Optimal land-use decisions in the presence of carbon payments and fertilizer subsidies: an Indonesian case study

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ABSTRACT

A meta-model was developed in this study to simulate soil-tree-crop interactions under various management regimes for a smallholding in Sumatra. The model was used within a dynamic-programming algorithm to determine profit-maximising management strategies for a landholder faced with opportunities to receive carbon credits and fertiliser subsidies. It was found that: 1) incentives to participate in carbon projects only exist when the soil is degraded in which case only trees should be grown and residues added to the soil to increase carbon stocks; 2) a threshold soil-carbon level exists where it becomes optimal to switch from trees to a steady-state system of crops with fertiliser; 3) tree-rotation lengths are positively related to fertiliser and carbon prices; and 4) in better quality soils profits are maximised by growing only crops and using fertiliser.

1. INTRODUCTION

Agroforests are often recommended as alternatives to the shifting-cultivation and continuous-cropping systems blamed for much of the land degradation in southeast Asia (de Foresta and Michon, 1997; Makundi and Sathaye, 2004). But, landholders may not consider tree-based systems as viable alternatives to crops because of high establishment costs, delayed revenues and lack of secure property rights. Recognising the environmental and social services provided by trees, such as mitigating climate change by sequestering carbon, may assist in overcoming these obstacles.

The conceptual basis of this paper can be illustrated by considering the Production Possibility Frontier (PPF) of a local economy that has a fixed amount of resources to produce bundles of products from two land uses: trees (Y_1) and crops (Y_2) with a given set of inputs and technology (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. If the external environmental benefits provided by trees are internalised through direct payments the price ratio (p_1/p_2) will become steeper and landholders will plant a larger area of their land to trees (point E_2, Figure 1).

[INSERT FIGURE 1]

The Kyoto Protocol (KP) provides the policy context for this analysis, in particular Article 3.3 (Land-use Change and Forestry, LUCF) and Article 12 (Clean Development Mechanism, CDM). These Articles give incentives to developed countries to invest in greenhouse gas mitigation activities, including carbon sinks such as small-scale forestry and agroforestry, in developing countries to help them meet their Kyoto emission limitations at minimum cost. The implications of this are that it becomes possible for landholders to benefit from the resulting technological and financial transfers by claiming credit for sequestered CO_2. Carbon credits[1], however, may only be claimed when sequestered carbon is certified, which requires that project proponents demonstrate a net reduction in emissions compared with the status quo or *baseline*. The effect of the baseline on the eligibility of carbon sequestered by LUCF projects can be significant (Wise and Cacho, 2005a). Here we assume a relatively stable carbon stock, representative of degraded grassland, as the baseline. The problem of the lack of *permanence* of carbon sequestered in biomass and soil is dealt with using the "ideal" accounting method proposed by Cacho *et al.* (2003).

In this paper we develop a meta-model of an agroforestry system and incorporate it into a dynamic programming (DP) algorithm to determine profit-maximising management strategies in the presence of carbon payments and fertiliser subsidies.

2. METHOD

2.1 Economic model

This paper extends the agroforestry model of Cacho (2001) by including carbon-sequestration payments in addition to the externalities provided by trees on crops. As a starting point, consider a landholder participating in a CDM project and receiving payments for CERs. The present value of net revenues (*NPV*) obtained from an area of land *A* over a project-investment period of *T* years is:

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[1] The proposed medium of exchange of C credits under the CDM is the Certified Emission Reduction (CER).

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

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, harvesting and fertilising activities; *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, applying fertiliser 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 change in eligible tree-biomass carbon, y_t^{sc} is the change in eligible 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) to include non-timber benefits. Such models require that the length of each cycle (T), the management variables defined within the vector $\boldsymbol{x}$, and initial land quality for each cycle S_n remain constant for all cycles n = 1,2,…N. 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 for an infinite planning horizon of n cycles by backward induction until convergence in $V(S_n)$ is achieved (Kennedy, 1986).

2.2. Model calibration

Agroforests involve growing trees and crops sequentially or simultaneously to improve the productivity and sustainability of the land. Capturing the benefits offered by agroforests necessitates that complementary interactions be maximised and competitive interactions be minimised through management. Agroforestry may involve commercially growing trees with food crops when the trees are young (Otsuka and Place, 2001) or intercopping food crops with nitrogen-fixing trees (Sanchez, 1995). In this study, a rainfed agroforestry system was investigated in which two maize crops per year were intercropped between Gliricidia (*Gliricidia sepium*) hedgerows over a period of 25 years[2]. The process model SCUAF (Young *et al.*, 1998) was used to generate a dataset for meta-modeling. SCUAF was used as it estimates the effects that changes in soil properties (nutrients, soil carbon and soil depth) have on tree and crop productivity based on the management regimes and net-primary-productivity (NPP) rates of the crops and trees. SCUAF has been tested for a range of environments and management conditions by authors such as Nelson *et al.* (1998) and Vermeulen *et al.* (1993).

Gliricidia was simulated because of its soil-amelioration capabilities and its ability to grow rapidly and produce various commodities such as firewood, fodder, or timber. Maize was selected because it is one of the more commonly grown food crops in Indonesia, along with rice, soybeans and cassava. The parameters selected for this

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[2] Many cropping patterns exist 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).

study define a 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. The lower values represent a run-down soil requiring regeneration. Calibration of much of the model was based on data from Nelson *et al.* (1998) and Grist *et al.* (1999).

The management parameters varied in this study 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, so $0 \leq k \leq 1$ (i.e. k also represents a fraction of the area of the smallholding). These values of management parameters were set at the beginning of a simulation and held constant throughout a rotation. A dataset was generated by increasing the area planted to trees (k) at intervals of 0.1, resulting in 11 tree/crop area combinations. Each of these strategies was then replicated under three prune/harvest regimes, resulting in 33 simulated management strategies. In SCUAF, pruning and harvesting intensities are defined as percentages of the annual increment in total tree biomass. In this study 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. 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 was affected by harvest regime (hr).

Each of the resulting 33 scenarios (11 tree/crop combinations x 3 harvest regimes) was then simulated for four fertiliser application regimes (*fr*) resulting in a total of 124 treatments. The four fertiliser regimes comprised a mix of nitrogen (N) and phosphorous (P) as follows: (1) *fr = 0*; (2) *fr = 50* (40 kg N, 10 kg P); (3) *fr = 100* (80 kg N, 20 kg P); and (4) *fr =150* (120 kg N, 30 kg P). These nutrients were added annually to the crop component. According to van Noordwijk *et al.* (1995) soils in southern Sumatra are often acidic and infertile due to high leaching rates and aluminium toxicity of the subsoil, hence the need for annual fertiliser applications. Adiningsih and Karama (1992) state that nitrogen and potassium deficiencies are probably the most severe constraints on plant productivity making fertiliser application essential[3]. Wise and Cacho (2005a) found that without fertiliser, yields from a Gliricidia-maize agroforest were not sustained beyond the first ten years of a 25-year simulation period. The biophysical parameter values used in this study were based on Wise and Cacho (2005a; 2005b). The parameter values for the economic model are listed in Table 1. Prices are quoted in US dollars using an exchange rate of 10,000 Indonesian Rupiah per US Dollar. A real discount rate of 15% was used to represent the rate of time preference of individual landholders in remote areas of Indonesia (Menz and Magcale-Macandog, 1999).

[INSERT TABLE 1]

A simplified econometric production model comprising a set of quadratic equations that interactively mimic soil-carbon changes, tree-biomass accumulation and crop-yield dynamics in response to changes in management was derived based on the

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[3] Nelson *et al*, (1999) and Fagi (1992) recommend between 120 and 248 kg urea ha^{-1} yr^{-1} and between 93 and 98 kg of triple super phosphate (TSP) be added when growing two maize crops ha^{-1} yr^{-1}.

dataset generated by SCUAF. The dataset contained 6,200 observations[4]. 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:

$$s_t = \beta_0 + \beta_1 \cdot s_{t-1} + \beta_2 \cdot (s_{t-1})^2 + \beta_3 \cdot s_{t-1} \cdot (1-k) + \beta_4 \cdot s_{t-1} \cdot fr + \beta_5 \cdot s_{t-1} \cdot hr + \beta_6 \cdot fr$$
$$+ \beta_7 \cdot (1-k) + \beta_8 \cdot (1-k)^2 + \beta_9 \cdot (1-k) \cdot hr + \beta_{10} \cdot hr \qquad (7)$$

$$b_t = \alpha_0 + \alpha_1 \cdot b_{t-1} + \alpha_2 \cdot (b_{t-1})^2 + \alpha_3 \cdot b_{t-1} \cdot s_t + \alpha_4 \cdot b_{t-1} \cdot k + \alpha_5 \cdot b_{t-1} \cdot hr + \alpha_6 \cdot s_t$$
$$+ \alpha_7 \cdot (s_t)^2 + \alpha_8 \cdot s_t \cdot k + \alpha_9 \cdot s_t \cdot fr + \alpha_{10} \cdot s_t \cdot hr + \alpha_{11} \cdot fr$$
$$+ \alpha_{12} \cdot k + \alpha_{13} \cdot k^2 + \alpha_{14} \cdot hr \qquad (8)$$

$$y_t^a = \delta_0 + \delta_1 \cdot s_t + \delta_2 \cdot (s_t)^2 + \delta_3 \cdot s_t \cdot b_t + \delta_4 \cdot s_t \cdot fr + \delta_5 \cdot fr$$
$$+ \delta_6 \cdot b_t \cdot fr + \delta_7 \cdot b_t + \delta_8 \cdot (b_t)^2 \qquad (9)$$

The explanatory variables in each equation (presented in Table 2) are those that fit the simulated treatments best ($P \le 0.05$). 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.

[INSERT TABLE 2]

This method of approximating a complex, process simulation model with a simple mathematical or econometric model is known as meta-modelling (Kleijnen and

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[4] The product of 124 management regimes, 25 years and 2 initial states of soil quality.

Sargen, 2000). Meta-models have been widely used to reduce the time required for full simulation and have been successfully applied to model a variety of environmental problems. Mas *et al.*, (2004), for example, apply meta-modelling techniques to simulate deforestation. Antle and Capalbo (2001) developed such meta-models based on simulated data using the Century model and field-level economic production data, although they refer to such models as “econometric process” or “econometric production simulation” models.

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).

3. RESULTS

Optimal decision rules and optimal state transitions were determined by solving the DP model for four carbon-price and fertiliser-price scenarios (Table 3), and the effects of tree externalities on the optimal path of the state variable were investigated for the base-case parameters listed in Table 1. The low fertiliser price (p^f = \$0.18 kg^{-1})

represents situations where fertilisers are subsidised (USAID, 2003) and the effect of removing this subsidy is investigated by making p^f = \$ 0.39 kg^{-1}, which is at the upper range for fertiliser prices as given by van Noordwijk *et al.*, (1995).

[INSERT TABLE 3]

3.1.1 Optimal-decision rules

The optimal tree area (k^*), cycle length (T^*), firewood-harvest regime (hr^*) and fertiliser regime (fr^*) associated with each of the scenarios in Table 3, holding all other variables constant at base-case values, are plotted in Figure 2. These plots show the optimal state-contingent decisions. The effect of p^c on optimal management is determined by comparing the solid and dashed curves within each of the eight graphs. The effect of p^f on optimal management is investigated by comparing the graphs between columns 1 and 2 (Figure 2).

The most significant finding is that it is either optimal to plant only trees or only crops, rather than any combination of the two (Figures 2A & B), which corresponds to points '*w*' and '*z*' respectively on the PPF in Figure 1 and implies a straight-line PPF. Trees are planted when the soil-carbon content is relatively low, because crops are less productive so the opportunity cost of growing trees is low, and to take advantage of the trees' ability to restore the soil through nitrogen-fixation and residue additions (Figures 2E & F). The higher the p^c and p^f the greater the stock of soil carbon required before the optimal solution switches from trees to crops because the opportunity cost of switching to crops is higher. Fertiliser is not used when growing trees because Gliricidia is nitrogen-fixing.

In the absence of carbon payments, and with a low fertiliser price (left panel in Figure 2), it is optimal to plant the entire plot to trees at s_t values less than about 17.5 Mg C ha^{-1} (Figure 2A) for rotations of between 7 and 22 years (Figure 2C), to return 80% of pruned biomass to the soil as residues (Figure 2G) and to not apply fertiliser (Figure 2E). It is optimal to do this because the soil is not productive enough to produce acceptable maize yields, even when fertiliser is used. However, at values of s_t greater than 17.5 Mg C ha^{-1} it is optimal to grow crops continuously and to apply 150 kg ha^{-1} of fertiliser because larger profits are made and maize yields can be sustained.

[INSERT FIGURE 2]

With unsubsidised fertiliser ($0.39) and without carbon payments (right panel in Figure 2) similar optimal-decision rules are observed but the lines shift to the right and s_t must now exceed 20.5 Mg C ha^{-1} to make crops the optimal land use. At a higher p^f the optimal cycle length increases to between 22 and 48 years, depending on the initial amount of carbon in the soil (Figure 2 D). Longer tree cycles are optimal because more time and tree biomass are required to increase s_t to 20.5 Mg C ha^{-1} than to 17.5 Mg C ha^{-1} as required at a low p^f; also, the higher p^f makes the opportunity cost of planting trees lower.

Carbon payments provide incentives to keep trees for longer and at higher soil-carbon levels (compare solid lines with dashed lines in Figure 2). It is now optimal to grow trees for s_t values up to 18.5 Mg C ha^{-1} for the low p^f and up to 25.5 Mg C ha^{-1} for the high p^f and to increase tree-cycle length to between 41 and 50 years depending on p^f. The critical value of s_t at which it becomes optimal to switch from trees to crops increases in the presence of carbon payments because a more productive soil is needed to make crops more profitable than trees.

3.1.2 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. If the initial soil quality is relatively good (s_0 = 33 Mg C ha^{-1}) it is optimal to exploit the system with continuous cropping and fertiliser application, reducing soil carbon for 57 years until it reaches an equilibrium value of 27.8 Mg C ha^{-1}. 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 (17.8, 22.8, or 28.1 Mg C ha^{-1} depending on p^f and p^c) by growing trees and returning pruned biomass to the system as residues and then switching to crops plus fertiliser.

[INSERT FIGURE 3]

With s_0 = 33 Mg C ha^{-1}, the presence of carbon payments and/or the removal of fertiliser subsidies has no effect on the optimal soil-carbon path; it is optimal to plant crops and not to participate in the carbon market. When the system is relatively degraded (s_0 = 12 Mg C ha^{-1}) it is optimal to grow trees to replenish soil-carbon stocks and to participate in the carbon market. When s_t reaches its target equilibrium, crops are grown because the opportunity cost of growing trees has increased as a result of the higher soil carbon. This means that the initial state of the soil (s_0) as well as prices influence the optimal level of soil carbon at equilibrium. Only when a high p^f is combined with carbon payments is it optimal to build soil carbon to a single equilibrium level (Figure 3C). The decisions that cause the s_t trajectories depicted in

Figure 3 may be determined from Figure 2 where the optimal decision rules associated with all states of the soil are plotted.

Finally, it is informative to investigate the trajectories of the total eligible-carbon stock associated with the optimal-decision rules, as this reflects the cumulative stream of annual carbon payments (Figure 4). The trajectories of the eligible-carbon stock emphasise the positive relationship between p^c and p^f on the quantity of CERs associated with each optimal management regime[5].

[INSERT FIGURE 4]

3.1.3 Sensitivity analysis

The optimal decisions (for the first five cycles only) that lead to the state paths depicted Figures 3 and 4 are presented, for both low (columns 2 to 5) and high soil carbon values (columns 8 to 11) in Table 4. The sensitivity of these optimal decisions to an increase in the price of fertiliser due to higher fuel prices was investigated by running the model for two further carbon-price and fertiliser-price scenarios (tabulated as scenarios 5 and 6 in Table 4). The fertiliser price was assumed to increase to US$0.6, and all other prices remained unchanged. Scenario 5 represents the optimal decisions at a higher fertiliser price and with p^c = US$15. Scenario 6 represents the higher fertiliser price with p^c = US$0.

[INSERT TABLE 4]

The most noticeable change, for both initial soil carbon levels, is that it is never optimal to plant crops but to grow trees only and use no fertiliser. When growing trees is a landholder's only option, the intensity with which the trees are harvested becomes

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[5] The equivalent trajectories when s_0 is high are not plotted as they are identical to those presented in Figure 4.

extremely important as the landholder must now balance the tradeoffs between harvesting the wood for firewood (and depleting the soil of carbon) or not harvesting and returning the biomass to the soil to increase the carbon stock of the system (and forgoing revenue from firewood sales). This decision depends on whether the opportunity to receive carbon payments exists or not. When receiving carbon payments (scenario 5) the optimal decision path involves harvesting an average of only 20% (when s_0 is low) or 40% (when s_0 is high) of the annual increment in aboveground biomass. When not receiving carbon payments (scenario 6) incentives exist to exploit the system and the optimal harvest regime increases to an average of about 50% of the annual increment in aboveground biomass, irrespective of initial soil carbon stock. The tree-rotation lengths are not particularly responsive to either initial soil-carbon stock or to whether receiving carbon payments or not.

4. DISCUSSION AND CONCLUSIONS

Our results indicate that the optimal-decision path through time depends on the initial carbon content of the soil (s_0). If the land has relatively high soil-carbon content, it is optimal to only grow crops and to apply fertiliser. The crops initially deplete the soil of carbon until a ‘target’ steady state is reached where it is then maintained over time. In this case, carbon payments have no effect on the optimal management of the system; but they do decrease profitability because landholders are required to pay for the carbon lost from the soil. Consequently, based on the assumptions of this paper, incentives do not exist for landholders to participate in the carbon market when soil quality is good. This is especially true when fertiliser is subsidised, as this increases crop profitability.

If the initial soil quality is relatively poor the results are quite different. Optimal management involves planting the entire area to trees for cycles lasting 20 to 100 years and returning 80% of pruned biomass to the soil to replenish soil nutrients. This increases the soil-carbon stock and the productivity of the system. Once the trees have built up the soil-carbon stock to a target steady state it becomes optimal to switch to only crops and to use fertiliser to help maintain the soil-carbon level. The optimal number of tree rotations and their optimal length depend on carbon and fertiliser prices. Payments for carbon make it optimal to lengthen the tree cycle and, if combined with a high fertiliser price, it becomes optimal to plant a second tree rotation. It is always optimal to participate in the carbon market when growing trees.

An important finding in this analysis is that it is generally not optimal to build poor quality soils (low soil-carbon content) up to the same target steady state as that reached for good quality soils. The target steady state to which the carbon content of poor quality soils is raised depends on the prices of carbon and fertiliser. Only when carbon and fertiliser prices are high is it optimal to build a low s_0 up to the same target steady state as that reached for soils with high s_0.

The currently high fuel prices may affect not only the cost of producing fertiliser, but also the cost of transportation to remote areas with poor roads. It was found that at a fertiliser price of \$0.6/kg it is never optimal to plant crops, but it is optimal to grow trees only and to use no fertiliser, irrespective of the initial soil carbon stock. When growing only trees, the intensity with which the trees are harvested becomes extremely important as the landholder must balance the tradeoffs between harvesting the wood for firewood (and depleting the soil of carbon) or not harvesting and returning the biomass to the soil to increase the carbon stock of the system (and forgoing the revenue from firewood sales). This decision depends on whether the opportunity to receive carbon payments exists or not.

Finally, this paper has identified issues requiring further investigation. Firstly, under certain economic and biophysical conditions it was optimal to grow only trees for periods between 20 and 100 years. Such a commitment has implications for landholder food security and traditional farming of food crops and it may be unlikely that farmers will adopt such practices. This might be overcome by adopting a landscape approach to land management whereby trees are planted to restore degraded areas while crops are planted in the better land. Secondly, property rights associated with trees and tree products often do not exist or are poorly defined in developing countries, which is likely to make the long-term adoption of trees unlikely unless the appropriate institutional arrangements are in place. Thirdly, the risks of growing trees (e.g., fires and illegal logging) have not been included in the model but may alter the decision rules found to be optimal. Fourthly, the implications of payments for emission reductions generated when firewood harvested is used to substitute for fossil fuels needs to be investigated. Lastly, the optimal decision rules and state paths identified for the assumptions in this study imply that the PPF of the simulated agroforestry system is a straight line because corner solutions were always obtained. The implications of assuming a more conventional PPF (e.g., a system with stronger complementarities between trees, soils and crops) can be investigated by modifying the parameters of the meta-model.

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Table 1. Base-case parameter values.

Description	Value	Units	Source
Firewood price	4.5	$ Mg^{-1}	a
Price of carbon	15.0	$ Mg^{-1}	d
Price of maize	140.0	$ Mg^{-1}	e
Fertiliser price	0.18	$ kg^{-1}	f
Discount rate	15	%	b
Hedgerow-establishment cost	64.5	$	c
C-monitoring costs	1.0	$ ha^{-1}yr^{-1}	h
Variable costs for crop	210.0	$ ha^{-1}	c
Price of labour	1.5	$ day^{-1}	g
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	%	i

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: USAID, (2003), g: NWPC, (2005), h: Wise and Cacho (2005a), i: Young *et al.* (1998).

Table 2. 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)	-0.7920	(-7.72)
1	0.9684	(238.65)	0.9910	(628.36)	0.1610	(12.24)
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	-0.00001	(-3.31)	0.2522	(121.85)	0.0001	(5.68)
5	0.00005	(5.25)	-0.0003	(-39.31)	0.0067	(26.72)
6	0.0007	(11.73)	0.0871	(11.55)	-0.0002	(-39.49)
7	-0.6216	(-24.49)	-0.0020	(-12.33)	-0.0370	(-17.56)
8	0.0804	(5.16)	0.0050	(2.88)	0.0010	(23.21)
9	0.0057	(39.99)	0.00002	(4.12)	-	-
10	-0.0066	(-31.12)	-0.0001	(-2.63)	-	-
11	-	-	-0.0004	(-3.49)	-	-
12	-	-	2.7750	(50.42)	-	-
13	-	-	-2.0200	(-40.82)	-	-
14	-	-	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 3. Four base-case carbon- and fertiliser-price scenarios simulated in the dynamic-programming model. Each of these is simulated for a 15% discount rate.

Scenario	**Carbon price ($ Mg C^{-1})**	**Fertiliser price ($ kg^{-1})**
1	15	0.18
2	0	0.18
3	15	0.39
4	0	0.39

Table 4. Optimal decisions over five cycles for base-case fertiliser- and carbon-price scenarios, and two high fertiliser-price scenarios (scenarios 5 and 6), at a low and high initial soil-carbon level, and a discount rate of 15%

Cycle	**Low initial soil carbon (s_0 = 12 Mg C ha^{-1})**						**High initial soil carbon (s_0 = 33 Mg C ha^{-1})**					
	Optimal tree area (k)*											
	Scenario						Scenario					
	1	2	3	4	5	6	1	2	3	4	5	6
1	1	1	1	1	1	1	0	0	0	0	1	1
2	0	0	1	0	1	1	0	0	0	0	1	1
3	0	0	0	0	1	1	0	0	0	0	1	1
4	0	0	0	0	1	1	0	0	0	0	1	1
5	0	0	0	0	1	1	0	0	0	0	1	1
	Optimal rotation (T, yrs)*											
	Scenario						Scenario					
	1	2	3	4	5	6	1	2	3	4	5	6
1	49	21	49	49	49	49	1	1	1	1	31	49
2	1	1	50	1	50	47	1	1	1	1	36	50
3	1	1	1	1	37	50	1	1	1	1	42	50
4	1	1	1	1	43	45	1	1	1	1	31	49
5	1	1	1	1	42	46	1	1	1	1	43	50
	Optimal harvest (hr, %)*											
	Scenario						Scenario					
	1	2	3	4	5	6	1	2	3	4	5	6
1	20	20	20	20	20	40	0	0	0	0	40	60
2	0	0	20	0	20	80	0	0	0	0	40	60
3	0	0	0	0	20	20	0	0	0	0	20	20
4	0	0	0	0	40	100	0	0	0	0	40	20
5	0	0	0	0	20	20	0	0	0	0	40	80
	Optimal fertiliser (fr, kg)*											
	Scenario						Scenario					
	1	2	3	4	5	6	1	2	3	4	5	6
1	0	0	0	0	0	0	150	150	150	150	0	0
2	150	150	0	150	0	0	150	150	150	150	0	0
3	150	150	150	150	0	0	150	150	150	150	0	0
4	150	150	150	150	0	0	150	150	150	150	0	0
5	150	150	150	150	0	0	150	150	150	150	0	0

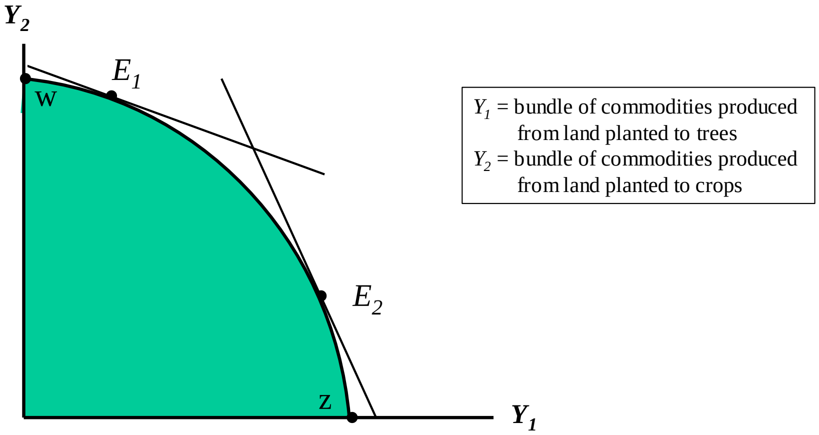


Figure 1. Pareto efficient production possibilities of an individual landholder when (1) not receiving payments for positive environmental externalities (E_1) and (2) when positive external effects are internalised through carbon-sequestration payments (E_2)

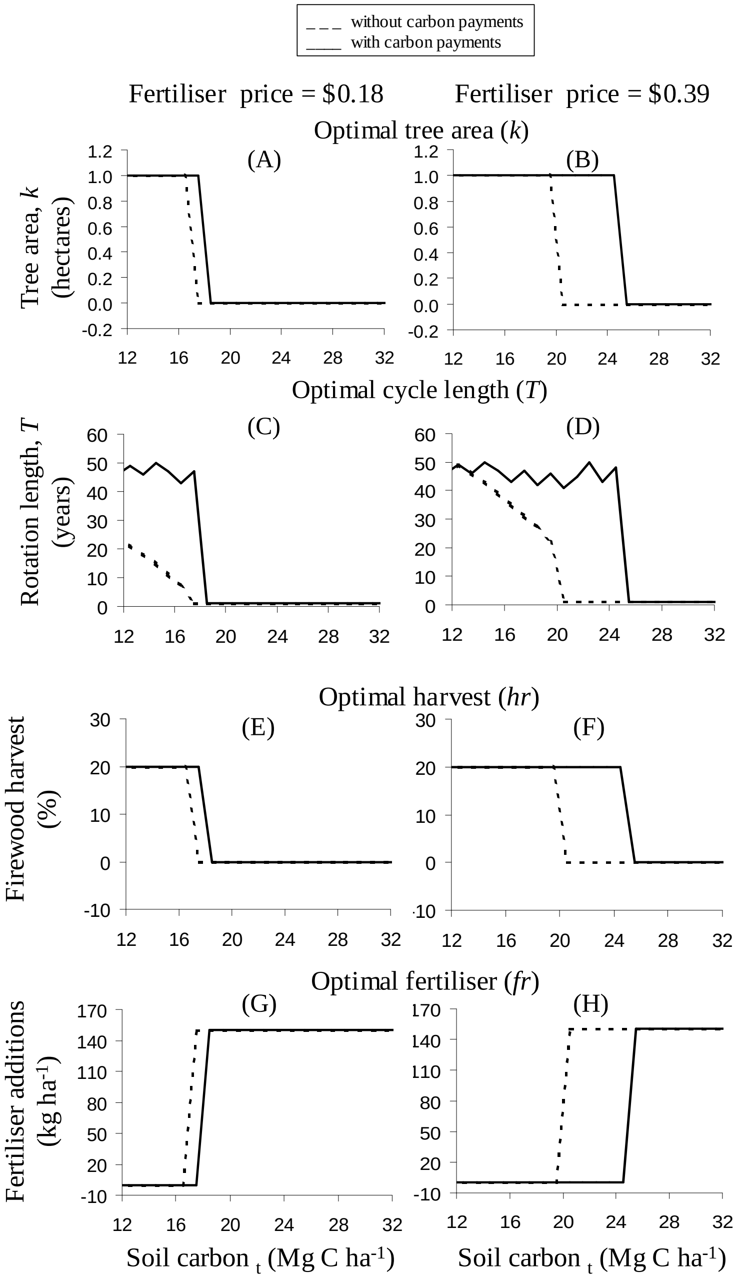
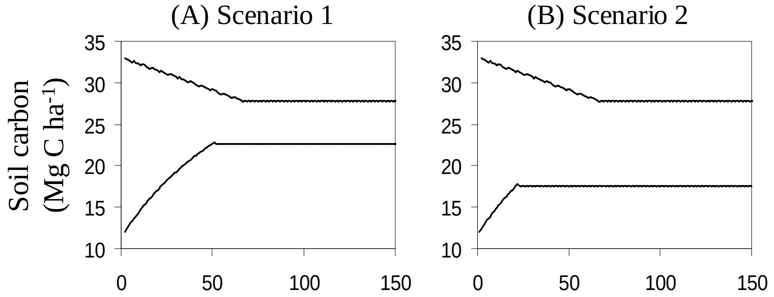


Figure 2. Optimal management regimes obtained by solving the Dynamic-Programming model for four combinations of fertiliser and carbon prices, at base-case parameter values.



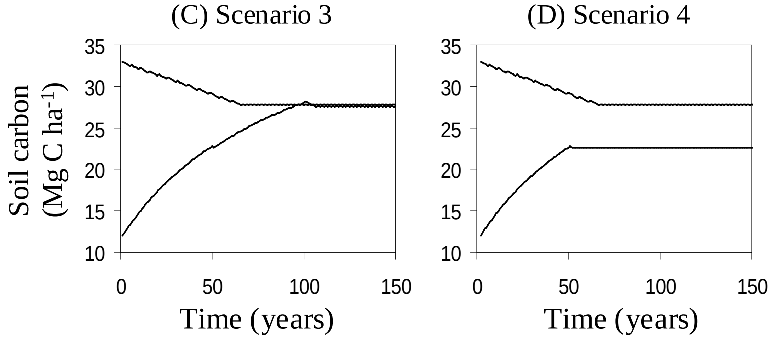


Figure 3. Optimal state paths associated with the optimal management decisions obtained by solving the Dynamic-Programming model for four combinations of fertiliser and carbon prices and two levels of initial soil carbon, at base-case parameter values.

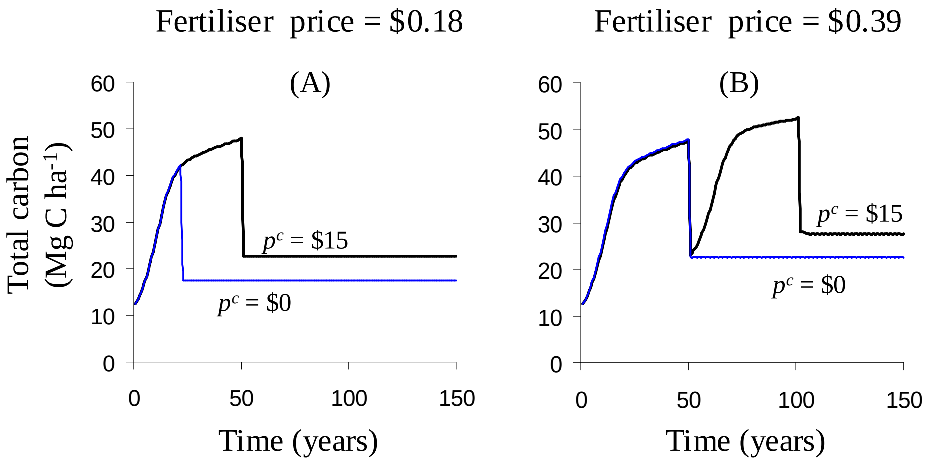


Figure 4. The trajectory of the eligible-carbon stock associated with the optimal management regimes for the different prices of carbon and fertiliser for a poor quality soil.