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

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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 often do not consider tree-based systems as viable alternatives to crops because of high establishment costs, delayed revenues and lack of secure property rights. However, the environmental services provided by trees, such as mitigating climate change by sequestering carbon (C), are increasingly being recognised for their associated social value.

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 C 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 C 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 C sequestered by LUCF projects can be significant (see, Wise and Cacho, 2005a) but such complexity is avoided here by using a relatively stable C stock, representative of grassland, as the baseline. The problem of the lack of *permanence* of C 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 optimal management strategies in the presence of C payments.

2. METHOD

2.1 General economic model

This paper extends the agroforestry model of Cacho (2001) by including C-sequestration payments. 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:

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

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-C content and soil fertility; $\boldsymbol{x}$ is a vector of management

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

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 is the discount factor with a discount rate r.

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

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

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:

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

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 C accumulation in tree biomass and soil relative to the baseline (referred to as 'eligible C'):

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

where y_t^{bc} is the change in eligible tree-biomass C, y_t^{sc} is the change in eligible soil-C stock, p^c is the price of CERs and cm_t is the annual C-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 included 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:

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

subject to:

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

where, S_n is defined above, $f_t(\cdot)$ 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

A rainfed agroforestry system was investigated in which two maize crops per year were grown between Gliricidia (*Gliricidia sepium*) hedgerows over a period of 25 years. The process model SCUAF (Young *et al.*, 1998) was used to generate a dataset for meta-modeling. 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) .

The parameters selected for this study define a site in a sub-humid climate, with acidic, medium-textured soils of felsic parent material and imperfect drainage. The C and nitrogen (N) 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*). A total of 124 treatments were simulated for a period of 25 years. Biophysical parameter values were based on Wise and Cacho (2005b; 2005a). The parameter values for the economic model are listed in Table 1. Prices are quoted in US dollars using an exchange rate of Rp10,000 to $1. 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 was derived based on the dataset generated by SCAUF. The dataset contained 6,200 observations[2]. 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:

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

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

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

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

The explanatory variables in each equation are those that fit the simulated treatments best ($P \leq 0.05$), coefficient values are not presented because of limited space.

This method of approximating a complex, process simulation model with a simple mathematical or econometric model is known as meta-modelling (Kleijnen and 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. 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 was used to generate values for equations (2), (3) and (4). The yields of crops, wood and C in these equations were calculated by simple differencing:

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

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

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

3. RESULTS

Optimal decision rules and optimal state transitions were determined by solving the DP model (equations (5) and (6)) for four C- and fertiliser-price scenarios (Table 2), 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 and the effect of removing this subsidy is investigated by making p^f = \$ 0.39 kg^{-1}.

[INSERT TABLE 2]

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 2, 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-C 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 N-fixation and residue additions (Figures 2E & F). The higher the p^c and p^f the greater the stock of soil C required before the optimal solution switches from trees to crops because the opportunity cost of switching to crops is higher. Fertiliser is not used with trees because Gliricidia is N-fixing.

In the absence of C 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 not apply fertiliser (Figure 2E) and to return 80% of pruned biomass to the soil as residues (Figure 2G). 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 C 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 C 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-C 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 C 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 crops and fertiliser which reduces soil C 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 C 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 and fertiliser.

[INSERT FIGURE 3]

With s_0 = 33 Mg C ha^{-1}, the presence of C payments and/or the removal of fertiliser subsidies has no effect on the optimal soil-C path; it is optimal to plant crops and not to participate in C-sink projects. When the system is relatively degraded (s_0 = 12 Mg C ha^{-1}) it is optimal to grow trees to replenish soil-C stocks and to participate in C-sink projects. When s_t reaches its target equilibrium crops are grown because the opportunity cost of growing trees has increased as the soil C increased. This means that the initial state of the soil (s_0) as well as prices influence the optimal level of soil C at equilibrium. Only when a high p^f is combined with C payments is it optimal to build soil C 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-C stock associated with the optimal-decision rules, as this reflects the cumulative stream of annual C payments (Figure 4). The trajectories of the eligible-C stock emphasise the positive relationship between p^c and p^f on the quantity of CERs associated with each optimal management regime[3].

[INSERT FIGURE 4]

4. DISCUSSION AND CONCLUSIONS

Our results indicate that the optimal-decision path through time depends on the initial C content of the soil (s_0). If the land has relatively high soil-C content, it is optimal to only grow

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

crops and to apply fertiliser. The crops initially deplete the soil of C until a ‘target’ steady state is reached where it is then maintained over time. In this case, C payments have no effect on the optimal management of the system; however they do decrease its profitability because landholders are required to pay for the C lost from the soil. Consequently, based on the assumptions of this paper, incentives do not exist for landholders to participate in C-sink projects 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-C stock and the productivity of the system. Once the trees have built up the soil-C stock to a target steady state it becomes optimal to switch to only crops and to use fertiliser to help maintain the soil-C level. The optimal number of tree rotations and their optimal length depend on C and fertiliser prices. Payments for C 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 C-sink projects when growing trees.

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

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 some areas are planted to trees while others are planted to crops. 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 substitutes 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. Four carbon and fertiliser price scenarios simulated in the DP model. Each of these is simulated for a 15% discount rate (base case) and a 5% discount rate (sensitivity analysis).

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

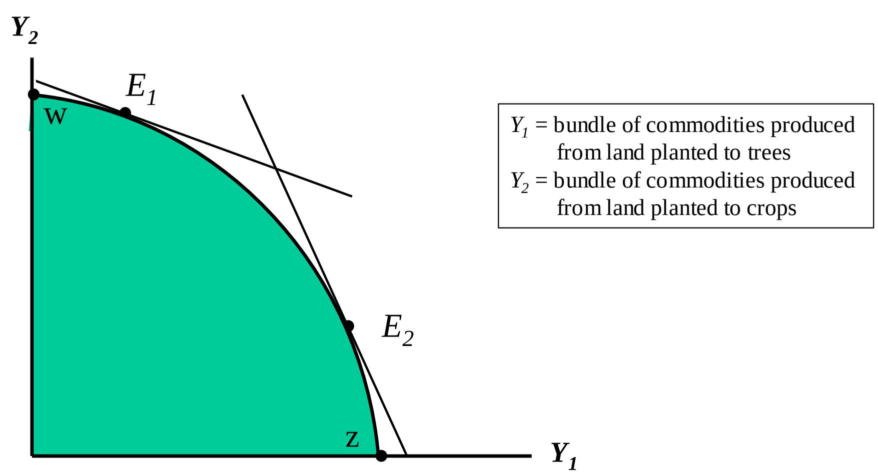

Figure 1. Pareto efficient production possibilities of an individual landholder when (1) not receiving payments for positive environmental externalities and (2) when positive external effects are internalised through carbon-sequestration payments

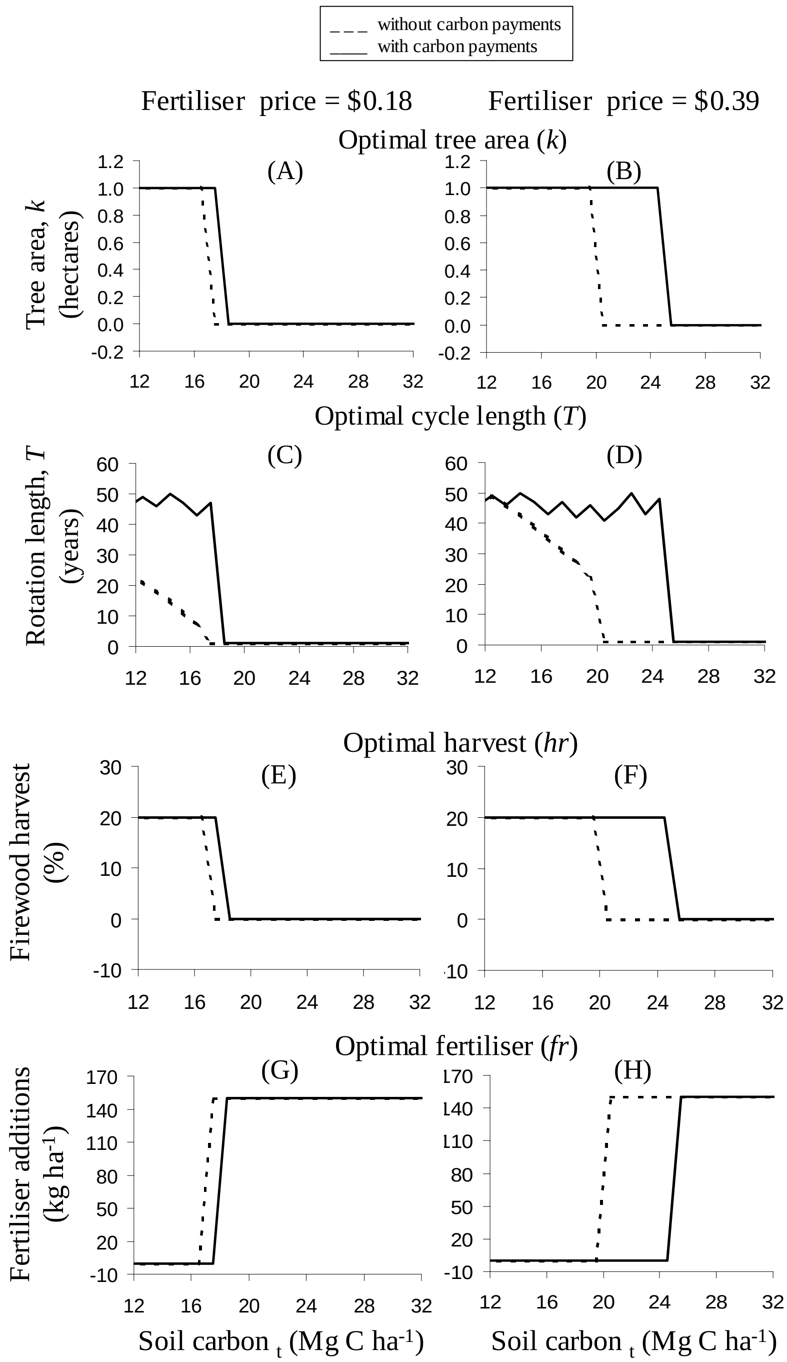

Figure 2. Optimal management regimes obtained by solving the Dynamic-Programming model for four combinations of fertiliser and carbon prices, at base-case parameter values.

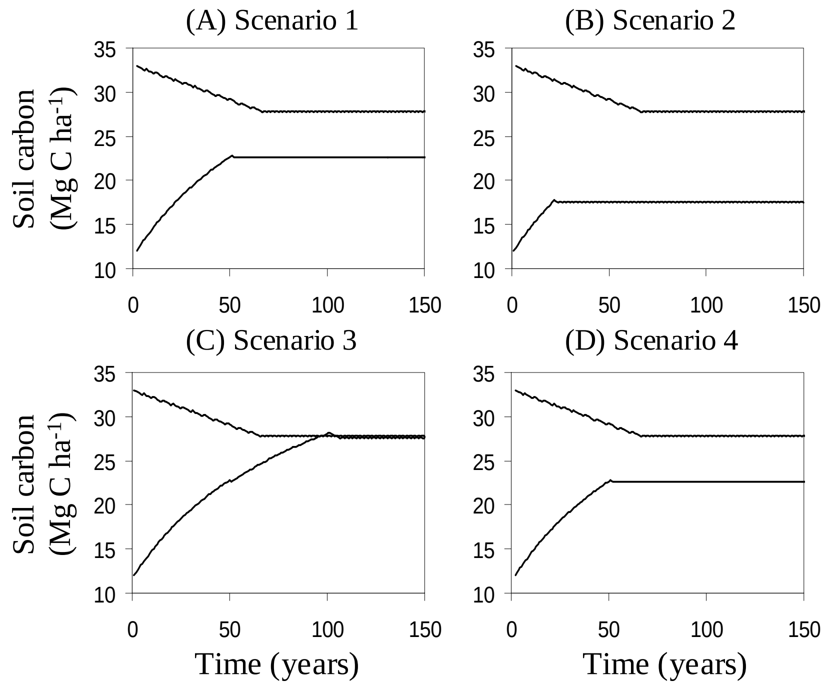

Figure 3. Optimal state paths associated with the optimal management decisions obtained by solving the Dynamic-Programming model for four combinations of fertiliser and carbon prices and two levels of initial soil carbon, at base-case parameter values.

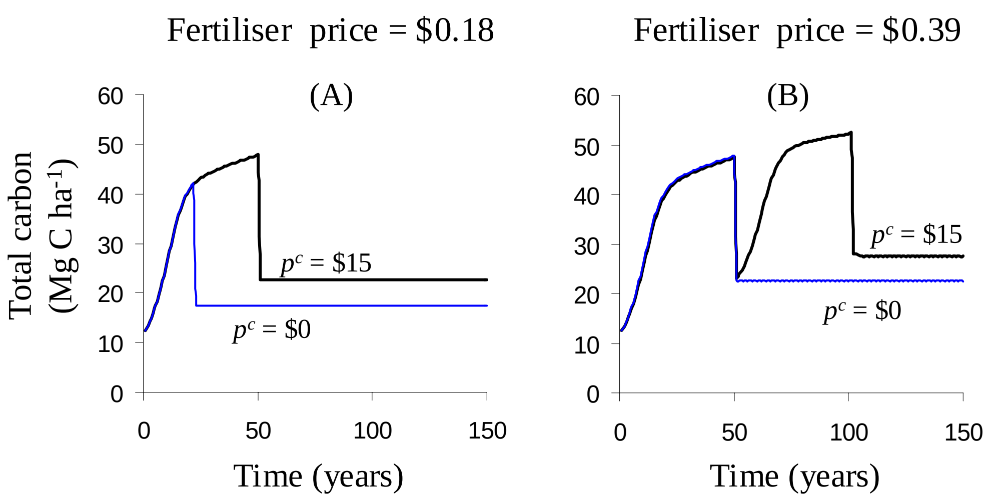

Figure 4. The trajectory of the eligible-carbon stock associated with the optimal management regimes for the different prices of carbon and fertiliser for a poor quality soil.