aboveground biomass of trees, *dbh* is the diameter at breast height of trees (measured 130 cm above ground). We further use an equation [3] provided by the IPCC (2003) to estimate C in belowground biomass,

$$Br = e^{(-1,0587\ +\ 0,88*Ln\ (Ba))} \qquad [3]$$

where *Br* is the belowground biomass of trees, *Ln* is the natural logarithm. SOC stocks of several representative land-use systems have been measured in different project sites of the Silvopastoral Project. Soil samples were taken at four depth intervals (0-10, 10-20, 20-40 and 40-100 cm) and were analyzed for soil C and N, bulk density, texture, pH and indices of soil mineralogy (Ibrahim et al., 2005). However, there is not enough data available to reconstruct the annual SOC accumulation pattern for the land-use systems in focus over a 30-year period. Due to the complexity of component interactions and a lack of data on the long-term C stock changes after establishment of silvopastoral and forestry systems on pastureland, simplifying assumptions have to be made for the purpose of this study. Land-use changes take place on old naturalized pastures (> 20 yr) which have constant C stocks during our 30-year simulation. We also use secondary data to be able to consider SOC in our accounting procedure and assume an annual increase of 0.5 MgC ha-1 for both silvopastoral and forestry systems (Hamburg, 2000) which seems to be a good approximation compared with the C stock changes which have been determined in the research region (Zamora, 2006).

For carbon accounting we apply the rules established for afforestation and reforestation (A/R) project activities in the Clean Development Mechanism (CDM) of the Kyoto Protocol which are also adhered to by other carbon offset standards of the voluntary carbon market (Merger, 2008).

We select a hypothetical issuance of temporary Certified Emission Reductions (tCER) which are temporary carbon credits generated for CDM sink projects. tCER for A/R project activities are issued at the end of a respective commitment period and expire at the end the following period.

Verification and certification of the project activity must be carried out every 5 years until the end of the crediting period. Project participants can choose between a crediting period of 20 years which can be renewed twice or a 30 year period with no option for further extension. Once tCER expire, owners have to replace them or have to find permanent solutions to comply with their emission reduction obligations. CDM project activities generate the tradable commodity CO2e which are the basis for the calculation of tCER, therefore we multiply our MgC values with the conversion factor 3.667. Following the temporary accounting approach, tCER are calculated based on the discounted net C accumulation of each commitment period. The issuance of credits starts in year 5 for the cumulative carbon stored since the beginning of the project activity and is followed by 4 more commitment periods before the final timber harvest takes place in year 30. Expiring credits can be reissued in a following period if the sequestered C remains in the land-use system, i.e. C sequestered during the years 0-5 can potentially be credited 5 times, C accumulated during the years 20-25 only once. We determine the minimum price per tCER which would have to be offered to cattle farmers as a compensation for revenue losses due to silvopastoral or forestry system adoption:

$$P_{tCER} = \frac{NPV_C - NPV_A}{\sum \beta^t tCER} \qquad [4]$$

CER prices are assumed to be constant during the entire crediting period. Equation [4] evinces that the price for tCER is determined by opportunity costs, net revenues generated by the alternative land-use, the cumulative amount of C sequestered during the project activity and the selected discount rate.

Results and discussion

Animal performance under shade

To allow for the natural regeneration of *Cordia alliodora*, we simulate the closure of paddocks for two years and adopt management practices recommended by Camargo et al. (2000) and Andrade et al. (2008). Camargo analyzed the dynamics of natural generation of laurel on grazing land in two ecological zones of Costa Rica and found an average of 1600 trees in the growth stage of seedlings (0.1 m > height ≤ 0.3 m), 547 saplings (0.3 m > height ≤ 1.5 m) and 265 poles/young trees (> 1.5 m of height and < 5 cm dbh) on one hectare pasture plots. We consider adequate stocking rates to help reduce damages from cattle trampling and browsing as well as selective weed control practices to prevent damages or the elimination of trees. At the re-opening of the paddock for grazing in the third year after the incorporation of laurel, 265 young trees remain on the paddock and for the following years, the point in time and frequency of thinnings are varied according to the desired final canopy cover levels. In the first scenario, the canopy cover increases from 0 to 15% based on the findings that this level of coverage does not affect cattle productivity.

In the following scenarios, final coverage is increased by 10%, respectively. On medium-quality sites with canopy cover ranging from 15 to 45%, 25 to 85 trees remain in the stand at the end of the 30-year rotation; about 5 trees are left on the paddock to facilitate the next cycle of natural regeneration. Annual average dry matter production of pasture without trees is 18.3 Mg ha-1yr-1 for improved and 5.4 Mg ha-1yr-1 for naturalized pasture which has a lower dry matter production during the dry and wet season (Andrade, 2007). Tree shadow starts to show a positive impact on animal production at a canopy cover of 20% resulting in an increase of 6 and 10% in milk and meat yields, respectively (Table 1).

Table 1. Stocking rates and cattle productivity under different percentages of canopy cover

	Costa Rica			Nicaragua		
Land-use system[a]	Cattle stock[b] (AU ha^{-1})	Milk production (l ha^{-1} yr^{-1})	Meat production (kg ha^{-1} yr^{-1})	Cattle stock (AU ha^{-1})	Milk production (l ha^{-1} yr^{-1})	Meat production (kg ha^{-1} yr^{-1})
NP	0.60	600	105	0.80	500	68
IP	1.30	1150	182	1.60	900	120
IP + 10% CC	1.30	1150	182	1.60	900	120
IP + 20% CC	1.25	1173	193	1.54	918	127
IP + 30% CC	1.06	840	163	1.30	657	108
IP + 40% CC	0.77	495	133	0.95	387	87

[a] Naturalized pasture (NP); improved pasture (IP), canopy cover (CC)
[b] One animal unit (AU) equals 450 kg of cattle

At a canopy cover of 30%, lower availability of forage dry matter results in a reduction of the stocking rate of 18.5% whereas milk and meat production decrease 27 and 10%, respectively. Shade levels of 40% significantly reduce milk production by 57% and meat production by 27%.

Cost and benefits of land-use alternatives

Farmers in the municipality of Esparza receive about US$ 0.38 l-1 of milk and US$ 1.18 kg-1 of meat; the average stumpage price per m3 of laurel is US$ 77 (ONF, 2008). To compensate the shortage and quality loss of forage biomass during the dry season (December to April), farmers use supplements like concentrates, chicken manure or fodder banks, e.g., with leguminous shrubs like *Cratylia argentea* or *Leucaena leucocephala*. In our model, 5 kg of chicken manure are offered daily per AU during a 120 day period at a cost of US$ 0.08 kg-1. We assume that activities related to cattle management, pasture and tree establishment and management, are paid according to the local prevailing wage which is US$ 10.30 per man-day. In the Matiguás, animal productivity is lower mainly due to a lack of supplementation during the dry season. Prices oscillate around US$ 1.08 kg- 1 of meat and around US$ 0.30 l-1of milk; the stumpage price for laurel per m3 is US$ 65 (Rodriguez, *pers. comm.*, 2008). The average wage for hired labor is US$ 3.10 per man-day.

Establishment costs for one ha of *Brachiaria brizantha* sum up to US$ 183 in Nicaragua and US$ 316 in Costa Rica, including costs of labor and materials for land preparation and seeding. The incorporation of laurel into improved pasture through natural regeneration increases establishment costs by 16% and 24% in Nicaragua and Costa Rica, respectively. Annual per-hectare opportunity costs of US$ 122 in Esparza and US$ 107 in Matiguás have to be added resulting from the closure of paddocks for two years during the early growth stages of laurel. At canopy cover levels above 20%, opportunity costs also result from a decrease of animal productivity due to lower pasture availability (Figure 1).

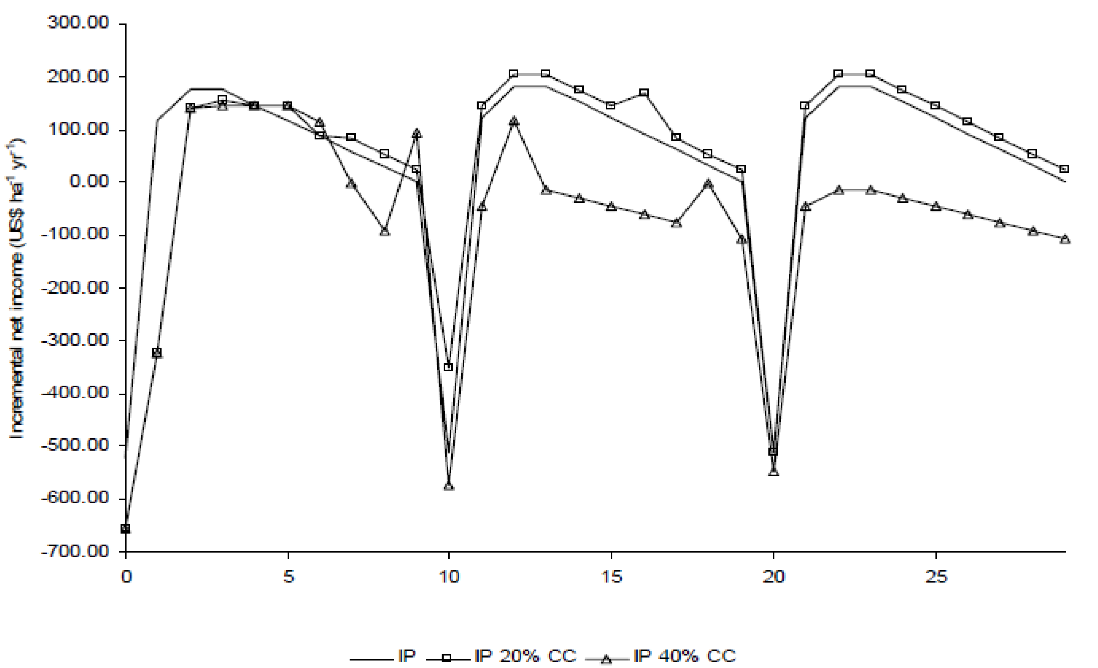

Fig. 1. Incremental net income resulting from the change of naturalized to improved pasture with and without trees on dual-purpose farms in Costa Rica

Additional maintenance costs for silvopastoral systems mainly arise during the first 4 years for manual weed control and formation pruning. The average annual maintenance and management costs of the different tree-pasture systems vary from US$ 254 to 334 in Costa Rica and from US$ 109 to 151 in Nicaragua. Establishment costs and the present value of management costs of a onehectare plantation of laurel amount to US$ 1200 in Esparza and US$ 750 in Matiguás. Management activities of secondary regrowth on abandoned pasture plots involve liberation thinnings to encourage the growth of commercial tree species like *Cordia alliodora*, *Cedrela odorata* and *Tabebuia rosea*; the present value of the management costs which accrue over a 30-year period is US$ 447 ha-1 in Esparza and US$ 134 ha-1 in Matiguás.

The annual net revenues from improved pasture are similar in both countries since farmers in Nicaragua can compensate lower animal productivity and prices for meat and milk through 70% lower wages for hired labor. During its productive life of 10 years, *Brachiaria brizantha* generates an average annual net income of US$ 198 and US$ 219 to Nicaraguan and Costa Rican farmers, respectively. For a comparison of the profitability of land-use systems if revenues of timber product sale are considered, the annual net income of each system is converted into NPV (Table 2).

Table 2. Net present value (NPV) (in US$ ha-1) of land-uses systems adopted on dual purpose farms in Esparza and Matiguás

	NPV (US$) (treeless pasture)		NPV (US$) (silvopastoral systems)				NPV (US$) (forestry systems)	
Land-use system	Naturalized pasture (NP)	Improved pasture (IP)	IP +10% NR	IP + 20% NR	IP+ 30% NR	IP + 40% NR	Secondary forest	Forest plantation
Costa Rica	1149	1462	1032	1313	1098	816	(1250)	(1451)
Nicaragua	1006	1480	1250	1432	1220	1011	(859)	(1012)

Tree-pasture systems with canopy cover levels from 15-45% produce about 21 to 85 m3 ha-1of timber in a 30-year period; laurel plantations produce 200 m3 ha-1 of timber.

Payments for carbon sequestration in silvopastoral systems

The average net increase in the stock of TOC of the selected land-use alternatives ranges from 83 tCO2 ha-1 in improved pasture with 10% of canopy cover to 278 t CO2 ha-1 in secondary forest at the end of the 30-year simulation. In Nicaragua, land-use changes from naturalized pasture to improved pastures with canopy levels from 10 to 40% are profitable without C payments whereas in Costa Rica only changes to pasture with 20% tree coverage do not need compensation for forgone revenues from livestock product sale (Table 3). Minimum prices per tCER for silvopastoral system establishment range from US$ 0.8 to US$ 12 per tCER; in the case of forestry alternatives, compensation payments from US$ 11.4 to US$ 25.5 are necessary.

Table 3. Minimum compensation payments for carbon sequestration in land-use alternatives adopted on farms in Esparza and Matiguás

Land-use change on NP	Net C accumulation	Costa Rica	Nicaragua	Land-use change on IP	Net C accumulation	Costa Rica	Nicaragua
Adopted land-use system	$tCO_2 ha^{-1}$	US$ tCO_2^{-1}	US$ tCO_2^{-1}	Adopted land-use system	$tCO_2 ha^{-1}$	US$ tCO_2^{-1}	US$ tCO_2^{-1}
IP + 10% CC	83	2.6	x	IP + 10% CC	83	12.0	7.3
IP + 20% CC	104	x	x	IP + 20% CC	104	4.3	2.4
IP + 30% CC	126	0.8	x	IP + 30% CC	126	7.4	5.6
IP + 40% CC	147	4.5	x	IP + 40% CC	147	10.1	7.6
Secondary Forest	278	14.7	11.4				
Forest Plantation	268	25.5	19.8				

A sensitivity analysis is carried out to test the impact of changes of milk, meat and timber prices and the discount rate on minimum tCER prices. In both countries, prices for C storage in silvopastoral systems are very sensitive to changes of milk and – to a minor degree – of meat prices (Figure 2).

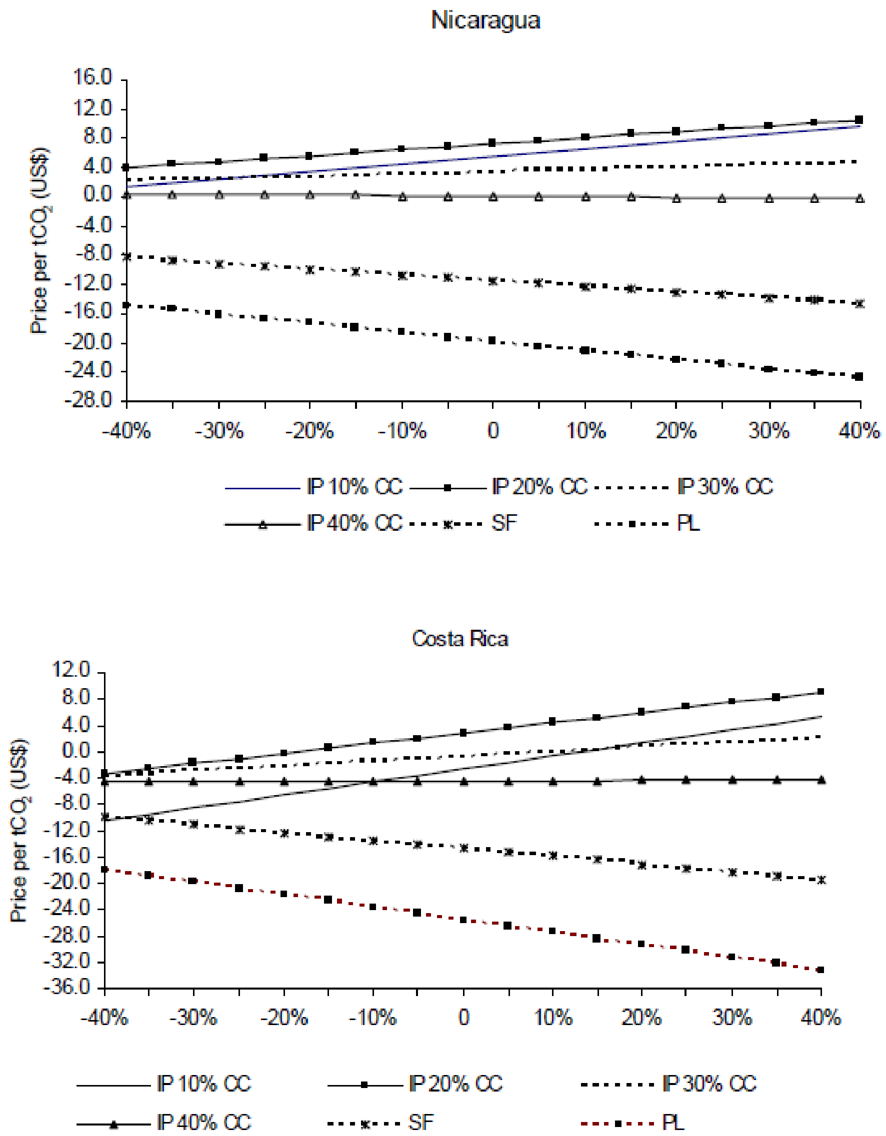

Fig. 2. Prices per tC02 sequestered in silvopastoral and forestry systems under different milk price scenarios

Nevertheless, in Nicaragua land-use changes which do not require C payments are less affected by product price changes than changes carried out in Costa Rica. Even with price variations of 40%, the establishment of improved pasture with up to 30% of tree canopy coverage remains profitable without payments; only at 40% coverage a minimum tCER price of US$ 0.1 would be necessary if a product price change of 10% occurred.

Conclusions

This study reveals that silvopastoral systems present a cost-efficient opportunity to sequester carbon – and its exploitation appears to be interesting and urgent in many respects. A comparison of tCER prices for silvopastoral systems indicates that the increase in system productivity resulting from a change of naturalized to improved pasture is an important factor for low costs of C sequestration or even sequestration which does not require compensation payments. The apparent increase in productivity might be a strong economic incentive itself for silvopastoral system adoption in particular for farmers who use naturalized pasture-based feeding strategies without additional supplementation. If trees are incorporated into already established improved pasture, economic benefits from shade and additional revenues from timber sale are significantly lower than the benefits resulting from a switch from *Hyparrhenia rufa* to *Brachiaria brizantha* therefore C payments are necessary for all levels of canopy cover. tCER prices for both forestry alternatives are high compared to prices for C sequestration in silvopastoral systems indicating high opportunity costs of cattle production in both countries. Secondary forests sequestered C at lower costs than forest plantations which require high establishment costs and more intensive management. But higher compensation payments for forestry systems certainly do not imply that these land-use alternatives have to be discarded as an option for C sequestration on cattle farms. A key to low-cost C sequestration appears to be a mix of productivity enhancing and intensifying measures as well as targeted incentives to induce the adoption of silvopastoral and forestry systems.

Our models simulate pasture establishment and management as they are actually carried out by cattle farmers in Matiguás and Esparza. Current practices often fail to exploit the full production potential of improved pasture what is indicated by the decline of milk and meat yields a few years after pasture establishment. The provision of technical assistance to farmers regarding adequate establishment and management practices of silvopastoral systems could not only increase their revenues from livestock and timber product sales but also lower the per ton prices of compensation payments. In addition, a productivity increase paired with economic incentives for C sequestration might encourage farmers to abandon some pasture paddocks for the establishment of forestry systems. The establishment of silvopastoral systems on naturalized pasture in more advanced stages of degradation than the pastures simulated for our scenarios would result in even more pronounced benefits in form of income increases and soil C accumulation. This demonstrates the importance of selecting sites for silvopastoral and forestry system establishment with low opportunity costs and a high C accumulation potential to be able to compete on carbon markets as cost-efficient solutions for C sequestration. Low adoption rates of silvopastoral systems suggest that farmers with little capital for investments might not respond to long-term C payments since they do not resolve the problem of a lack of immediate cash to cover establishment and opportunity costs which arise due to the paddock closure to allow for natural regeneration. Access to credits to cover establishment costs paired with technical assistance to secure adequate silvopastoral establishment might be a better fit for an incentive which could be issued with the requirement to maintain trees with 20% of canopy coverage on pasture paddocks. Compensation payments for C sequestration appear to be an interesting instrument to encourage the establishment of forest plantations and secondary forest on dual-purpose farms, especially on paddocks which can be taken out of the grazing cycle due to the intensification of the production through the establishment of improved pasture. In a next step our per-hectare models have to be extended to the farm level to consider all relevant socio-economic and environmental aspects which are necessary for the design of sustainable silvopastoral systems and efficient and effective instruments to compensate cattle farmers for the provision of environmental services.

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