Bioeconomic meta-modelling of Indonesian agroforests as carbon sinks

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Abstract

In many areas of developing countries, economic and institutional factors often combine to give farmers incentives to clear forests and repeatedly plant food crops without sufficiently replenishing the soils. These activities lead to large-scale land degradation and contribute to global warming through the release of greenhouse gases into the atmosphere. We investigate whether agroforestry systems might alleviate these trends when carbon-credit payments are available under the Clean Development Mechanism of the Kyoto Protocol. A meta-modelling framework is adopted, comprising an econometric-production model of a smallholding in Sumatra. The model is used within a dynamic-programming algorithm to determine optimal combinations of tree/crop area, tree-rotation length, and firewood harvest. Results show the influence of soil-carbon stocks and discount rates on optimal strategies and reveal interesting implications for joint management of agriculture and carbon.

Keywords: bio-economic meta-modelling, Indonesia, agroforestry, carbon credits, dynamic programming,

1. Introduction

In rural areas of developing countries, economic and institutional factors often combine to give farmers incentives to clear forests and repeatedly plant food crops without sufficiently replenishing the soils. These activities erode the natural capital upon which poor, rural communities depend. Associated with large-scale deforestation and land degradation are substantial losses of stored soil and biomass carbon which contribute to global warming and climate change (Fearnside, 2001; Antle and McCarl, 2002; Lal, 2004; Makundi and Sathaye, 2004). Agroforestry systems[1] have the potential to mitigate these emissions by sequestering atmospheric carbon in biomass and soil while maintaining sustainable productivity and meeting local cultural requirements (Roshetko *et al.*, 2007). Albrecht and Kandji (2003), for example, estimate the carbon sequestration potential of agroforestry systems to be between 12 and 228 Mg ha^{-1} (with a median value of 95 Mg ha^{-1}) with between 585 and 1215 million ha of the earth's area suitable for agroforestry. Oelbermann *et al.* (2004) estimate the potential to sequester carbon in aboveground components in agroforestry systems to be 2.1×10^9 Mg C year^{-1} in tropical biomes and 1.9×10^9 Mg C year^{-1} in temperate biomes; but emphasise that the type of agroforestry systems and their capacity to sequester carbon do vary globally.

Diverse policies and approaches for alleviating these trends have increasingly been developed and implemented. Community-based Natural Resource Management initiatives (Frost and Bond, 2006) and the Clean Development Mechanism (CDM) of the Kyoto Protocol (with many supporting Funds such as the World Bank's BioCarbon Fund and Community Development Carbon Fund) are just two such examples. These mechanisms primarily focus on influencing the economic incentives driving behaviour often using market-based approaches with caveats to promote environmental sustainability and equity. The Kyoto Protocol (KP) provides the policy context for this analysis. In particular, Articles 3.3 and 12 (Land-use, Land-use Change and Forestry and the Clean Development Mechanism, respectively) are designed to give incentives to developed countries to invest in greenhouse-gas mitigation activities in developing countries to help meet their Kyoto emission

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[1] Agroforestry systems are agricultural lands where trees have been introduced and judiciously managed together with crops and/or animals (Albrecht and Kandji, 2003)

limitations. Allowable activities include terrestrial carbon sinks such as small-scale forestry and agroforestry. However the uptake of these activities within the CDM has been quite low, representing only 1% of registered CDM projects by volume (Capoor and Ambrosi, 2007).

Numerous projects around the developing world have been financed and implemented under the CDM and these are reviewed in detail by the FAO (FAO, 2004). The economics of agroforestry systems in the presence of carbon-sequestration payments has been intensively studied over the last decade by authors such as Cacho *et al.* (2003; 2004; 2005) and De Jong *et al.* (2004) among others. In this paper we develop a model conceptually based on a Production Possibility Frontier (PPF) representing the trade offs facing landholders with fixed resources and technologies to produce bundles of products from two land uses trees (Y_1) and crops (Y_2) (Figure 1). The optimal combination of Y_1 and Y_2 is determined by the price ratio p_1/p_2. If the present value of crop outputs exceeds the present value of tree outputs, the optimal point is likely to be located closer to the vertical axis (point E_1) reflecting the current situation in much of the developing world where continuous cropping is often the preferred land-use option (Wise and Cacho, 2007). If the external environmental benefits provided by trees are internalised through direct payments for sequestered carbon the price ratio (p_1/p_2) will increase and landholders will plant a larger area of their land to trees (point E_2, Figure 1).

[INSERT FIGURE 1 – PPF]

This paper builds on the study of Wise and Cacho (2007), who found that soil quality should drive planting decisions of an economically rational landholder. For example, in degraded soils it pays to plant trees to improve soil quality when incentives exist to participate in carbon projects. But, a threshold soil-carbon level (quality) exists where it becomes optimal to switch from trees to a steady-state system of crops with fertiliser and to not participate in carbon trading. The corner solutions of either trees or crops reflect a land-use system where the complementarities between the tree and crop components are relatively weak. In this study, we use a similar bioeconomic meta-model of a tree-crop system to identify profit-maximising land-management strategies, but in this case the complementary interactions between trees and crops are stronger and we assume no inorganic fertilisers are available; a common situation in rural regions of developing countries where access to markets and finance is limited – this situation is exacerbated by high energy prices. Therefore we assume that soil fertility can only be improved through nitrogen-fixation of plants and the addition of organic matter.

2. Study area

The study area for this analysis is the Jambi province of southern Sumatra, Indonesia. Jambi is situated in the humid tropics and is largely covered by Sumatra's broad 'peneplain' agro-ecological zone. It is almost flat land, less than 100 m above sea level, and is divided into a lowlands area (10%) made up of river levees and floodplains with fertile alluvial soils; and an uplands area (90%) with a gently undulating landscape (slopes of 5-17%) (Tomich *et al.*, 2001).

This region is chosen because it is one of the Alternatives to Slash-and-Burn (ASB) benchmark sites and represents the equatorial rainforests of southeast Asia where primary forests are being cleared. The internal forces driving these land conversions are resettlement programs and the increasing population densities resulting from the inflow of migrants[2], facilitated by road construction and the lack of economic opportunity elsewhere (Tomich *et al.*, 2001; Palm *et al.*, 2004). The indigenous practice of slash-and-burn shifting cultivation, for example, has been widely adopted to meet the growing food requirements of the high population densities in many regions in Indonesia (Menz and Grist, 1999). However, growing crops on a continuous basis, with few residue and fertiliser additions, depletes the soil of its nutrients. Often these soils become so degraded that they have to be left fallow, and are usually invaded by *Imperata* grassland. *Imperata* grasslands do have a number of uses for local people but these uses are of relatively low value (Tomich *et al.*, 1996), which makes their possible conversion to more profitable uses a research priority. International drivers of land-use change in Indonesia have been strengthened recently due to increasing demands for bio-energy which create powerful incentives to clear indigenous forests to plant monocultures of palm oil, rape, maize and jatropha.

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[2] The range in population density in Sumatra in 2000 was between 191 people km^{-2} in Lampung Province and 45 people km^{-2} in Jambi Province (BPS, 2000).

2.1. The agroforestry system

The upland land-use systems found in Indonesia are determined by the availability of standing water throughout the growing season. Where standing water is not available, non-rice crops such as maize, grain legumes and tuber crops are grown (Fagi, 1992). The presence of standing water largely depends on the slope of the land. Where the land is relatively flat, waterlogging tends to occur and wetland rice is grown. But, where the topography is sloping, the land is planted in a patchwork of rain-fed crops including tuber crops, maize, grain legumes, vegetables and tree crops (Fagi, 1992). Hedgerow-intercropping systems are often found on steeper slopes, where rice or maize is grown alongside tree-covered terraces. Many cropping patterns are found in dryland areas of Indonesia, including sequential plantings of maize (Fagi, 1992) and relay cropping of maize, soybean (*Glycine max*) and velvet bean (*mucuna pruriens*) (Sitompul *et al.*, 1992).

In this analysis, a rainfed hedgerow-intercropping system of *Gliricidia sepium* and maize is investigated. Gliricidia was selected because of its soil-amelioration capabilities (it is N-fixing and produces large quantities of biomass for mulch) and its ability to rapidly produce various commodities including firewood, fodder, or timber (Sanchez, 1995; Stewart, 1996). Tree crops have a greater potential to sequester carbon than food crops, which in the presence of carbon credits, adds to the earning capability of this land-use system. The system and the management regimes investigated are presented in detail in Section 3.2.

3. Method

3.1. Economic model

This paper uses a similar bioeconomic model to that of Wise and Cacho (2007). The model accounts for effects of the competitive and complementary interactions between trees and crops on the quantities of marketable outputs produced such as firewood and maize in addition to the carbon sequestered in the soil and tree biomass. The analysis is based on a landholder participating in a CDM project and receiving payments for carbon sequestration services. Carbon payments are based on the production of certified emission reductions (CERs), the medium of exchange under the CDM. The present value of net revenues (*NPV*) obtained from an area of land *A* over a project-investment period of *T* years is:

$$NPV(T,k,x) = (A-k)\cdot\sum_{t=1}^{T} a_t(s_t,k,x_t)\cdot\delta^{-t} + k\cdot\sum_{t=1}^{T} h_t(s_t,k,x_t)\cdot\delta^{-t}$$

$$+ A\cdot\sum_{t=1}^{T} CER_t(s_t,k,x_t)\cdot\delta^{-t} - k\cdot c_E \qquad (1)$$

where s_t represents the state of the land in year *t* and may be defined by a set of land-quality indicators such as soil depth, soil-carbon content and soil fertility; ***x*** is a vector of management decisions such as the timing and frequency of pruning and harvesting, weeding and fertilising; *k* is the area of the farm planted to trees, which remains constant throughout the *T* years, and *A* – *k* is the area planted to crops. The cost of establishing a hectare of trees is c_E and δ=(1+*r*) for the discount rate *r*.

The net annual revenues obtained from the area planted to a single agricultural crop are:

$$a_t = p^a \cdot y_t^a(s_t,k,x_t) - c_t^a \qquad (2)$$

where, y_t^a is crop yield, p^a is the price of the crop and c_t^a is the per-hectare variable costs of preparing the land, sowing seeds and harvesting.

The net annual revenues provided by trees are:

$$h_t = p^h \cdot y_t^h(s_t,k,x_t) - c_t^h \qquad (3)$$

where, y_t^h is the quantity of tree product harvested in year *t*, p^h is the price of tree product and c_t^h is the variable costs of harvesting.

The last term in equation (1) is the monetary benefit received for the sale of CERs, which depends on carbon accumulation in tree biomass and soil relative to the baseline (referred to as ‘eligible carbon’):

$$CER_t = p^c \cdot (y_t^{bc}(s_t, k, x_t) + y_t^{sc}(s_t, k, x_t)) - cm_t \tag{4}$$

where y_t^{bc} is the eligible change in the stock of tree-biomass carbon, y_t^{sc} is the eligible change in soil-carbon stock, p^c is the price of CERs and cm_t is the annual carbon-monitoring cost per hectare.

Equation (1) represents a single rotation and does not include the opportunity cost of keeping trees in the ground. The Faustman model is the standard approach to solving the infinite forestry planning horizon, and it has been extended by authors such as Hartman (1976), Comolli (1981), Bowes and Krutilla (1985), van Kooten *et al.* (1995) and Gutrich and Howarth (2007) to include non-timber benefits. Such models require that the length of each cycle (*T*), the management variables defined within the vector **x**, and initial land quality for each cycle S_n remain constant for all cycles $n = 1,2,\ldots\infty$. These assumptions do not hold when the quality of the land changes over time, possibly resulting in optimal tree areas and rotation lengths changing between cycles. Thus our decision model is:

$$V_n(S_n) = \max_{k_n, x_n, T_n} \left(NPV_n(S_n, k_n, x_n, T_n) + V_{n+1}(S_{n+1}) \cdot \delta^{-T_n} \right) \tag{5}$$

subject to:

$$S_{n+1} = S_n + \sum_{t=T_{n-1}+1}^{T_{n-1}+T_n} f_t(s_t, k, x) \tag{6}$$

where, S_n is the quality of the land at the beginning of forestry cycle *n*, $f_t(\cdot)$ is the annual change in the state variable, and *NPV* is as defined in equation (1). The problem is solved by backward induction until convergence in $V(S_n)$ is achieved

(Kennedy, 1986). This involves combining a dynamic programming algorithm with the simulation model described below.

3.2. The biophysical simulation model

The meta-model of Gliricidia hedgerows intercropped with two maize crops per year – developed by Wise and Cacho (2007) – was used in this study. The model comprises three quadratic equations that interactively mimic soil-carbon changes, tree-biomass accumulation and crop-yield dynamics of the Gliridicia-maize system in response to changes in management. The equations were estimated econometrically from the dataset of 6,200 data points created by Wise and Cacho (2007) using the SCUAF[3] model.

Wise and Cacho (2007) calibrated the SCUAF model to represent a 'typical' site in a sub-humid climate, with acidic, medium-textured soils of felsic parent material and imperfect drainage. The carbon and nitrogen contents of the system range between 10 and 33 Mg C ha^{-1} and 1.0 and 3.3 Mg N ha^{-1}, respectively – depending on previous land use and degree of degradation[4]. The lower values of this range represent a run-down soil requiring regeneration. The biophysical parameter values used to calibrate SCUAF are reported in Wise *et al.* (2007) and are not repeated here.

The management parameters varied in SCUAF to create the original dataset were area planted to trees (k), fertiliser-application rate (fr), and firewood prune and harvest regime (hr). Total area (A) was set to 1.0 hectare so $0 \leq k \leq 1$ (i.e. k also represents a fraction of the area of the smallholding). The values for these parameters were set at the beginning of a simulation and held constant throughout each 25-year rotation. The dataset was generated by increasing k at intervals of 0.1, resulting in 11 tree/crop area combinations. These were then replicated for three prune/harvest regimes and four fertiliser regimes, resulting in 124 simulated management strategies. The pruning and harvesting intensities are defined as percentages of the annual increment in total tree

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[3] SCUAF (Soil Changes Under Agriculture, Agroforestry, and Forestry) is a process model designed to estimate the effects that changes in soil properties (nutrients, carbon and soil depth) have on tree and crop productivity in response to changes in management (Young *et al.*, 1998).

[4] These values fall at the lower end of the expected range of 10 to 120 Mg C ha^{-1} for soils under a range of land uses in Sumatra (Delaney *et al.*, 2002).

biomass. The sum of the prune and harvest intensities was set at 70% of the annual increment in total tree biomass. The remaining 30% of annual biomass increment was not removed from the trees; consequently the carbon contained in trees increased throughout the rotation. The three prune/harvest scenarios simulated were: (1) 52.5% prune / 17.5% harvest; (2) 35% prune / 35% harvest; and (3) 0% prune / 70% harvest. Pruned biomass was returned to the soil to decompose and replenish soil carbon and nutrients whereas harvested biomass was removed for sale as firewood; therefore the soil-carbon stock is affected by harvest regime (*hr*). The four fertiliser regimes comprised various combinations of nitrogen (N) and phosphorous (P) that were added annually to the crop component. In this study, however, it is assumed that no inorganic fertiliser is available and landholders are only able to manage soil quality and total carbon stocks by changing *k* and *hr*. The resulting quadratic equations for the state of the soil (s_t), the tree biomass (b_t) and crop yield (y_t^a), respectively are:

$$\begin{aligned} s_t = {} & \beta_0 + \beta_1 \cdot s_{t-1} + \beta_2 \cdot (s_{t-1})^2 + \beta_3 \cdot s_{t-1} \cdot (1-k) + \beta_4 \cdot s_{t-1} \cdot hr + \beta_5 \cdot (1-k) \\ & + \beta_6 \cdot (1-k)^2 + \beta_7 \cdot (1-k) \cdot hr + \beta_8 \cdot hr \end{aligned} \tag{7}$$

$$\begin{aligned} b_t = {} & \alpha_0 + \alpha_1 \cdot b_{t-1} + \alpha_2 \cdot (b_{t-1})^2 + \alpha_3 \cdot b_{t-1} \cdot s_t + \alpha_4 \cdot b_{t-1} \cdot k + \alpha_5 \cdot b_{t-1} \cdot hr + \alpha_6 \cdot s_t \\ & + \alpha_7 \cdot (s_t)^2 + \alpha_8 \cdot s_t \cdot k + \alpha_9 \cdot s_t \cdot hr + \alpha_{10} \cdot k + \alpha_{11} \cdot k^2 + \alpha_{12} \cdot hr \end{aligned} \tag{8}$$

$$y_t^a = \delta_0 + \delta_1 \cdot s_t + \delta_2 \cdot (s_t)^2 + \delta_3 \cdot s_t \cdot b_t + \delta_4 \cdot b_t + \delta_5 \cdot (b_t)^2 \tag{9}$$

The explanatory variables in each equation (presented in Table 1) are those that fit the simulated treatments best ($P \leq 0.05$). The estimated R^2 and *t* values reported purely indicate the fit of the quadratic equations to the SCUAF output and are not an indication of the sampling/measurement errors that is required for statistical inference. The parameter values for which no *t* values are indicated are those that have been modified to represent a system with stronger complementary tree-crop interactions than those reported by Wise and Cacho (2007).

[INSERT TABLE 1]

The meta-model, defined by equations (7), (8) and (9), was used to generate values for equations (2), (3) and (4). The crop, wood and carbon yields in these equations were calculated by simple differencing:

$$y_t^{sc} = \left((s_t - s_t^0) - (s_{t-1} - s_{t-1}^0)\right) \tag{10}$$

$$y_t^h = (b_t - b_{t-1}) \cdot hr \tag{11}$$

$$y_t^{bc} = \left((b_t - b_t^0) - (b_{t-1} - b_{t-1}^0)\right) \cdot \eta \tag{12}$$

The resulting biophysical and economic outputs were used within the DP model represented by equations (5) and (6). The values for the economic variables in the model are listed along with their sources in Table 2. The prices are quoted in US dollars using an exchange rate of 10,000 Indonesian Rupiah per US Dollar. A real discount rate of 15% has been used to represent the rate of time preference of individual landholders in remote areas of Indonesia (Menz and Magcale-Macandog, 1999).

[INSERT TABLE 2]

4. Results and Discussion

Optimal decision rules and associated optimal state transitions were determined by solving the DP model for two carbon prices representing a 'with carbon credits' scenario (US$17.5) and a 'without carbon credits' scenario (US$0). The sensitivity of these optimal results to a change in discount rate was also tested by decreasing the base-case rate of discount from 15% to 5%.

4.1. Optimal decision rules

The optimal state-contingent decisions – tree area (k^*), cycle length (T^*), and firewood-harvest regime (hr^*) are plotted in Figure 2. The effects of changing the carbon price (p^c) on optimal management are indicated in Figure 2 by the solid and dashed curves within each of the six graphs. The sensitivity of the optimal decisions to a lower discount rate is determined by comparing the graphs between columns 1 and 2 (Figure 2).

[INSERT FIGURE 2]

The most noticeable finding from the simulated outputs is that planting only crops is always the profit-maximising strategy for landholders to adopt when soil quality (soil-carbon content) is relatively high (> 22 Mg C ha^{-1}, for the base-case parameters used in this study). But, where the soil-carbon stock is relatively degraded (< 22 Mg C ha^{-1}) it becomes optimal to convert some of the area to trees ($0 > k < 1$). Combining trees with crops when soil quality is relatively poor is optimal because crops are less productive in degraded soils (i.e., the opportunity cost of growing trees is lower) and because Gliricidia trees, when appropriately managed, are able to restore soil quality through nitrogen-fixation and residue additions. When optimal management strategies involve growing trees with crops this implies that the complementarities between the tree and crop components exceed the competitive interactions and represents any point along the PPF between 'w' and 'z' in Figure 1. The actual optimal point along this section of the PPF depends on the prices of tree products relative to the price of maize and on the discount rate. This is discussed in more detail below.

Assuming a 15% discount rate (left panel in Figure 2) and in the absence of carbon payments (dotted lines), it is optimal to convert a minimum of 10% of the area to trees when s_t is between 15.5 and 17.5 Mg C ha^{-1} (Figure 2A) for rotations of between 7 and 9 years (Figure 2C), and to return none of the pruned biomass to the soil as residues (Figure 2E). It is optimal to undertake this minimal move towards trees because the soil is still productive enough to produce acceptable maize yields. However, at values of s_t less than 15.5 Mg C ha^{-1} it is optimal to convert between 70 and 90% of the land to trees for rotations of between 24 and 44 years, and to only harvest 20% of pruned biomass. This larger commitment towards trees occurs because the profitability of crops has been reduced and it is in the interests of the landholder to improve the quality of the soil through residue additions and nitrogen fixation.

If a lower discount rate of 5% is assumed and carbon still has no recognised market value (right panel in Figure 2) similar optimal-decision rules are observed but the lines shift to the right and the soil-carbon content must now decrease to only 20.5 Mg C ha^{-1} before a minimal shift towards trees (10% of the area for rotations of between 9 and 13 years with no residue additions) becomes optimal (Figures 3B & D). Also, at this lower discount rate, a larger commitment to trees becomes optimal at a slightly higher soil-carbon value of 16.5 Mg C ha^{-1}, and involves converting slightly lower proportions of the area to trees (60 to 80%) for longer rotations of between 43 and 50 years and harvesting only 20% of pruned biomass (Figures 3B, D & F, respectively). When discount rates are lower, the present value of the delayed benefits from trees is larger making longer tree cycles optimal.

Carbon payments provide incentives to convert crops to trees earlier (i.e., at higher s_t values) and to keep trees for longer rotations (compare solid lines with dashed lines in Figure 2); and these effects are greater at higher discount rates. When the discount rate is 15%, for example, carbon payments make it optimal to switch to 10% trees for between 31 and 48 years (compared with the 7 to 9 years without carbon payments) when the soil-carbon content is between 17.5 and 20.5 Mg C ha^{-1} (compared with the 15.5 to 17.5 Mg C ha^{-1} without carbon payments) and to between 70% and 90% for between 43 and 49 years (compared with the 24 to 44 years without carbon payments), when less than 17.5 Mg C ha^{-1} (compared with 15.5 Mg C ha^{-1} without carbon payments) (compare Figures 3C & D). These threshold values for the soil-carbon stock at which it becomes optimal to convert some of the land from crops to trees increases in the presence of carbon payments because trees become more financially competitive and because soil-carbon stocks across the entire area are maintained or increased (i.e., liabilities from soil-carbon losses that occur under crops are avoided).

It is noticeable that irrespective of soil-carbon level, discount rate and whether carbon payments are being received or not, it is never optimal to switch entirely from crops to trees. This is because the complementary interactions between the trees and the crops exceed the competitive interactions.

4.2. Optimal state paths

The trajectories of the state variable (s_t) that result from applying the optimal-decision rules over a period of 150 years are plotted in Figure 3. The associated optimal decisions (for the first 8 cycles) that drive the trajectories of soil-carbon stocks over time are listed in Table 3. If the initial soil quality is relatively good (s_0 = 33 Mg C ha^{-1}) it is optimal to exploit the system by continuously planting maize crops annually which reduces soil carbon for 44 years until it reaches an equilibrium value of 28.67 Mg C ha^{-1}, where it can be maintained through the addition of crop residues.

When the initial soil quality is relatively poor (s_0 = 12 Mg C ha^{-1}) it is optimal to build up soil carbon to a plateau (21.97, 18.34, 22.0 or 21.02 Mg C ha^{-1} depending on the price of carbon and the discount rate) by converting between 10% and 90% of the area from crops to trees for between 42 and 111 years and returning up to 80% of the pruned biomass to the system as residues (Table 3). Once these plateaus have been reached it is then optimal to switch the entire area back to a cropping system that can be maintained at an equilibrium state through the addition of crop residues. It is unlikely that an equilibrium state would be reached without trees if crop residues were not returned to the system.

[INSERT FIGURE 3]
[INSERT TABLE 3]

The introduction of carbon payments and the change in discount rate have no effect on the optimal soil-carbon path when s_0 = 33 Mg C ha^{-1}; it is always optimal to plant crops and not to participate in a carbon-sink project. When the system is relatively degraded (s_0= 12 Mg C ha^{-1}), however, carbon-sequestration payments only give landholders incentives to increase carbon stocks (compare Figures 4A & B) when the discount rate is high (Figures 3 & 4 and Table 3). In this situation, landholders have short-term planning horizons and will minimise the time their land is planted to trees (because this incurs opportunity costs in the form of forgone crop revenues) by converting to crops as soon as the soil-carbon level is sufficiently high to sustain crop productivity. Without carbon-sequestration payments, landholders convert from 90% trees to 90% crops within 24 years (Figure 4A and Table 3). Carbon payments give incentives to these landholders to increase the rotation length of their trees from 24 to 43 years in order to increase carbon-stock levels. Landholders with lower rates of time preference (5% discount rate) tend to have a medium- to long-term planning horizon and this is reflected in the longer tree rotation of 44 years; even though a slightly smaller area of 80% is planted to trees. For these landholders, carbon payments have little effect on the optimal carbon stock and on the optimal management strategies. Instead, the complementary role of trees on crop productivity – for example their ability to fix nitrogen in soils – is taken advantage of by extending the duration that at least 10% of the area is planted to trees.

So far only soil-carbon stocks have been discussed, but it is also informative to investigate the optimal trajectories of total eligible-carbon (Figure 4), which includes aboveground biomass carbon as well as soil carbon, as this reflects the cumulative stream of annual carbon payments. The trajectories of the eligible-carbon stock emphasise the positive relationship between p^c and discount rate on the quantity of CERs associated with optimal management regimes. The gradual increase in total eligible carbon stock after the initial tree rotation reflects the situation where it is optimal to plant trees in only 10% of the area. Since no trees are grown in cases where the initial soil-carbon level is high, total eligible-carbon stock trajectories are the same as those presented in Figure 3, and are therefore not shown.

[INSERT FIGURE 4]

5. Summary and conclusions

In this study we investigated whether agroforestry systems might be a profitable way of alleviating existing trends in increasing deforestation, soil degradation and land-based greenhouse-gas emissions in Sumatra under the assumption that carbon-credit payments are available. An econometric-production model capable of simulating tree-crop-soil interactions was developed and used within a dynamic-programming algorithm to determine optimal combinations of tree/crop area, tree-rotation length, and firewood harvest. Results show that the initial soil-quality (soil-carbon stock) and assumptions about landholders' rate of time preference drive land-management strategies.

In relatively good quality soils, irrespective of discount rate (5% or 15%) and whether participating in a carbon-sink project or not, profit maximising landholders will always only plant crops. This strategy leads to soil-carbon stocks declining to a steady state where it can be maintained provided crop residues are returned to the system. In this situation, no incentive exists to participate in carbon-sink projects because landholders are liable for soil-carbon losses.

In relatively poor quality soils optimal management strategies involve planting trees with crops to take advantage of the positive effects of trees on soil quality (soil nutrient and carbon levels) and the additional income from carbon payments for the larger stocks of carbon. In these cases optimal management involves a mix of tree-crop areas, tree-rotation lengths and firewood harvest regimes that is sensitive to the discount rate of landholders and whether carbon payments are available or not. For example, landholders with short-term planning horizons (high discount rates) minimise the time their land is planted to trees to between 42 and 84 years ('without' and 'with' carbon payments, respectively) because growing trees incurs opportunity costs in the form of forgone crop revenues. Landholders with lower rates of time preference (5% discount rate), however, tend to have a medium- to long-term planning horizon and allow their trees to grow for between 81 and 111 years ('without' and 'with' carbon payments, respectively). In both cases, as soon as the soil-carbon level is sufficiently high to sustain crop productivity the landholders convert all their land back to crops, where the system is maintained at a steady state by returning crop residues to the soil. The soil-carbon level at which this equilibrium is reached depends on the price of carbon and the discount rate. These findings are consistent with those of Wise and Cacho (2007), although in these cases, crop residues and not fertilisers are used to maintain the system's steady state.

An additional complexity to the optimal management strategies of landholders with low discount rates is that the payments for sequestered carbon have little effect on the optimal carbon stocks and are not what is driving the decision to plant trees. In these cases, it is the trees' abilities to improve soil quality (nitrogen fixation and soil amelioration) and therefore crop productivity that drives the landholders' decisions to extend the duration that trees are grown.

Finally, certain issues presented in this paper require further investigation. Firstly, it is uncertain what the implications for landholder food security would be if landholders did adopt the optimal strategies of converting 80 to 90% of their land to trees for 24 to 44 years. Secondly, in many areas of south-east Asia crop residues are often not returned to the soil but are burnt before the land is replanted to crops. To investigate the implications of this on optimal management and the steady-state reached by the system will require that the necessary parameters of the meta-model are modified accordingly and the dynamic-programming algorithm rerun. Thirdly, the analysis reported here is deterministic and many of the real-world risks and uncertainties (such as poorly defined property rights, poor governance, fires, drought, and illegal harvesting) that threaten the productivity and profitability of such systems have not been accounted for. Areas of future research would therefore involve modifying the model to make it stochastic and investigating mechanisms for promoting good governance. Finally, the implications of payments for emission reductions generated when the firewood that is harvested is used to substitute for fossil fuels needs to be investigated. This area of research is particularly relevant and urgent since oil prices were fluctuating between US$90 and US$100 per barrel at the end of 2007, and there is a growing global demand for bio-energy.

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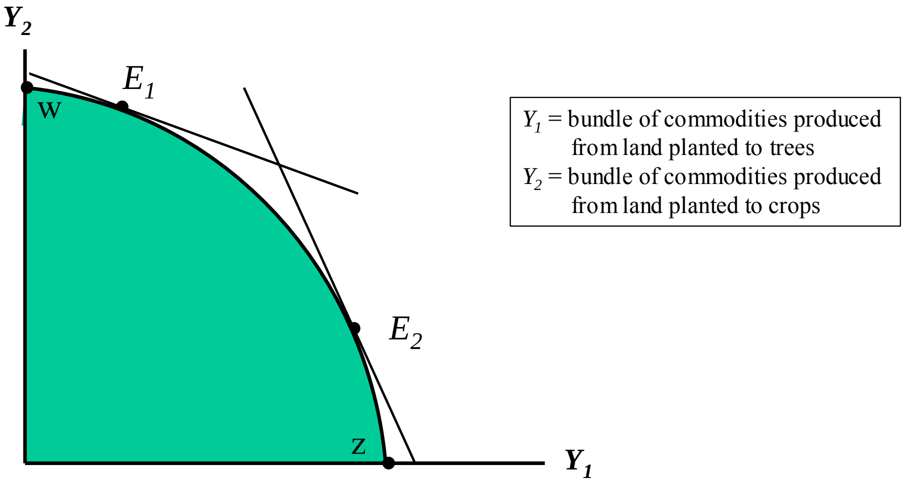


Figure 1. Pareto efficient production possibilities of landholders when (1) not receiving payments for positive environmental externalities and (2) when positive external effects are internalised through carbon-sequestration payments

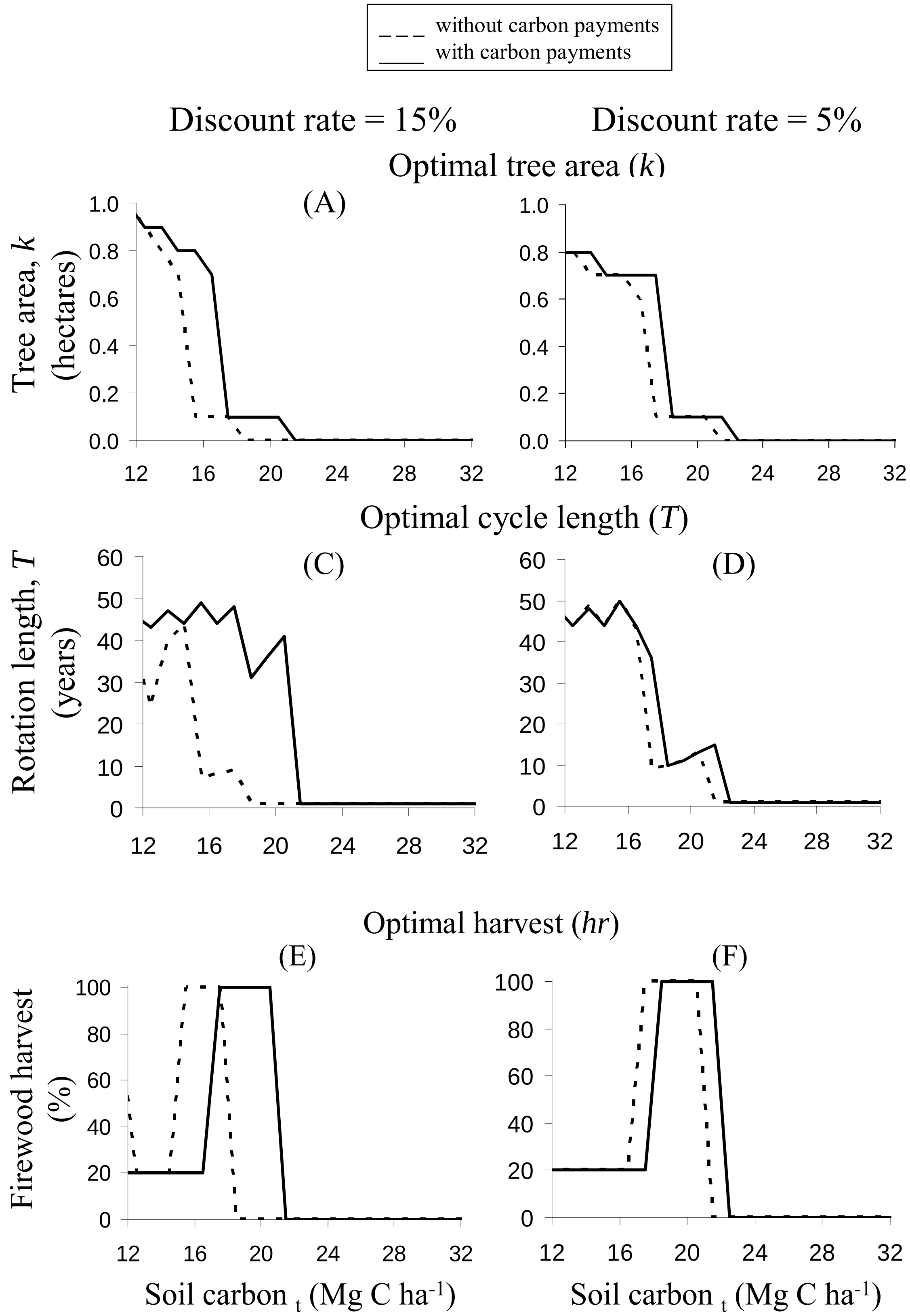


Figure 2. Optimal management regimes obtained by solving the dynamic-programming model for ‘with carbon payment’ and ‘without carbon payment’ scenarios under two discount rates, at base-case values for the economic and biophysical parameters

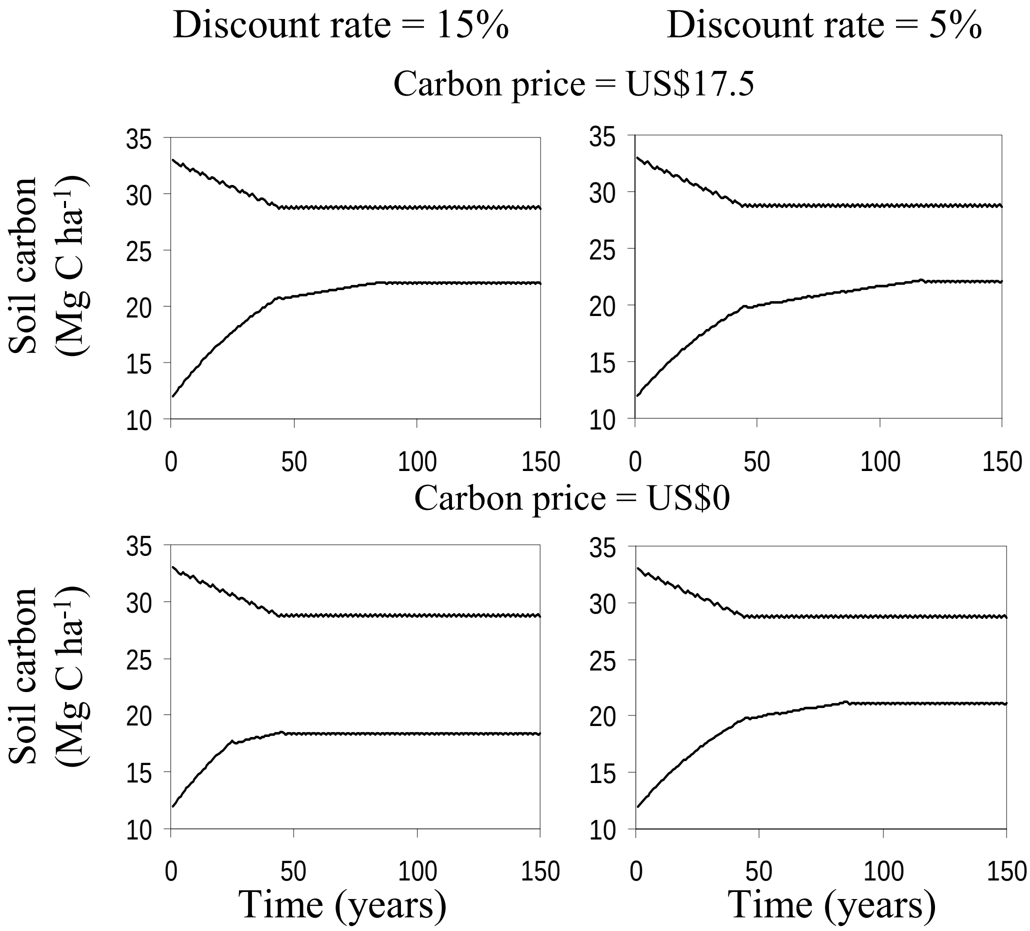
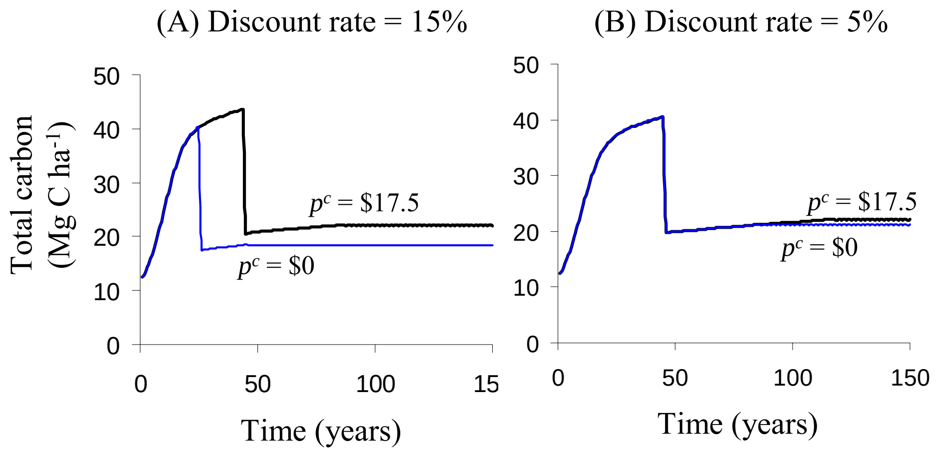


Figure 3. Optimal state paths associated with the optimal management decisions obtained by solving the dynamic-programming model for ‘with carbon payment’ and ‘without carbon payment’ scenarios under two discount rates, at base-case values for the economic and biophysical parameters



(A) Discount rate = 15%

(B) Discount rate = 5%

Figure 4. The trajectory of the total eligible-carbon stock associated with the optimal management regimes for the different carbon prices and discount rates for the poor-quality soil scenarios

Table 1. Base-case values (coefficients) for the dependent variables of the quadratic equations defining the biophysical numerical model

	Soil carbon (β)		**Tree biomass (α)**		**Crop yield (δ)**	
	Coefficient	**t-value**	**Coefficient**	**t-value**	**Coefficient**	**t-value**
0	0.7790	(17.18)	-0.8730	(-11.16)	-0.3920	
1	0.9684	(238.65)	0.9910	(628.36)	0.1737	
2	0.0004	(4.28)	-0.0048	(-161.99)	-0.0031	(-11.31)
3	0.0062	(8.45)	-0.0005	(-11.59)	-0.0003	(-4.48)
4	0.00005	(5.25)	0.2522	(121.85)	-0.0017	
5	-0.6216	(-24.49)	-0.0003	(-39.31)	0.0010	(23.21)
6	0.0804	(5.16)	0.0871	(11.55)	-	-
7	0.0077		-0.0021	(-12.33)	-	-
8	-0.0066	(-31.12)	0.0051	(2.88)	-	-
9	-	-	-0.00005	(-2.63)	-	-
10	-	-	2.7750	(50.42)	-	-
11	-	-	-2.0200	(-40.82)	-	-
12	-	-	0.0020	(4.84)	-	-
R^2		**0.99**		**0.70**		**0.99**

The associated t-values are given as a measure of the significance of each coefficient (a 95% significance requires the t-value be $\geq +2.08$ or ≤ -2.08).

Table 2. Base-case parameter values for economic variables

Description	Value	Units	Source
Firewood price	6.0	\$ Mg^{-1}	a
Price of carbon	17.5	\$ Mg^{-1}	d
Price of maize	180.0	\$ Mg^{-1}	e
Discount rate	15	%	b
Hedgerow-establishment cost	64.5	\$	c
C-monitoring costs	1.0	\$ $ha^{-1}yr^{-1}$	g
Variable costs for crop	210.0	\$ ha^{-1}	c
Price of labour	1.5	\$ day^{-1}	f
Maize-harvest labour	5	days Mg^{-1}	c
Prune and harvest labour	3	days Mg^{-1}	c
Labour for weeding	40	days ha^{-1} yr^{-1}	c
Carbon content of wood	50	%	h

Sources: a: Wise and Cacho (2005a) , b: Menz and Magcale-Macandog (1999) c: Nelson *et al.* (1998) & Grist *et al.* (1999), d: Cacho *et al.* (2003), e: Katial-Zemany and Alam (2004), f: NWPC, (2005), g: Wise and Cacho (2005a), h: Young *et al.* (1998).

Table 3. Optimal decisions over eight cycles for the two carbon-price scenarios (scenario 1 = US$17.5; scenario 2 = US$0), at a high (15%) and low (5%) discount rate

	Optimal tree area (k)*				*Optimal cycle length (T*, yrs)*			
Cycle	15% discount rate		5% discount rate		15% discount rate		5% discount rate	
	1	2	1	2	1	2	1	2
1	0.9	0.9	0.8	0.8	43	24	44	44
2	0.1	0.1	0.1	0.1	41	9	11	11
3	0	0.1	0.1	0.1	1	9	13	13
4	0	0	0.1	0.1	1	1	13	13
5	0	0	0.1	0	1	1	15	1
6	0	0	0.1	0	1	1	15	1
7	0	0	0	0	1	1	1	1
8	0	0	0	0	1	1	1	1
	Optimal harvest (hr, %)*				*Cumulative NPV (US$ ha $^{-1}$)*			
	15% discount rate		5% discount rate		15% discount rate		5% discount rate	
	1	2	1	2	1	2	1	2
1	20	20	20	20	88.1	-52.4	396.3	206.6
2	100	100	100	100	89.0	-48.7	436.8	247.9
3	0	100	100	100	89.0	-47.4	466.0	277.4
4	0	0	100	100	89.0	-47.3	482.6	294.3
5	0	0	100	0	89.0	-47.3	493.1	295.4
6	0	0	100	0	89.0	-47.2	498.4	296.4
7	0	0	0	0	0	0	498.6	297.4
8	0	0	0	0	0	0	498.9	298.3