Tree-crop interactions and their environmental and economic implications in the presence of carbon-sequestration payments[1]

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Abstract

Growing trees with crops has environmental and economic implications. Trees can help prevent land degradation and increase biodiversity while at the same time allow for the continued use of the land to produce agricultural crops. In fact, growing trees alongside crops is known to improve both the productivity and sustainability of the land. However, due to high labour-input requirements, high costs of establishment, and delayed revenue returns, trees are often not economically attractive to landholders. Because of the Kyoto Protocol, and the growing emphasis on market-based solutions to environmental problems, the ability of trees to sequester and store CO_2 has altered the economic landscape of agroforestry systems. The economic and management implications of carbon-sequestration payments on agroforestry systems are addressed in this study using a bioeconomic modelling approach. An agroforestry system in Indonesia is simulated using a biophysical process model. A general economic analysis of this system, from the standpoint of individual landholders, is then developed and the implications for management and policy are discussed.

Keywords: agroforestry, bioeconomics, tree/crop interactions, carbon credits, baselines

1. Introduction

The Kyoto Protocol (KP) recognizes that land-use activities provide cost-effective opportunities to reduce net greenhouse-gas emissions by acting as carbon sinks and can therefore "contribute to the transition to a lower emissions environment" (Brown *et al.*, 2001; Marland *et al.*, 2001).

The KP also allows for emissions trading. The Clean Development Mechanism (CDM), for example, allows Annex I countries to invest in and develop emission-reduction activities such as afforestation and reforestation in non-Annex I countries and to use the reductions against their own commitments[2]. Examples of activities that sequester and store carbon which could then be traded as Certified Emission Reductions (CERs) are forests and agroforests.

[1] This research was funded by the Australian Centre for International Agricultural Research (ACIAR) under project ASEM 1999/093 (http://www.une.edu.au/febl/Econ/carbon/).

[2] Annex I lists the 34 countries (developed countries and countries with economies in transition to a market economy) that submitted their first national communications on or before 11 December 1997. Non-Annex 1 countries includes all developing countries not included in this list.

Agroforests are land-use systems where trees, crops and/or livestock are grown in close proximity to each other. Growing trees with crops and livestock or rotating crops with trees have been observed to enhance crop yields, improve soil quality, and recycle nutrients while simultaneously producing subsistence and marketable outputs such as firewood, fodder, fruit and timber. Also, the growing of trees increases the potential to sequester and store carbon, which, in the presence of carbon sequestration payments, adds to the number of marketable outputs being produced. Hence, agroforests are a way of maintaining or enhancing land productivity, sustainability and profitability in the medium to long term. However, when trees and crops grow in close proximity to each other they do not always interact in positive (complementary) ways, they may often interact in negative (competitive) ways too.

Complementary interactions between and within crops and trees can occur when pruned tree biomass is added to the system. This leads to microclimatic changes on the soil surface (which affects decomposition rates), weed suppression prior to litter decomposition and increased soil-nutrient levels as the biomass decomposes. Along with the benefits listed above, growing/rotating trees with crops is also known to control erosion and enhance biodiversity (Hairiah *et al.,* 1992). All these benefits, however, are only realized if nutrient outtake is balanced by nutrient input via litter and the strategic use of fertilizers, particularly phosphorous (Sanchez, 1995). Competitive interactions, on the other hand, occur when soil nutrients, water or sunlight are limited and when the growth rates (demand for inputs) of the crop and tree components reach their maximum simultaneously. In the humid tropics, for example, where moisture is not expected to be limiting but fertility may be, trials still show a major competition effect, presumably because of competition for light and nutrients (Sanchez, 1995). Interestingly, most of the successful examples of agroforestry have come from high-potential environments, where water or nutrients were not major limiting factors (Sanchez, 1995).

Two types of agroforestry systems are currently practiced in Indonesia and other developing countries. The first, *simultaneous* agroforestry, is where the tree and crop components grow at the same time and in close enough proximity for interactions to occur (Sanchez, 1995). Examples of this type include alley cropping, contour hedges and homegardens (Nelson *et al.*, 1998; Roshetko *et al.*, 2002). The second, *sequential* agroforestry, is where the maximum growth rates of the crop and the tree components occur at different times even though both components may have been planted at the same time and are in close proximity (Sanchez, 1995). Examples of this type are shifting cultivation, improved fallows, and some multi-strata systems (Tomich *et al.*, 1998; Grist *et al.*, 1999b; Menz and Grist, 1999; Palm *et al.*, 1999). It is worth noting that the former can be transformed into the latter when, for example, the trees in an alley-cropping system are allowed to grow into a fallow and cropping is discontinued (Sanchez, 1995).

In this study we consider only the alley-cropping system. This system involves planting food crops in alleys in-between hedgerows or regularly pruned trees or shrubs. Many factors affect alley-cropping performance: the choice of tree species and crop species, alley width, biomass production, number of crop cycles, time and frequency of pruning, tillage, fertilization and weed dynamics. Alley-cropping systems are successful only in limited and very site-specific circumstances because competition between the different components often exceeds the beneficial, complementary effects. Necessary conditions for alley-cropping systems to succeed include: the soil must be fertile, there must be adequate rains during the cropping season, the land must be prone to erosion, an ample supply of labour coupled with a scarce supply of land must exist, and land tenure must be secure (Sanchez, 1995).

This paper presents an economic model of a privately-owned agroforestry system on a smallholding in Indonesia. The agroforest is represented by one tree species (*Gliricidia sepium*) and one agricultural crop (Maize). The economic model is combined with a biophysical simulation model to analyse the productivity[3] and profitability effects of growing trees and crops together in the medium to long term. The effects of carbon sequestration payments on the profitability and management of the system are investigated. The sensitivity of the system to changes in both economic and biophysical variables is then analysed. The paper concludes with implications for policy and management.

2. The economic model

This section presents a general economic model of a forest cycle starting with bare ground and including carbon-sequestration payments. The model is based on that developed by Cacho (2001) to estimate the optimal land allocation between forestry and agriculture in a watershed experiencing dryland salinity. The profit function in this paper extends Cacho's model by including carbon-sequestration payments and carbon-monitoring costs.

The profit function faced by a landholder for a given area A over a planning horizon of T years is:

$$V(T,k,x) = [A-k]\sum_{t=0}^{T}\left[y_t(k,x)\cdot p_y - c_y\right]\delta^{-t}$$

$$+k\sum_{t=0}^{T}\left[h_t(k,x)\cdot p_h \cdot c_h\right]\delta^{-t} - c_E + V_C(T,k,x) \qquad (1)$$

V is the profit per hectare obtained by the owner of the agroforestry system using the discount factor $\delta = 1+r$ for the discount rate r. The decision variable k is the area planted to trees ($0 \le k \le A$) and x is a vector of management variables. The establishment costs are c_E. The first term on the right-hand side of (1) is the present value of the cropping area ($A-k$); y_t is the annual crop yield, p_y is the price of the crop and c_y is the variable cost of producing the crop. The second term is the present value of the tree harvest; h_t is the yield of wood harvested, p_h is the price of wood and c_h are the variable costs of harvesting the wood. The last term is the present value of carbon-sequestration payments defined as:

[3] Measured in terms of tree-biomass accumulation, firewood production and maize yields

$$V_C(T,k,x) = k\sum_{t=0}^{T}\Delta b_t(k,x)\cdot p_C\cdot\delta^{-t} + A\sum_{t=0}^{T}\left[\Delta s_t(k,x)\cdot p_C - c_M\right]\delta^{-t} \qquad (2)$$

where, Δb_t and Δs_t are the annual changes in biomass carbon in trees and soil carbon respectively; p_C is the price of carbon and c_M are annual carbon-monitoring costs. The changes in soil and biomass carbon are dependent upon biophysical processes and management regimes. These dynamics are presented and discussed by Wise and Cacho (2002). Both Δb_t and Δs_t can have negative values when more CO_2 is released than sequestered. This occurs particularly at final harvest.

The optimal area of trees for a given rotation length *T*, can be determined by maximising equation (1) with respect to *k*. The economics of forestry and estimation of the optimal forest cycle (the Faustmann model) are well covered in the literature and are not reviewed here. A single cycle is evaluated in this study because this is the relevant measure at the project level, where it cannot be guaranteed that the land will remain in the same use in perpetuity. So this is a financial analysis, rather than a fully-costed economic analysis.

3. Method

3.1 The agroforestry system

The system modelled in this study is based on the hedgerow intercopping systems simulated by Sitompul *et al.* (1992), Nelson *et al.* (1998), and Magcale-Macandog *et al.* (1999). In these systems, annual crops are cultivated between contoured hedgerows of perennial shrubs or tree species, usually legumes. Examples of trees typically used as hedgerows in Indonesia are *Gmelina, Gliricidia sepium, Leucaena leucocephala, Paraserianthes falcataria* and *Peltophorum pterocarpa*. *Gliricidia sepium* was chosen for this study because it meets many of the criteria of a successful agroforestry tree species[4] and because the WaNuLCAS model (van Noordwijk and Lusiana, 1999) has been parameterized for this species. Desirable features of this species include: it can be grown from cuttings which makes it easy to establish, it is tolerant of acid soil conditions, it grows very quickly, it is nitrogen-fixing and therefore recycles nitrogen through the system and produces mulch with high nutrient values, it also produces several outputs (commercial and subsistence) such as firewood, fencing, mulch and fodder (Hairiah *et al.,* 1992).

Annual crops typically cultivated between hedgerows include maize, soybean, mucuna (velvet bean), cassava and rice. These can be grown as multiple-crop rotations such as the maize-soybean-mucuna rotation presented by Sitompul *et al.* (1992) or as single-crop rotations such as that discussed by Nelson *et al.* (1998). The crop chosen for this study was maize, as WaNuLCAS is already parameterized for this crop. The model involves simulating the growth of two maize crops per year, between *Gliricidia* hedgerows, over a

[4] See Grist *et al.* (1999b) and Stewart (1996) for examples of where *Gliricidia sepium* has been successfully grown as an agroforestry tree species and the reasons why it was successful.

25-year rotation. The *Gliricidia* trees are grown at a planting density of 5,000 trees per hectare and are fully harvested after 25 years.

Preparing a hedgerow intercropping system involves removing existing vegetation, usually by burning (Tomich *et al.*, 2002, p. 132), and ploughing the site. Establishing the hedgerows involves constructing bunds (laying out the hedgerows), collecting and planting cuttings, and weeding. Establishing the maize-crop component involves preparing the land between the hedgerows, sowing and fertilizing maize seeds at planting, replanting of maize seeds to replace dead seedlings, and inter-row and hand weeding. These activities need to be done biannually – once each for the wet- and dry-season crops.

In practice, maize crops are fertilized using nitrogen, TSP and KCL (Sitompul *et al.*, 1992; Nelson *et al.*, 1998). In this study, however, no fertilizers are applied so the effect of tree residues on land productivity can be determined. To enhance nutrient recycling, pruning is done frequently. Pruning is simulated in WaNuLCAS based on canopy density, where pruning only occurs when the total tree leaf area index (LAI) exceeds a user-defined critical value. Harvesting the pruned material involves removing a predefined percentage of the pruned wood, twigs and leaves from the system.

To determine the possible effects that growing trees with crops might have on land productivity, the relative area planted to trees and crops was varied by modelling increasing areas planted to trees relative to crops. For convenience, A was set to 1.0, so $0 \leq k \leq 1$ and results are expressed per hectare of land-use system (LUS).

The area planted to trees was increased at intervals of 0.1 resulting in 11 scenarios. Each of these scenarios was then replicated under three harvest regimes: low (25%), medium (50%) and high (100%). Consequently, 33 scenarios were simulated. The different combinations of tree/crop area and harvest regime are detailed in Table 1.

Table 1: Scenarios simulated in WaNuLCAS

Tree Area	*Crop area*	*Pruning*	*Harvest (%)*		
(k)	$(A-k)$	*(%)*	L	M	H
0	1	0	25	50	100
0.1	0.9	50	25	50	100
0.2	0.8	50	25	50	100
0.3	0.7	50	25	50	100
0.4	0.6	50	25	50	100
0.5	0.5	50	25	50	100
0.6	0.4	50	25	50	100
0.7	0.3	50	25	50	100
0.8	0.2	50	25	50	100
0.9	0.1	50	25	50	100
1.0	0	50	25	50	100

The scenarios listed in Table 1 are referred to by the area (k) planted to trees and an H, M or L indicating whether the harvest regime is 100%, 50% or 25%. For example 'k = 0.5H' represents the situation where 50% of the total area is planted to trees and 100% of the pruned material is harvested. The pruning regime and initial soil-carbon level were held constant for all scenarios at 50% and 16.21 Mg C ha^{-1}, respectively. The initial soil-carbon value falls at the lower end of the range of soil-carbon values recorded for soils in Sumatra, Indonesia (Delaney and Roshetko, 1999).

In WaNuLCAS, a hedgerow intercopping system is simulated by dividing the total area into four zones and growing the *Gliricidia* trees in zones 1 and 4 and the maize crops in zones 2 and 3. When the entire area is dedicated to growing maize, zones 1 and 4 are set equal to zero. As the maize area is converted to *Gliricidia*, zones 1 and 4 are enlarged incrementally and zones 2 and 3 are made smaller by the same magnitude. This is done until the entire area is dedicated to growing *Gliricidia* i.e. when zones 1 and 4 each comprise 50% of the total area and zones 2 and 3 take up 0% of the area.

WaNuLCAS simulates the growth of maize and *Gliricidia* and generates many outputs. The outputs of most relevance to this study include: harvested tree biomass or firewood (h_t), crop yield (y_t), standing biomass, standing biomass carbon (SBC) and soil carbon.

The annual changes in soil carbon (s_t), biomass carbon (b_t), harvested biomass (h_t) and maize-crop yield (y_t) obtained from each 25-year simulation were inserted into equations (1) and (2) and net present values were calculated using the base-parameter values presented in Table 2.

Table 2. Base parameter values

Parameter	Value	Units	Description	Source
p_h	45,000	Rp Mg^{-1}	firewood price	a
p_C	150,000	Rp Mg^{-1}	price of carbon	e
p_y	300,000	Rp Mg^{-1}	price of maize	d & f
p_S	2,350	Rp kg^{-1}	seed price	d
r	15	%	discount rate	b & d
C_L	6,000	Rp day^{-1}	price of labour	e
CM_t	10,000	Rp ha^{-1} yr^{-1}	annual carbon measuring costs	g
C_E	480,000	Rp	hedgerow establishment costs	c
Lanp	1	days Mg DM^{-1}	labour required to prune	c
Lanh	0.5	days Mg DM^{-1}	labour required to harvest	c
phw	80	%	% harvest sold as firewood	
η	0.42	-	carbon content of wood	d

Sources: a: CESERF (1999), b: midway between the 10% used by Menz and Magcale-Macandog (1999, p. 10) and the 20% used by Tomich *et al.* (1998, p. 63), c: adapted from Grist *et al.* (1999b), d: van Noordwijk and Lusiana (2001), e: Grist *et al.* (1999a) use \$US 5, \$US 10 and \$US 20 MgC^{-1}, f: Wayan Rusastra *et al.* (1999, p.152), g: Cacho, Wise and MacDicken (2002)

3.2 Time-averaged carbon stocks and baselines

The time-averaged carbon stock for each scenario *i* of the project (TAC_i^p) is calculated by summing the annual stock of carbon, C_t, for each scenario *i* and dividing by the duration of the project (T), for example:

$$TAC_i^p = \frac{\sum_{t=1}^{T} C_{it}}{T} \quad (3)$$

C_{it}, the annual stock of carbon for scenario *i* at time *t,* may represent the biomass carbon (b_t), soil carbon (s_t) or total carbon ($b_t + s_t$), depending on the quantity of interest.

The time-averaged carbon stock provides a simple measure to compare different scenarios in terms of their capacity to sequester carbon, but it does not reflect any differences in the time paths of biomass accumulation.

Only carbon over and above that which would have been sequestered without the carbon project is certifiable as an emission reduction and eligible for sale in a carbon market. Therefore, it is necessary to determine a baseline carbon stock with which carbon changes directly attributable to the carbon project may be compared. Two baselines have been identified: a *static* baseline where it is assumed that the carbon stock of the previous land use remains constant through time, and a *dynamic* baseline where the carbon stock of the previous land use varies through time. The former may represent an *Imperata* grassland that contains a stable level of soil carbon and the latter represents a bi-annual maize-cropping system with no fertilizer inputs. The time-averaged total carbon stock of each scenario, relative to each baseline[5], is therefore calculated as:

$$TAC^e{}_{ij} = TAC^p{}_i - TAC^b{}_j \quad (4)$$

where, $TAC^e{}_{ij}$ represents the 'eligible' time-averaged total carbon stock for scenario *i* relative to the previous land-use type (baseline) *j;* $TAC^p{}_i$ is the time-averaged carbon stock of the 'with-project' scenario *i*, and $TAC^b{}_j$ represents the time-averaged carbon stock of the previous land-use type (baseline) *j*. The first term on the right hand side is explained above, and in this case C_{it} is the annual, total carbon stock ($b_{it} + s_{it}$). The second term on the right hand side is the time-averaged total carbon stock of the baseline *j*, and is calculated by summing the annual soil (s_{jt}) and biomass (b_{jt}) carbon stocks for the previous land-use system, *j*, and dividing by the number of years, *T*, in the planning horizon:

$$TAC^b{}_{ij} = \frac{\sum_{t=1}^{n} s_{jt} + b_{jt}}{T} \quad (5)$$

The time-averaged soil-carbon stock under *Imperata* is assumed to be 16.21 Mg C ha^{-1} and the time-averaged biomass-carbon stock of *Imperata* grass is taken as 0.7 Mg C ha^{-1} (Roshetko *et al.*, 2002), hence the total $TAC^b{}_j$ for the static baseline is 16.91 Mg C ha^{-1}.

[5] Henceforth, the term 'time-averaged total carbon stocks relative to baseline' will be referred to as 'eligible carbon stocks'.

The *dynamic* baseline is calculated as the time-averaged carbon stock of the WaNuLCAS-simulated scenario 1 (tree area, $k = 0$) and equals 12.32 Mg C ha^{-1}. This scenario only includes the soil-carbon stock. Biomass carbon is not included in this baseline because the maize crops are harvested annually and therefore all the biomass is assumed to be removed annually.

4. Biophysical results

This section presents some biophysical results obtained from the WaNuLCAS model.

4.1 Standing biomass carbon

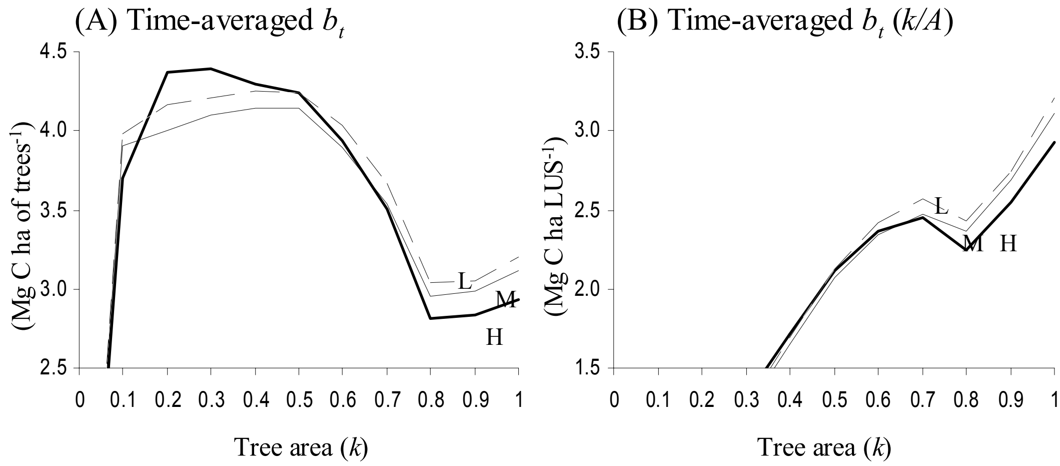

Figure 1. The effect of tree area on average standing biomass; (A) carbon per hectare of trees; (B) carbon per hectare of land-use system (LUS), under high (H), medium (M) and low (L) harvest regimes.

For all harvest regimes, average standing biomass carbon (SBC) per hectare of trees (Mg C ha^{-1}) increases as k increases, but only up to $k = 0.4$ for low and medium harvests and up to $k = 0.3$ for high harvests (Figure 1A). Further increases in k cause average carbon stocks to decrease. The decrease is caused by increased competition between trees for nutrients and light. This is particularly relevant at high harvests where no nutrients are being returned to the system.

The pattern described above, combined with increasing proportions of the farm planted to trees, results in increasing carbon stocks per hectare of land-use system (LUS) up to about k=0.7 (Figure 1B).

Beyond k=0.8 there are increases in the carbon stocks both per hectare of trees (Figure 1A) and per hectare of LUS (Figure 1B). This seems to be caused by increased productivity as the lower area of crop decreases competition for nutrients. However, values of k beyond 0.8 may not be desirable by landholders with small plots and who need to produce food for home consumption. So the model results with $k > 0.8$ do not cause much concern; particularly in view of the economic results presented later, which indicate that the optimal value of k is always below 0.2.

4.2 Soil carbon

Average soil-carbon stock increases dramatically as k increases from 0 to 0.1 ha and then remains relatively constant as k increases further (Figure 2). For high harvests, the soil-carbon stock reaches its highest level when $k = 1.0$ and involves an increase of 3% compared with the crop-only scenario ($k = 0$). For medium and low harvests, the soil-carbon stock reaches its highest level at $k = 1.0$ ha and $k = 0.5$ ha, respectively. These involve increases in soil carbon of 14% (from 11.85 Mg C ha^{-1} to 13.79 Mg C ha^{-1}) for medium harvests and 19% (from 11.85 Mg C ha^{-1} to 14.60 Mg C ha^{-1}) for low harvests.

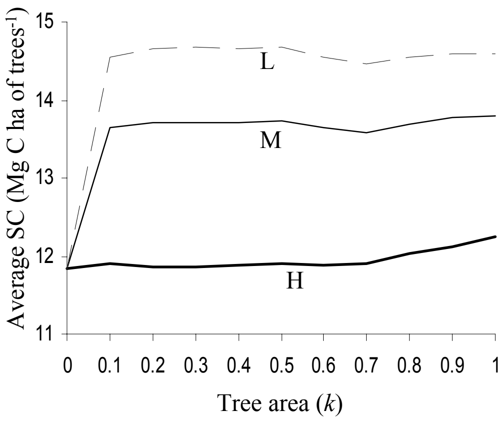

Figure 2: Average soil-carbon stock (s_{it}) per hectare of trees, under three harvest regimes.

For low and medium harvest regimes, most of the increase in soil carbon occurs when tree area (k) increases from zero to 0.1. Soil-carbon changes are heavily dependent on the amount of residue inputs available, which is a function of the amount of standing biomass produced. Consequently changes in soil carbon reflect the pattern of SBC production discussed above. Soil-carbon stock, as expected, is inversely related to harvest regime. At high harvests soil-carbon stock is low and it gets progressively larger as harvest regime decreases (Figure 2).

4.3 Harvested tree biomass

The output of harvested firewood per hectare of trees planted increases up to a point and decreases thereafter (Figure 3A). For low and medium harvest regimes firewood productivity is not very sensitive to increases in tree area beyond $k = 0.2$. Maximum harvests of 1.3 Mg C ha^{-1} and 2.6 Mg C ha^{-1} are reached at $k = 0.2$ for low and medium harvests, respectively. At high harvest, firewood output is more sensitive to tree area; a maximum of 5.4 Mg C ha^{-1} is reached with $k = 0.2$ (Figure 3A), with a decline to 4 Mg C ha^{-1} at k=1.0. The decline in firewood production as k increases beyond 0.2 is caused by lower net primary production (NPP) due to increased competition. A lower NPP means less biomass will be available for pruning and harvesting.

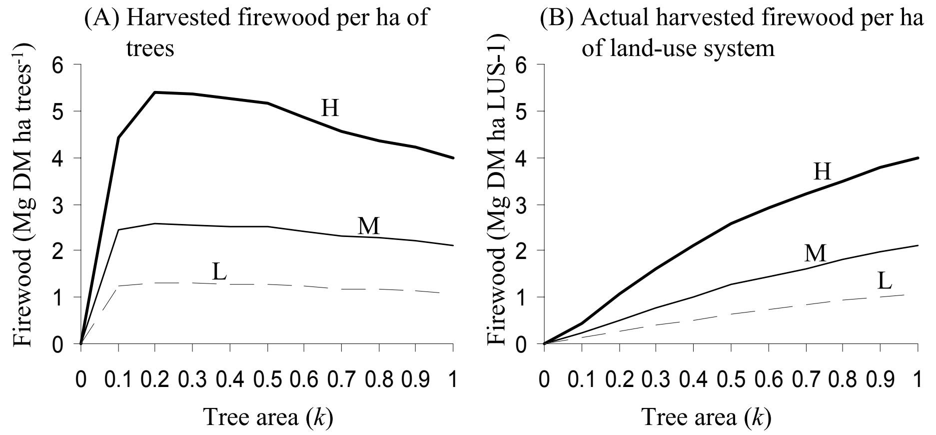

Figure 3. The effect of tree area on average harvested biomass under three harvest regimes.

The pattern described above, combined with increasing tree area, results in monotonic but nonlinear increases in actual firewood production per hectare of LUS (Figure 3B). As *k* increases from 0 to 1.0 the actual amount of firewood harvested increases to 1.07, 2.11 and 3.99 Mg DM for low, medium and high harvests respectively.

4.4 Crop yield

When the whole area is planted to maize ($k = 0$), the average annual maize yield is 4.09 Mg DM ha^{-1} from two crops per year (Figure 4A). As *k* is increased from 0 to 0.6, maize yields increase by 29% and 26% under low and medium harvest regimes, respectively, but decline by 86% under high harvest regimes. Most of these changes occur within the first 10 percent of area converted from maize to trees. When *k* is increased beyond 0.6, maize yields decline under low and medium harvests and remain relatively constant under high harvest, except for an increase as *k* approaches 1.0.

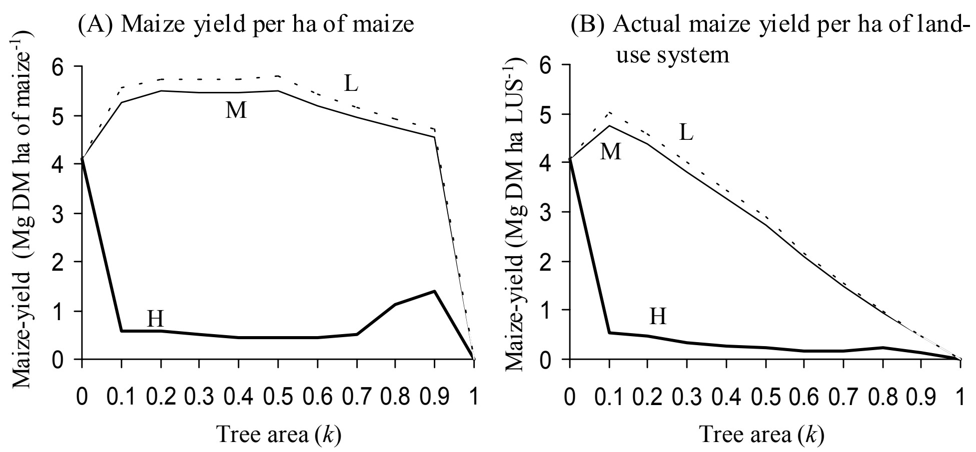

Figure 4. The effect of tree area on maize production

Under low and medium harvests, the patterns described above combined with decreasing crop areas as *k* increases, result in actual maize-yield peaks (per ha of LUS) at *k*=0.1 (Figure 4B).

These results show that under low and medium harvests the benefits from adding pruned biomass to the system outweigh the negative effects of shading and belowground competition for water and nutrients. Whereas the large drop in maize yield under high harvests as *k* increases is due to the trees out-competing the crops for the very limited resources available with no nutrients returned to the system.

The results above are average maize yields over a 25-year period, but they do not reflect temporal changes in yields. The trajectories associated with selected scenarios are presented in Figure 5. Maize yields decline throughout the 25 years for all harvest levels and areas of trees planted. This indicates that two maize crops a year on a continuous basis deplete the nutrients in the soil. The speed of the decline in yields depends on the firewood-harvest regime. The decline is more rapid at high harvests (Figure 5A) and when *k* is between 0.1 and 0.5. At the low harvest regime, yields decline faster when *k* = 0 and the decline slows down when trees are planted (Figure 5B). However, the system remains unsustainable under all scenarios used in this study, indicating that more nutrients need to be added to the system to maintain productivity.

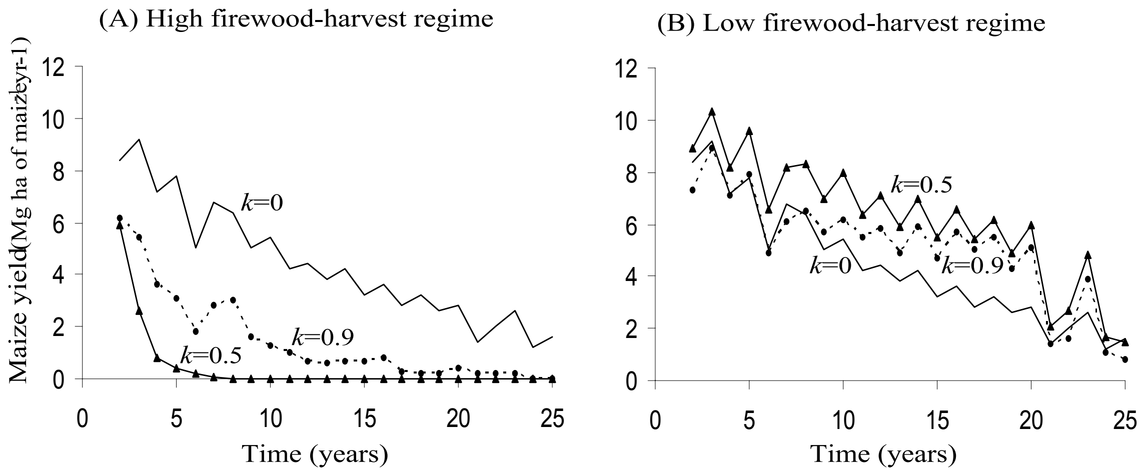

Figure 5. The trajectory of maize yield over 25 years for selected values of *k* and for high (A) and low (B) firewood-harvest regimes.

5. The baseline

As mentioned earlier, only stocks of carbon above the baseline are eligible for trading, so agreement on the baseline is critical for biomass-carbon trading. If the current land use has a fairly stable average carbon content (eg. a pasture), the baseline can be static, represented by a constant stock of carbon overtime. However, if the current land use is unsustainable continuous cropping, as represented in Figure 5, a dynamic baseline is more appropriate; because the 'business as usual' consists of decreasing carbon stocks overtime.

The trajectories of total carbon stocks (biomass plus soil) are presented for selected scenarios in Figure 6. In the absence of trees (k=0) total carbon decreases overtime. When trees are planted (k>0) total carbon increases during the first few years and decreases thereafter.

When trees are planted, higher harvest regimes are associated with quicker declines in total carbon after the peak (compare Figures 6A, 6B and 6C). As with the crop in the previous section, these patterns indicates that this system is unsustainable, but that the relative productivity of the system improves as firewood-harvest regime decreases (more organic matter is returned to the plant-soil system).

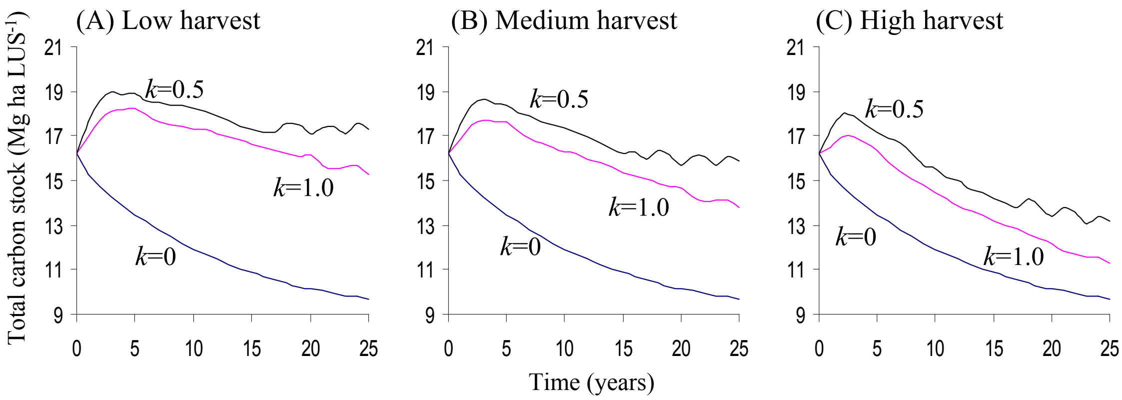

Figure 6. The trajectory of total carbon stock, under three firewood-harvest regimes and for selected tree areas (k).

A static baseline could be represented in Figure 6 by a horizontal line at the intercept of all the curves (at 16.2 Mg C ha^{-1}), whereas a dynamic baseline could be represented by the curve labelled k=0. The eligible carbon for any given scenario is obtained by subtracting the baseline carbon from the actual carbon stock.

The trajectories of eligible carbon stocks (Figure 7) are the difference between the total carbon stock of three different scenarios and the baseline, based on previous land use. The static baseline represents an *Imperata* grassland with a constant 16.91 Mg C ha^{-1}. Figure 7A shows that, if landholders were to convert grassland into a maize-*Gliricidia* system and enter the carbon market, they would be liable for carbon emissions in several years (when eligible carbon stocks are below zero).

If the current land use is continuous cropping, the dynamic baseline applies (Figure 7B). Under the dynamic baseline, were landholders to enter a carbon market, they would be eligible for credits on carbon sequestered throughout the rotation for all values of $k>0$. So the baseline is critical in determining whether landholders will have incentives to adopt agroforestry systems.

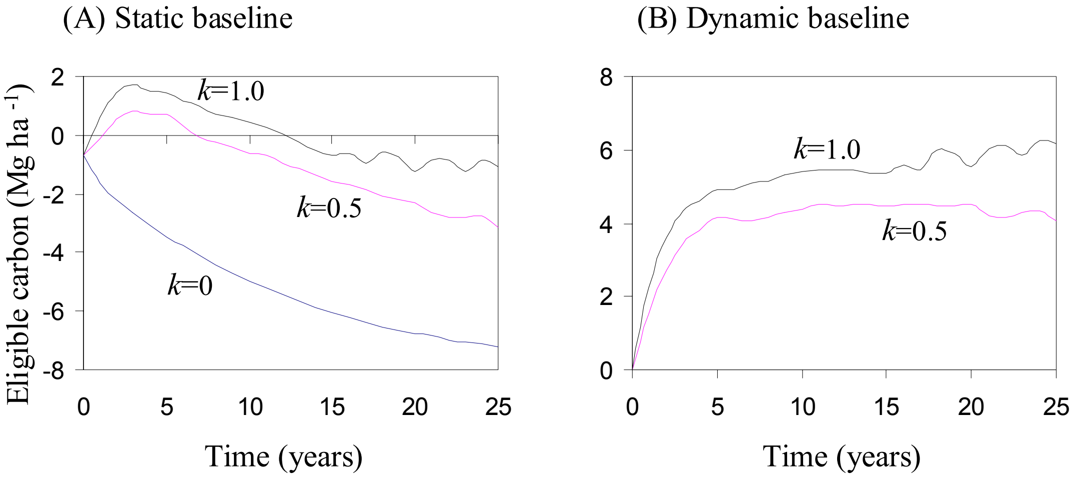

Figure 7. The trajectory of eligible carbon, calculated relative to either a static baseline representing a grassland (A), or a dynamic baseline representing continuous cropping (B) under a medium harvest regime and for selected tree areas (*k*).

6. Economic analysis

The economic performance of any agroforestry system depends on economic variables such as output prices, establishment costs, labour costs and discount rate. Also, for agroforests such as the hedgerow intercropping system simulated in this study, economic performance depends on management decisions such as area planted to crops and trees and the intensity of the harvest regime.

Investment in a carbon project will occur only if the net present value (NPV) of the 'with-carbon' alternative exceeds that of the 'without-carbon' alternative. Three alternatives are considered here: (a) where only traditional outputs (maize and firewood) are accounted for (the 'no C credits' alternative); (b) where traditional outputs and carbon are included, and eligible carbon is measured relative to a static baseline; and (c) as in b, but with eligible carbon measured relative to a dynamic baseline. Alternative (a) is implemented by setting the third term in equation (1) equal to zero whereas alternatives (b) and (c) incorporate all three terms in equation (1) but with different baselines as explained in equations (4) and (5).

6.1 Base-case results

Economic results under base parameter values are presented in Table 3 for selected scenarios. The financial benefits of growing trees with crops are only realized when the harvest regime is medium or low. Under these regimes (L and M) the maximum NPV is obtained at k=0.1 (Table 3).

At high harvest the best alternative is not to grow trees (k=0). The large drops in NPV between $k = 0$ and $k = 0.1$, for all scenarios involving high harvest, is due to the decline in crop yields caused by the trees out-competing the crops for soil nutrients and sunlight, with no nutrients being returned to the system, since all prunings are harvested.

Table 3. Net Present Values (Rp '000 ha^{-1}) for selected scenarios

	Baseline	Firewood Harvest	Tree area (*k*) *0*	*0.1*	*0.2*	*0.3*	*0.4*	*0.5*
With no C credits	None	*L*	3,473	**4,316**	4,007	3,491	2,991	2,559
		M	3,473	**3,858**	3,733	3,251	2,824	2,457
		H	**3,473**	-2,342	-1,974	-1,930	-1,702	-1,377
With C credits	Static	*L*	3,019	**4,164**	3,927	3,474	3,038	2,670
		M	3,019	**3,626**	3,568	3,149	2,785	2,483
		H	**3,019**	-2,736	-2,303	-2,194	-1,904	-1,513
	Dynamic	*L*	3,413	**4,557**	4,320	3,868	3,431	3,064
		M	3,413	**4,019**	3,962	3,543	3,178	2,877
		H	**3,413**	-2,343	-1,910	-1,800	-1,511	-1,120

The low-harvest regime produces higher NPVs under all three baselines (none, static and dynamic) than the medium- and high-harvest regimes. The effect on NPV of carbon trading is very different depending on whether a static or dynamic baseline is used. Under a static baseline it is not worthwhile trading carbon, as this will result in a lower NPV than with no C credits (Rp 4,164,000 vs. Rp 4,316,000). This is because, at tree areas lower than 0.5, there is a net loss of carbon compared with the static baseline and this loss produces a debit in the carbon market. This pattern is reversed when *k* exceeds 0.5 because the rate of carbon accumulation in the standing biomass now exceeds the rate of soil carbon loss and there is a net gain in carbon compared with the static baseline.

When a dynamic baseline is used, it is attractive to trade carbon, as the maximum NPV is higher with than without C credits (Rp 4,557,000 vs Rp 4,316,000). NPVs for all values of *k* are greater under the dynamic baseline than under the no C credits alternative (Table 3). This is because the dynamic baseline reflects a land-use system that involves carbon losses over 25 years, and the agroforestry system increases the carbon stocks relative to the business-as-usual case.

The optimal area to plant to trees with no C credits' is 0.1 for low and medium harvests and zero for high harvests. The same applies to the two alternatives with C credits. The NPVs are larger when trees are grown at *ks* between 0.1 and 0.4 compared with the no-trees case, even though the direct monetary benefit from the tree component is extremely small. The indirect benefits of growing trees with crops more than compensate for the small direct monetary benefits from forestry over the interval $0<k<0.5$. Thus, a limited area of trees provides financial benefits even in the absence of C credits.

Within the set tested in this study the dominant strategy is to plant 0.1 of the area to trees and follow a low firewood-harvest regime (Table 3). Trees provide indirect financial benefits by helping slow down the rate of land degradation. This finding is consistent with the results of Cacho (2001) for land subject to salinity emergence.

To gain better insight into the effect of tree area on profits, the model was solved at smaller increments of k for the range $0 \le k \le 0.25$ (Figure 8). These refined results show that, for all baselines, the maximum NPV is reached when k is between 0.15 and 0.16 hectares.

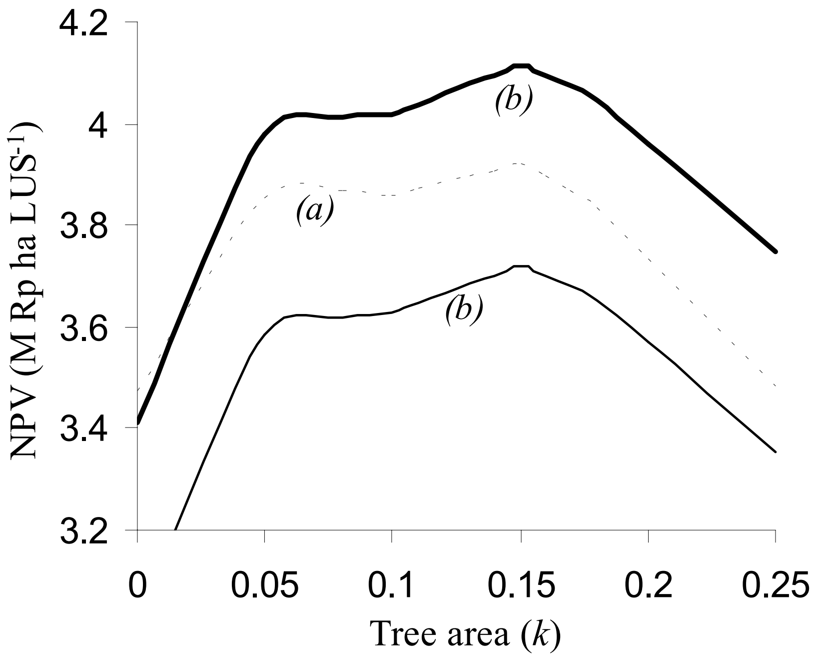

Figure 8. The effect of tree area on NPV at medium harvest regime under three alternatives: (a) no C credits, (b) static baseline, (c) dynamic baseline.

The optimal k shown in Figure 8 is that which maximizes equation (1). At the optimal point, the marginal benefit of growing trees equals the marginal benefit of growing crops (Cacho, 2001, p. 133)

It must be pointed out that, although NPVs are lower under the static baseline than under the no C-credits alternative (Table 3), the former reflects the true costs of production in the absence of market failure. In other words, if an *imperata* grassland is converted into a maize/*Gliricidia* system, the social cost of this change is partly reflected by the difference in NPV between the no-credits alternative and the static baseline results. This loss is Rp 152,000/ha (i.e. 4,316,000 – 4,164,000 at k=0.1). When carbon is not accounted for, the global-warming effect of the land-use conversion is not made explicit and so the social cost is not considered.

6.2 Sensitivity analysis

Sensitivity analysis was undertaken with respect to carbon price, maize price, and the discount rate. Net present values were obtained for each of the different tree/crop-scenarios simulated (21 scenarios in total[6]), at medium harvest, for each of the three accounting methods. The scenario with the highest NPV for a given baseline was taken as the optimal management strategy for that baseline. So the term "optimal" is used here to refer to the management option (*k*) that gives the highest NPV from among the set tested by simulation.

Table 4: Optimal strategies under a range of discount rates and prices with a static baseline

Exogenous variables			Optimal results			
Discount rate (%)	Carbon price	Maize price	C-trading	NPV	Tree area (k)	Eligible TAC
0.05	100,000	200,000	No	2,014	0.18	-1.85
0.15	100,000	200,000	No	1,125	0.16	-1.96
0.25	100,000	200,000	No	564	0.15	-2.01
0.05	150,000	200,000	No	2,014	0.18	-1.85
0.15	150,000	200,000	No	1,125	0.16	-1.96
0.25	150,000	200,000	No	564	0.15	-2.01
0.05	200,000	200,000	No	2,014	0.18	-1.85
0.15	200,000	200,000	No	1,125	0.16	-1.96
0.25	200,000	200,000	No	564	0.15	-2.01
0.05	100,000	300,000	No	8,084	0.15	-2.01
0.15	100,000	300,000	No	3,921	0.15	-2.01
0.25	100,000	300,000	No	2,233	0.00	-4.59
0.05	150,000	300,000	No	8,084	0.15	-2.01
0.15	150,000	300,000	No	3,921	0.15	-2.01
0.25	150,000	300,000	No	2,233	0.00	-4.59
0.05	200,000	300,000	No	8,084	0.15	-2.01
0.15	200,000	300,000	No	3,921	0.15	-2.01
0.25	200,000	300,000	No	2,233	0.00	-4.59
0.05	100,000	400,000	No	14,367	0.05	-2.57
0.15	100,000	400,000	No	6,796	0.05	-2.57
0.25	100,000	400,000	No	3,993	0.00	-4.59
0.05	150,000	400,000	No	14,367	0.05	-2.57
0.15	150,000	400,000	No	6,796	0.05	-2.57
0.25	150,000	400,000	No	3,993	0.00	-4.59
0.05	200,000	400,000	No	14,367	0.05	-2.57
0.15	200,000	400,000	No	6,796	0.05	-2.57
0.25	200,000	400,000	No	3,993	0.00	-4.59

[6] The percentage of total area converted to trees include: 0, 5, 8, 10, 12, 13, 14, 15, 16, 17, 18, 20, 25, 30, 40, 50, 60, 70, 80, 90, 100.

With a static baseline it is always optimal not to participate in the carbon market (Table 4), and the optimal tree area ranges between 0 and 0.18. Eligible time-averaged carbon is negative in all cases, reflecting the loss in soil carbon that results from converting a grassland into a maize/*Gliricidia* system.

With a dynamic baseline (Table 5) it is generally optimal to participate in the carbon market, except at high discount rates combined with high maize prices. As before, the optimal tree area ranges between 0 and 0.18.

Table 5: Optimal strategies under a range of discount rates and prices with a dynamic baseline

Exogenous variables			Optimal results			
Discount rate (%)	Carbon price	Maize price	C-trading	NPV	Tree area (k)	Eligible TAC
0.05	100,000	200,000	Yes	2,120	0.18	2.75
0.15	100,000	200,000	Yes	1,242	0.17	2.63
0.25	100,000	200,000	Yes	662	0.17	2.59
0.05	150,000	200,000	Yes	2,243	0.18	2.75
0.15	150,000	200,000	Yes	1,332	0.18	2.63
0.25	150,000	200,000	Yes	730	0.18	2.59
0.05	200,000	200,000	Yes	2,365	0.18	2.75
0.15	200,000	200,000	Yes	1,423	0.18	2.63
0.25	200,000	200,000	Yes	799	0.18	2.59
0.05	100,000	300,000	Yes	8,178	0.15	2.59
0.15	100,000	300,000	Yes	4,030	0.15	2.59
0.25	100,000	300,000	Yes	2,255	0.15	0.00
0.05	150,000	300,000	Yes	8,294	0.15	2.59
0.15	150,000	300,000	Yes	4,115	0.15	2.59
0.25	150,000	300,000	Yes	2,319	0.15	0.00
0.05	200,000	300,000	Yes	8,410	0.15	2.59
0.15	200,000	300,000	Yes	4,200	0.15	2.59
0.25	200,000	300,000	Yes	2,382	0.15	0.00
0.05	100,000	400,000	Yes	14,414	0.05	2.03
0.15	100,000	400,000	Yes	6,861	0.05	2.03
0.25	100,000	400,000	No	3,993	0.00	0.00
0.05	150,000	400,000	Yes	14,507	0.05	2.03
0.15	150,000	400,000	Yes	6,923	0.05	2.03
0.25	150,000	400,000	No	3,993	0.00	0.00
0.05	200,000	400,000	Yes	14,601	0.05	2.03
0.15	200,000	400,000	Yes	6,996	0.15	2.03
0.25	200,000	400,000	No	3,993	0.00	0.00

The eligible time-averaged carbon ranges between 0 and 2.75 Mg C ha^{-1}. These levels of eligible carbon per hectare are quite small compared with carbon stocks of 200 Mg C ha^{-1} or more in secondary forests. It is possible that the transaction costs (per tonne of carbon) of monitoring and certifying these small amounts of carbon will exceed the financial benefits. These issues are discussed by Cacho, Marshall and Milne (2002) and Cacho, Wise and MacDicken (2002) and are not pursued here.

The foregoing analysis provides some useful insights, but recall that our results relate to an agroforestry system with no nutrient additions. The trees simulated can fix nitrogen and there are transfers of organic matter between trees and crops, but this is not enough to maintain a sustainable system, as land productivity declines over the 25-year planning horizon for all scenarios. Hence, the next step in this research should be to repeat the analysis with fertiliser additions. Then it will be possible to determine to what extent nutrients (particularly nitrogen and phosphorus) can increase the optimal level of carbon stocks in agroforestry systems.

7. Summary and Conclusions

This paper presents an analysis of an agroforestry system in the presence of carbon-sequestration payments. The analysis is based on a model representing an alley system in Indonesia. The results are analysed from both biophysical and economic standpoints. The importance of baselines is illustrated by comparing the business-as-usual (baseline) case with a project where trees are introduced into a continuous cropping system. Two possible baselines are studied: a static baseline representing conversion of a grassland into an agroforestry system, and a dynamic baseline representing continuous cropping as the current land use. Economic analysis shows that, under a broad range of assumptions regarding carbon and crop prices and discount rates, the static baseline offers no incentive for landholders to participate in the carbon market, whereas the dynamic baseline does. However, the optimal levels of carbon stored per hectare of land are small and may not cover the transaction costs of participating in the carbon market. Further research is needed to determine to what extent our findings will change when nutrients are added to the system in the form of fertiliser.

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