Dynamic optimisation of land-use systems in the presence of carbon payments[¥][Ω]

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ABSTRACT

Sustainable resource use requires that an inter-generational approach to management be adopted. Therefore the effects of current decisions on the future state of resource stocks must be considered. The Clean Development Mechanism (CDM) of the Kyoto Protocol presents an interesting context in which this can be applied and dynamic-optimisation theory provides the methodological framework. A relatively simple numerical model that simulates carbon stocks and flows in trees, crops and soils under a range of management regimes is developed for a landholding in Sumatra. The model is used within a dynamic-programming (DP) algorithm to determine optimal tree/crop areas, fertiliser regimes, tree-rotation lengths and firewood-harvest regimes. The DP model is solved for an individual landholder faced with deteriorating land quality and the opportunity to receive carbon credits by participating in a CDM-carbon project. The model is run for various combinations of fertiliser and carbon prices and land quality. It is found that optimal management depends on initial soil quality; that carbon and fertiliser prices only affect optimal management when land quality is poor; and that incentives to participate in carbon-sink projects only exist when soil quality is poor.

Keywords: agroforests, bioeconomics, carbon credits, dynamic programming, simulation modeling

1. INTRODUCTION

This paper investigates the appropriateness of agroforests as alternatives to shifting-cultivation and continuous-cropping systems, which are responsible for much of the land degradation in Southeast Asia. Landholders often do not consider trees or tree-based systems as viable alternatives to crops because of the high establishment costs, delayed revenues and the lack of secure property rights associated with them. However, the environmental services provided by trees, such as improving land productivity and mitigating climate change through carbon sequestration, are increasingly being recognised for their associated social values and there is growing interest in the use of market-based instruments to internalise these benefits (i.e. giving them direct market values). If these environmental benefits are successfully internalised and landholders receive direct financial payment for them, this may make the growing of trees more appealing to landholders. This paper therefore investigates whether payments for sequestered carbon (C) will give incentives to landholders to grow trees and how management will be affected by such payments?

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There are several examples of financial transfers for C-sequestration services provided by land-use systems (LUS). Most of these are bilateral arrangements between governments, private companies and investment funds. The World Bank's Community Development Carbon Fund, for example, came into operation in 2004 and invests in small-scale projects in the least developed countries and poor communities of developing countries.

The Kyoto Protocol (KP) provides the policy context for this analysis. In particular, KP Articles 3.3 and 12[1], are designed to give incentives to developed countries to invest in greenhouse-gas (GHG) mitigation activities, including C sinks such as small-scale forestry and agroforestry, in developing countries to help meet their Kyoto emission limitations. The objectives behind these Articles are to minimise the costs of climate-change mitigation while promoting technological and financial transfers to developing countries. Prerequisites to land-use change and forestry (LUCF) projects being eligible to receive payments for certified emission reductions (CERs) under the Clean Development Mechanism (CDM) are that they be sustainable, alleviate poverty, and complement the cultural and development goals of the host nation (Metz *et al.*, 2001).

In this analysis the appropriateness of agroforests is measured in terms of their profitability, sustainability and their ability to meet subsistence food requirements. To investigate the sustainability of resource-management strategies over time requires that the effects of current actions on natural-resource stocks in the future be considered. Dynamic Programming (DP) provides a methodological framework for this to be done (Kamien and Schwartz, 1991).

A relatively simple numerical model that simulates biophysical interactions between trees, crops and soils under a range of management regimes is developed and used within a dynamic-programming (DP) algorithm to determine optimal tree/crop areas, fertiliser regimes, tree-rotation lengths and firewood-harvest regimes. The analysis is undertaken from the perspective of an individual landholder considering a land-use change from continuous cropping or grassland to a hedgerow-intercropping system. The landholder is assumed to have the opportunity to participate in a CDM C-sequestration project and therefore is eligible to receive payments for emission reductions and for C sequestered in biomass and soils. Only C that is sequestered above the 'business-as-usual' C stock (baseline) is eligible to be certified as emission reductions (Article 3.4 of the KP). The terms 'eligible C' and "Certified Emission Reductions" (CERs) are used to refer to the C sequestered above the baseline. The performance of the system, with and without C-sequestration payments is determined and the improvements in productivity directly attributable to trees are quantified. The effect of fertiliser use on carbon stocks and system productivity and profitability is also investigated. It is recognised that smallholders in some regions of Indonesia have access to government-subsidised fertilisers. Hence the economic implications of these subsidies are investigated by comparing systems receiving subsidies with those not receiving subsidies. The paper ends with a brief discussion of the implications of the findings of this study for policy and management.

2. METHOD

A bioeconomic approach, based on simulation modelling within a dynamic-programming algorithm, is used in this analysis. Simulation modelling is necessary because empirical values for the annual fluctuations in the biomass and C stocks of agroforestry systems under various management regimes over many years are not available. And, since an objective of this study is to determine optimal resource-use decisions over time, a DP model is developed that allows for the feedback effects between decisions and outcomes through time.

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[1] Referred to as "Land Use, Land-use Change and Forestry" and the "Clean Development Mechanism", respectively.

2.1 General economic model

2.1.1 Single cycle of the land-use system

Consider a landholder participating in a C-sink project within the CDM and receiving payments for CERs. It is assumed that the landholding is of homogenous quality, that the landholder may freely plant the entire area to trees or crops or any area-combination of the two, and that the trees provide land-conservation services. The net present value (*NPV*) obtained from an area (*A*) of land, assumed to be one hectare in size, over a project-investment period of *T* years with a discount factor $\delta = 1+r$ for the discount rate *r* is:

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

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

where s_t represents the state of the land in year *t* and may be defined by a single or a set of land-quality indicators such as soil depth, soil-C content, soil fertility or soil salinity. *X* is a vector comprising the management decisions under the control of the landholder such as species type, planting density, crop rotations, and the timing and frequency of pruning, harvesting, fertilising and weeding activities. The management decisions investigated are the area planted to trees (*k*) and crops (*A – k*), the quantity of pruned tree biomass (firewood) harvested from the system (*hr*), and the quantity of fertiliser applied to the soil (*fr*). System productivity is also affected by environmental factors such rainfall and temperature. The climate variables are calibrated to the conditions of Jambi province in Sumatra, Indonesia (presented in section 2.2.1) and are held constant for the entire rotation of each simulation. System productivity is assumed to be unaffected by fire. The cost of establishing a hectare of trees ($ ha^{-1}) is represented by c_E.

The first term on the right-hand side of equation (1) is the present value of the flow of net revenues obtained over *T* years from the area planted to a single agricultural crop. The value of $a(\cdot)$ may be extended to include a group of annual crops. The net annual monetary benefits provided from the crop component are calculated as:

$$a_t = p^a \cdot y_t^a - c_t^a \qquad (2)$$

where, y_t^a is the crop yield (Mg DM ha^{-1}) obtained in year *t*, p^a is the price of corn (US$ Mg^{-1}) and c_t^a represents the per-hectare variable costs of preparing the land, sowing seeds and applying fertiliser (US$ ha^{-1}) and the cost of harvesting yields (US$ Mg^{-1}).

The second term on the right hand side of equation (1) is the present value of the flow of net benefits obtained from the sale of tree products, $h(\cdot)$, over *T* years from the area, *k*, planted to trees. The value of $h(\cdot)$ may include profits from products such as firewood, timber, fruits, oils or latex. The annual, net monetary benefits provided by the tree component are calculated from expected yields and costs as:

$$h_t = p^h \cdot y_t^h - c_t^h \qquad (3)$$

where, y_t^h is the quantity of tree product harvested (Mg ha^{-1}), p^h is the price of tree product (US$ Mg^{-1}) and c_t^h represents the variable costs of harvesting (US$ Mg^{-1}).

The last term on the right-hand side of equation (1) is the monetary benefit received for the C-sequestration services measured as the present value of the stream of benefits obtained from the sale of CERs over *T* years. The annual sale of CERs depends on C accumulation in tree biomass and the soil:

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

where y_t^{bc} is the change in eligible tree-biomass C in year *t*, y_t^{sc} is the change in eligible soil-C stock in year *t*, p^c is the price of CERs (US\$ Mg^{-1}) and cm_t represents annual C-monitoring cost per hectare. Annual crop, tree and CER yields (and associated costs) depend on *X*, s_t and the age of the trees.

The dynamic nature of land quality (i.e., the state variable, however it is defined) can be captured through the difference equation:

$$s_{t+1} = s_t + \Delta s_t(s_t, X) \tag{5}$$

Since *X* = [*k, hr, fr*], this means that the state of the land in time period $t+1$ depends on its current state s_t, the area planted to trees (*k*), the harvest regime (*hr*), and the quantity of fertiliser added to the soil (*fr*).

The optimal solution to equation (1) may be determined analytically or numerically. The former approach involves deriving the first-order conditions (FOC) of equation (1) with respect to the decision variables: tree area (*k*), rotation length (*T*), harvest regime (*hr*), and fertiliser regime (*fr*). This is done for each decision variable in turn while holding all other variables constant. Cacho (2001) presents the derivations of the FOCs for maximising an objective function such as equation (1) with respect to changes in tree area (*k*) for a given forest-cycle length of *T* years. An analytical approach is not adopted here because the requirements that the functions defining the simulation model be smooth, continuous and differentiable are commonly violated or are non-linear and therefore have complex derivatives and are difficult to solve. A numerical approach to solving this problem is therefore adopted.

To solve an optimisation problem numerically requires that a biophysical-simulation model be developed, expressed in terms of a set of difference equations, that is able to mimic tree and crop growth and tree-crop-soil interactions. It also requires that the initial values for all state variables be known and that the rate of change of the state variables be known and defined as in equation (5).

2.1.2 Multiple cycles

Equation (1) represents a single rotation only and does not take account of the opportunity cost of keeping trees in the ground rather than clear felling them in year *T.* The Faustman forestry model overcomes this limitation by considering an infinite planning horizon. Faustman's original model has been extended by authors such as Hartman (1976), Comolli (1981) and Bowes and Krutilla (1985) to include externalities and Cacho *et al.* (2003) developed an infinite rotation model able to deal with payments for CERs. Such models, however, require that the length of each cycle (*T*), the management variables defined within the vector X, and initial land quality ($s_0, s_{T+1,} s_{2T+1} \ldots . s_\infty$) remain constant for all rotations. These assumptions are violated for many land-use systems because the quality of the land changes over time, so subsequent rotations are different from the first and consequently optimal tree areas and rotation lengths are likely to change between rotations. In other words, decisions in the present have impacts on the future state of the system. This is overcome using dynamic programming (DP), a useful Operations Research technique that incorporates feedbacks between decision variables and outcomes over time.

The DP recursive equation for this problem is:

$$V_n(s_n) = \max_{X_n}\left(NPV_n(s_n, X_n, T_n) + V_{n+1}(s_{n+1}) \cdot \delta^{-T_n}\right) \quad (6)$$

subject to equations (1) to (5). 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. Numerical model

Solution of the model described by equations (1) to (6) requires annual estimates of crop yields (y_t^a), firewood yields (y_t^h), eligible soil C (y_t^{sc}) and eligible tree-biomass C (y_t^{bc}) for a given set of management variables (*X*), cycle length (*T*) and initial state (s_0). Empirical values for these data are not available therefore the process model SCUAF[2] is used to generate them.

2.2.1 The simulation model – SCUAF

SCUAF is a process-response model designed to mimic the effects of tree/crop systems on soils and commodity products under various management and environmental conditions. Users may calibrate the environment and management parameters of the model, which are easily accessible in MS Excel® spreadsheets linked to the SCUAF model. Some of the input parameters that define management include: species type, tree and crop rotation length, firewood pruning and harvest intensities, organic and inorganic fertiliser use, and slash-and-burn practices. Input parameters that define the biophysical conditions of a study site include: slope, parent material, soil type and organic matter decomposition rates. Users may also define the magnitude of the feedback effects between management and the physical environment.

The SCUAF model does not simulate plant growth directly but simulates how changes in soil quality (fertility and structure) affect the potential productivity of plants. The interaction between crops and trees is therefore accounted for on an annual basis through the varying effects that plants have on soil fertility and soil structure. SCUAF also does not model soil-water dynamics or its availability to plants. This is because soil-water dynamics require modelling on a short-term basis of no more than 10-days which is not possible within the annual framework of SCUAF (Young *et al.*, 1998). Hence, SCUAF is primarily intended for simulations over periods of 10-20 years and is best used for assessing land-use sustainability within the medium term.

All soil-plant interactions and processes are modelled using annual iterations. For instance, SCUAF models processes that take place during the year based on user-defined conditions for the beginning of the year. At the end of the year it obtains the outputs for that year and uses these as the starting values for the succeeding year. The annual outputs generated by SCUAF are presented in MS Excel® spreadsheets. Some of the outputs generated include: the stocks and flows of mineral and labile C and nitrogen in the soil, soil depth, biomass C in trees and crops, and the quantities of harvested tree and crop biomass.

SCUAF is an appropriate process model for this study because it has parameter values for a range of tree and crop species, soils, climate and topography commonly found throughout southeast Asia. The model has also been tested for a range of environments and management conditions by a range of authors including: Ehui *et al.* (1990), Nelson *et al.* (1997), Vermeulen *et al.* (1993) and Tamubula and Sinden (2000).

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[2] SCUAF – A model to estimate **S**oil **C**hanges **U**nder **A**griculture, **A**groforestry, and **F**orestry (Young *et al.*, 1998).

2.2.2 Calibration of the SCUAF model

The agroforestry system

The upland crop-production systems found in Indonesia are determined by the availability of standing water throughout the growing season (waterlogging). 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 (or irrigation systems) depends on the slope of the land. Where the land is relatively flat, waterlogging is likely to occur and wetland rice is grown. But, where the topography is sloping, the land is planted in a patchwork of rain-fed crops such as tuber crops, maize, grain legumes, vegetables and tree crops (Fagi, 1992). Hedgerow-intercropping systems are often found on steeper slopes. Many cropping patterns are found in dryland areas of Indonesia, including sequential plantings of maize (*zea mays*) (Fagi, 1992) and relay cropping of maize, soybean (*Glycine max*) and velvet bean (*mucuna pruriens*) (Sitompul *et al.*, 1992).

In this paper, a rainfed hedgerow-intercropping system is investigated. SCUAF is calibrated to simulate the growth of two maize crops per year between *Gliricidia sepium* hedgerows subject to the climatic and topographical conditions of Jambi province, South Sumatra. Jambi is chosen because it is one of the benchmark sites for the Alternatives-to-Slash-and-Burn (ASB) project and represents the equatorial rainforests of southeast Asia suffering deforestation and land degradation (Palm *et al.*, 2004). Parameter values are not for a specific site, but are based on the general characteristics of the area. The parameters selected 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 the previous land use and the degree of land degradation. The lower values of this range represent a run-down soil requiring regeneration.

The *Gliricidia* hedgerows are simulated to grow at a planting density of 5,000 trees per hectare and are clear-felled after 25 years. Calibration of the model is based on data from the studies and simulations of Sitompul *et al.* (1992), Nelson *et al.* (1998), and Grist *et al.* (1999b). *Gliricidia sepium* is simulated because it meets many of the criteria of a successful agroforestry tree species[3] the most important being its soil-amelioration capabilities (fixing nitrogen and producing large quantities of biomass for mulch) and its ability to produce various commodity products such as firewood, fodder, or timber. Tree crops also have a greater potential to sequester C than food crops, which in the presence of C credits, adds to the earning capability of the land-use system. Maize is selected for this study because it is one of the more commonly grown food crops in Indonesia, along with rice, soybeans and cassava. SCUAF has default parameter values for both *Gliricidia* and maize.

SCUAF simulations

In this study, tree area (k), fertiliser-application rate (fr), tree-pruning intensity and firewood-harvest regime (hr) are the only parameters varied. These parameters are changed at the beginning of a simulation and are held constant for an entire rotation. The area planted to trees is increased at intervals of 0.1 resulting in 11 tree/crop scenarios. For convenience, total area (A) is set to 1.0, so $0 \le k \le 1$. Each of these scenarios is then replicated under three prune/harvest regimes, resulting in 33 simulated scenarios. The prune/harvest combinations are listed in Table 1. Tree 'pruning' involves cutting a user-defined percentage of the annual increment in total tree biomass and adding the pruned material to the soil where it decomposes and adds to soil C and soil nutrients. 'Harvesting' tree biomass involves cutting a user-defined percentage of the annual increment in tree biomass and removing this biomass from the system for sale as firewood or fodder. Residues added to the soil are from the tree component as most crop biomass is removed from the system at harvest. All residues are evenly distributed across the smallholding.

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[3] See Wise and Cacho (2005a) for a summary of the features of *Gliricidia* that make it a desirable agroforestry tree species.

Table 1. Pruning and harvesting combinations (as percentages of the annual increment in total tree biomass) used in the SCUAF simulation model.

	Prune	Harvest
Low	52.5%	17.5%
Medium	35%	35%
High	0%	70%

In practice, maize crops are fertilised using nitrogen (urea), Triple Super Phosphate (TSP) and Potassium Chloride (KCL) (Fagi, 1992; Sitompul *et al.*, 1992; Nelson *et al.*, 1998). Fertilisers are applied because soil-nutrient supply and the efficiency of soil-nutrient use are low in these areas[4]. Nelson *et al.* (1999) and Fagi (1992) recommend that between 120 and 248 kg Urea and between 93 and 98 kg of TSP ha^{-1} yr^{-1} should be added to the soil when growing two maize crops per hectare per year. Therefore, each of the 33 scenarios (11 tree areas x 3 prune/harvest regimes) is simulated for four combinations of N and Phosphorous (P) additions, listed in Table 2. Fertiliser is only added to the crop component and is added annually. The added P is slightly less than recommended but is enough to ensure plant P requirements are met. The quantities of N added might be considered high but are warranted because fertiliser efficiency is low due to the rapid leaching of N (Adiningsih and Karama, 1992). Potassium is not simulated by SCUAF.

Table 2. Fertiliser scenarios simulated in the numerical model. Each entry in the table identifies a scenario and is preceded by a tree area (*k*) specification.

Fertiliser regime[5]	**Harvest regime**		
	High	Medium	Low
High (180 kg N 45 kg P)	H225	M225	L225
Medium (120 kg N 30 kg P)	H150	M150	L150
Low (60 kg N 15 kg P)	H75	M75	L75
Zero (0 kg N 0 kg P)	H0	M0	L0

The zero-fertiliser scenarios are simulated because landholders in remote areas may not have access to credit or to fertiliser markets. Also, the N-fixing capability of *Gliricidia* can be tested in the scenarios where no fertiliser is added. The 12 combinations of fertiliser and harvest regime are presented in Table 2. The 124 scenarios[6] simulated when all combinations of tree area, harvest/prune regime and fertiliser regime are combined are referred to by the tree-area fraction followed by the number in the factorial representation in Table 2, where the letters H, M and L represent high, medium and low harvest and the number represents the total quantity of fertiliser added to the system. For example 'k = 0.5*H225*' represents the scenario where 50% of the land is planted to trees, the harvest regime is high and 180 kg N and 45 kg P ha^{-1} yr^{-1} is applied.

SCUAF estimates the effects of changes in soil properties (nutrients, C and depth) based upon user-defined net primary productivity (NPP) rates for crops and trees (Young *et al.*, 1998). The NPP values used for maize and *Gliricidia,* for five user-defined time periods, are summarized in Table 3. These values represent the maximum NPP (NPP^{max}) for each period, in the absence of nutrient constraints. The NPP^{max} values for *Gliricidia* are derived from empirical and simulated estimates in the literature (Grist *et al.*, 1999b; Wise and Cacho, 2005a) and are presented in Table 3. The NPP^{max} for maize is

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[4] According to van Noordwijk *et al.* (1995), Ultisol soils in southern Sumatra are acidic and infertile due to high leaching rates and aluminium toxicity of the subsoil. Adiningsih and Karama (1992) state that nitrogen (N) and potassium (K) deficiencies are probably the most severe constraints on plant productivity making fertiliser additions essential.

[5] The quantities of N and P should be doubled to get their approximate equivalents in terms of Urea and TSP.

[6] There are 124 scenarios and not 132 (33 x 4) because fertiliser is not applied when $k = 1$.

assumed to be 11,000 kg DM yr^{-1} of which a third is harvestable as grain, making the maximum attainable yield slightly less than the world-wide average of 4,000 kg DM yr^{-1} (FAO., 2000). The mean maize yield in Indonesia from 1996 to 1999 was 2,600 kg DM yr^{-1} (FAO., 2000).

Table 3. Net primary productivity parameters for *Gliricidia sepium* and maize.

Period	*Gliricidia* (Mg DM ha^{-1})	Maize (Mg DM ha^{-1})	Duration (years)
1	4,000	11,000	5
2	7,000	11,000	10
3	3,500	11,000	5
4	2,000	11,000	3
5	500	11,000	2

The SCUAF-generated outputs for harvested firewood (h_t), crop yields (y_t), biomass C (b_t) and soil C (s_t) are used as inputs in the economic model (equations 1 and 2) to calculate the net present value (NPV) of each scenario for the 25-year period simulated.

2.2.3 Calibration of the economic model

The parameter values needed to calibrate the economic model include: establishment costs, annual labour requirements, discount rate and input and output prices for both the tree and crop components of the simulated agroforestry system. The value used for each parameter is explained in this section and listed in Table 4. The prices are quoted in US dollars using an exchange rate of Rp 10,000 to US $1.

Gliricidia-hedgerow input costs

The economic data required include prices and quantities for all inputs and outputs. These are collated from a range of sources. The cost of establishing a *Gliricidia* hedgerow-intercropping system is based on the labour required to prepare the land and collect and plant cuttings. Adapted from Nelson *et al's* (1998) simulation of a *Gliricidia* fallow where 43 days are required to establish the system and assuming the daily wage rate is US$ 1.5 (NWPC, 2005), an establishment cost of US$ 64.5 ha^{-1} is used. Annual costs depend on the labour required to prune and harvest firewood (days Mg^{-1} dry matter). This depends on site productivity, planting density, frequency of pruning and the pruning techniques used. The base-case prune and harvest labour input is assumed to be 3 days Mg^{-1} firewood (Wise and Cacho, 2005a).

Maize-crop input costs

The costs associated with the maize component are derived from six sources. The annual cost of growing two maize crops per year is US$ 210 ha^{-1}. This annual cost includes labour and seed costs. According to Nelson *et al.*, (1998), 83 days ha^{-1} yr^{-1} of labour is required to plant seeds, weed the land, and harvest corn. Which, at a wage rate of US$ 1.5 day^{-1} equates to US$124.5. About 450kg ha^{-1} yr^{-1} of seeds are required to grow two maize crops per year (Wayan Rusastra *et al.*, 1999), which at a price of Rp 1,900 kg^{-1} equates to US$85.5 (van Noordwijk and Lusiana, 2001). The costs of fertiliser and harvesting grain are calculated separately. The cost of harvesting corn is determined by the labour required. According to Grist *et al.* (1999b) it takes approximately 9 days to harvest about 1.8 Mg of corn therefore 5 days Mg^{-1} is used in this study. The cost of fertiliser depends on type and whether it is subsidised or not. A base-case price for fertiliser US$ 1.8 kg^{-1} is used (USAID, 2003), which falls within the range (Rp1,700 to Rp2,200) given by van Noordwijk and Lusiana (2001).

Output prices and discount rate

The farm-gate price for maize in 2004 ranged between Rp 1,400 to Rp 1,600 Mg^{-1}. Therefore, at an exchange rate of Rp 10,000 to US\$1, a price of US\$ 140.0 Mg^{-1} of corn is used in this study. The base-case price for C is assumed to be US\$ 15.0 MgC^{-1}. This falls within the range typically used in such analyses. Grist *et al.* (1999a), for example, use values between \$US5 and \$US20 Mg C^{-1} and Smith *et al.* (2000) state that the market price for C is expected to range from US\$ 5 to US\$ 25 Mg C^{-1}. The base-case price for firewood is set at US\$ 4.5 Mg^{-1}, which is on the conservative side of the expected price range of US\$ 2.7 to US\$ 12.0 Mg^{-1} for South Sumatra, Indonesia (pers. comm. Ginoga, 2001).

Table 4. Base-case parameter values.

Description	Value	Units	Parameter (equation)	Source
Firewood price	4.5	US\$ Mg^{-1}	p^h (1)	a
Price of carbon	15.0	US\$ Mg^{-1}	p^c (2)	d
Price of maize	140.0	US\$ Mg^{-1}	p^a (1)	e
Fertiliser price	0.18	US\$ kg^{-1}	c^f	f
Discount rate	15	%	r (1)	b
Hedgerow-establishment cost	64.5	US\$	c_E (1)	c
C-monitoring costs	1.0	US\$ $ha^{-1}yr^{-1}$	c_m (2)	h
Variable costs for crop	210.0	US\$ ha^{-1}		c
Price of labour	1.5	US\$ 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	%	η	i

Sources: a: Ginoga (pers. comm. 2001), b: Between the 10% used by Menz and Magcale-Macandog (1999) and 20% used by Tomich *et al.* (1998a), c: Nelson *et al.* (1998) & Grist *et al.* (1999b), d: Smith *et al.* (2000), e: Katial-Zemany and Alam (2004), f: (USAID, 2003), g: (NWPC, 2005), h: Cacho *et al.,* (2004), i: Young *et al.* (1998).

A real discount rate of 15% is used to represent the rate of time preference of individual landholders in remote areas of Indonesia. This rate falls well within the range of real discount rates presented in the literature. Menz and Magcale-Macandog (1999), for example, use two levels of discount rates: 10% to represent the lower end of the market discount rate[7] and 25% to represent the higher end faced by upland farmers. Tomich *et al.* (1998b) use a discount rate of 20%. And, according to Nelson *et al.* (1997), government-sponsored co-operatives have provided real discount rates of approximately 10 to 12%, even though real interest (discount) rates for upland farmers of over 100% have been reported.

2.2.4 Solving the Dynamic model

The recursive equation (6) is solved for a discrete set of values defining *k*, *hr*, *fr*, *T* and s_t, where s_t is defined by the C content of the soil and *k*, *hr*, *fr*, *T* are defined in sections 2.2.2 and 2.2.3. The biophysical simulation model is solved for 11 values of *k* (ranging from 0.0 to 1.0 at increments of 0.1), three values of *hr* (25, 50 and 100%), four values of *fr* (0, 50, 100, 150) and 24 values of s_t (ranging from 10 to 33 at increments of 1.0 Mg C) over a period of 25 years. In other words, equation (6) is solved for 576 (24 x 24) possible state transitions, controlled by 124 combinations of the management variables for 25 possible values of *T*.

Solving a dynamic problem with these dimensions by interactively running the SCUAF model as part of the DP model is not possible within acceptable time limits. Therefore a set of quadratic equations

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[7] The lower rate approximates the social discount rate where risks of default/high transaction costs are less relevant issues (Menz and Magcale-Macandog, 1999).

that accurately mimic soil-C changes, tree-biomass accumulation and crop-yield dynamics is used instead. The quadratic equations (with interaction terms) are estimated econometrically from data generated by running SCUAF for the discrete set of values described in section 2.2.2. Only the explanatory variables found to be statistically significant ($P \leq 0.05$) are included and the coefficients for these are listed in Table 5.

The equation defining the state of the soil at any time *t* is estimated as:

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

The values for y_t^{sc} that are required to calculate CERs for equation (4) are determined from equation 7 as follows:

$$y_t^{sc} = \left((s_t - s_t^0) - (s_{t-1} - s_{t-1}^0)\right) \tag{8}$$

where s_t^0 is the soil-C stock of the previous land-use system (the baseline) at time *t*. Only C changes that are net of the expected changes in the baseline-C stock are eligible.

Tree growth determines two of the critical model outputs (commodity products), y_t^h and y_t^{bc}, required in equations (3) and (4). The tree-growth function is defined by:

$$b_t = \alpha_0 + \alpha_1 \cdot b_{t-1} + \alpha_2 \cdot (b_{t-1})^2 + \alpha_3 \cdot b_{t-1} \cdot s_t + \alpha_4 \cdot b_{t-1} \cdot k + \alpha_5 \cdot b_{t-1} \cdot hr + \alpha_6 \cdot s_t$$
$$+ \alpha_7 \cdot (s_t)^2 + \alpha_8 \cdot s_t \cdot k + \alpha_9 \cdot s_t \cdot fr + \alpha_{10} \cdot s_t \cdot hr + \alpha_{11} \cdot fr$$
$$+ \alpha_{12} \cdot k + \alpha_{13} \cdot k^2 + \alpha_{14} \cdot hr \tag{9}$$

where, b_t is standing tree biomass (Mg DM ha^{-1}).

Values for y_t^h are determined from b_t as follows:

$$y_t^h = (b_t - b_{t-1}) \cdot hr \tag{10}$$

and values for y_t^{bc} are determined as:

$$y_t^{bc} = \left((b_t - b_t^0) - (b_{t-1} - b_{t-1}^0)\right) \cdot \eta \tag{11}$$

where, η represents the fraction of standing biomass that is C and b_t^0 represents the standing biomass of the previous land-use system (the baseline) in time *t*.

The equation for crop yield, needed to calculate a_t in equation (1), is estimated as:

$$y_t^a = \delta_0 + \delta_1 \cdot s_t + \delta_2 \cdot (s_t)^2 + \delta_3 \cdot s_t \cdot b_t + \delta_4 \cdot s_t \cdot fr + \delta_5 \cdot fr$$
$$+ \delta_6 \cdot b_t \cdot fr + \delta_7 \cdot b_t + \delta_8 \cdot (b_t)^2 \tag{12}$$

The outputs from running this set of equations for all combinations of s_t, *X* and base-case biophysical-parameter values, are used in the economic model defined by equation (1) to calculate the associated net revenues. These biophysical and economic outputs are saved for use in the DP model in order to solve equation (7).

Table 5. Base-case values (coefficients) for the dependent variables of the quadratic equations defining the biophysical numerical model.

	Soil C (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).

3. RESULTS

The performance of the system over a single 25-year cycle is not reported in this paper. Wise and Cacho (2005a; 2005b) carried out detailed evaluations of the economic and biophysical performance of *Gliricidia* plantations and *Gliricidia*/maize agroforests implemented as C-sink projects under the CDM. The intergenerational implications of land-use management are considered here; therefore the analysis focuses on the multi-cycle outputs from the dynamic-programming model. However, because the state variable of the dynamic model is defined by the C content of the soil a brief discussion of the soil-C fluctuations of the system under varying management and land quality over 25 years is given. An understanding of the dynamics of soil C in response to management is essential to understanding the long-term implications of management on land-use systems.

3.1 Soil-carbon trajectories under varying management and land quality

The effects of tree area (*k*), harvest (*hr*), fertiliser (*fr*) and time (*T*) on soil-C stocks are presented in Figure 1. Soil C increases as *k, T,* and *fr* increase but decreases for higher values of *hr.* Fertiliser and harvest regime (*fr* and *hr*) have a greater affect on soil-C stocks than do tree area and rotation length (*k* and *T*), which have a greater influence on tree biomass-C stock.

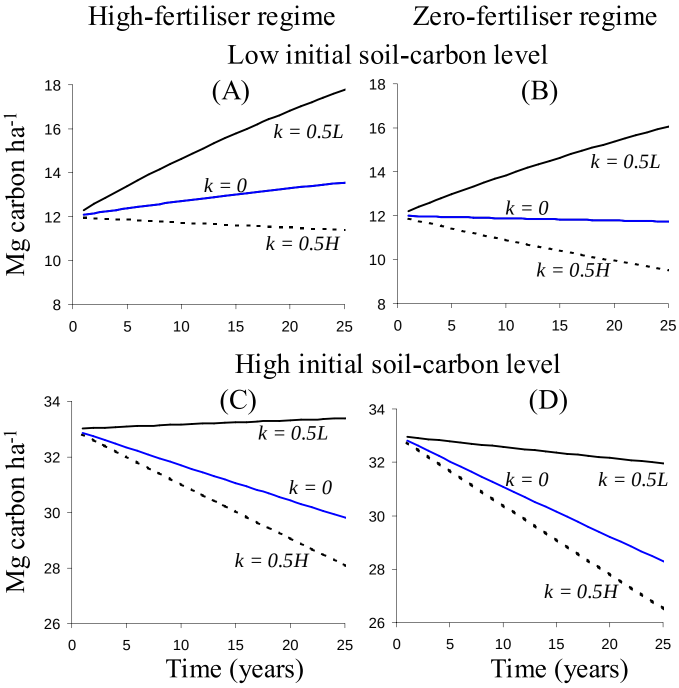

Figure 1. The trajectory of soil-carbon stock over 25 years, under selected tree areas (*k*), two fertiliser regimes and a high (*H*) and low (*L*) harvest regime - for low and high initial soil-carbon levels.

When only crops are grown ($k = 0$) soil C (s_t) declines over the 25 years if no fertiliser is used and this decline is larger at high[8] s_0 (- 0.18 Mg C ha^{-1} yr^{-1}) than at low s_0 (– 0.01 Mg C ha^{-1} yr^{-1}). Planting some of the area to trees ($k > 0$) causes s_t to increase over time (and the larger the size of k the greater this increase in s_t), provided the harvest regime (*hr*) is low (i.e. provided residues are added to the soil). However, if the pruned material is removed for firewood and/or fodder (hr = 100%), then growing trees with crops ($k > 0$) causes s_t to decline more than when only growing crops. In other words, trees only improve soil quality at low harvest. The application of fertiliser improves soil quality for all *hr*, s_0 and k (Figure 1) and these improvements are greater for higher values of initial soil quality and tree area but lower when harvest is high.

3.2 Multiple-cycle optimisation

Soil-C stocks and flows are sensitive to management and to initial soil quality (Figure 1). The implications of this on the long-term sustainability of land-use systems and on optimal management are investigated using the dynamic-programming model developed above. The DP model is solved using the outputs generated by the bioeconomic-simulation model and the sensitivity of management to changes in C and fertiliser prices and discount rate is analysed. Four carbon- and fertiliser-price scenarios are investigated (Table 6) for the base-case parameters listed in Tables 1 and 5.

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[8] This is 'high' relative to the 'low' s_0 in this analysis and is not in absolute terms since soil-C stocks greater than 100 Mg C ha^{-1} have been recorded in Indonesia (Delaney *et al.*, 2002).

Table 6. 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 (US\$ Mg C^{-1})	Fertiliser price (US\$ kg^{-1})
1	15	0.18
2	0	0.18
3	15	0.39
4	0	0.39

When the price of C (p^c) is zero, no C payments are being received. When C payments are being received a price of US\$ 15 Mg C^{-1} is used. Where landholders have access to subsidised fertilisers they pay between US\$ 0.10 and US\$ 0.20 kg^{-1} (USAID, 2003). Therefore, the base-case price for fertiliser (p^f) is assumed to be US\$ 0.18 kg^{-1} and the effect of removing this subsidy is investigated by increasing p^f to US\$ 0.39 kg^{-1}.

The effect of discount rate on optimal management over periods of about 150 years may be significant so the DP model is run for the price scenarios in Table 6 at a 5% and a 15% discount rate. The results for the base-case discount rate are discussed first and then compared with those where a 5% discount rate is used.

3.2.1 Optimal-decision rules

The optimal tree area (k^*), cycle length (T^*), harvest regime (hr^*) and fertilizer regime (fr^*) associated with each of the scenarios in Table 6, holding all other variables constant at base-case values, are plotted in Figure 2. These plots show the optimal decisions as functions of the current state of the land (the soil-C stock). The effect of C payments on optimal management is determined by comparing the solid and dashed curves within each of the eight graphs in Figure 2. The effect of p^f on optimal management is investigated by comparing the four graphs in column 1 of Figure 2 with those in column 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 (Figure 2 A & B). Trees are planted when the soil-C content is relatively low to take advantage of the trees' ability to restore the soil through N fixation and the addition of pruned biomass (Figure 2 E & F). Crops are only planted on better quality soils, the minimum soil-C content of which depends on the relative profitability of trees and crops. The higher the prices of C and fertiliser the greater the stock of soil C required for crops to be more profitable than trees. Another consistent finding is that fertiliser is only used when maize is grown since crop productivity is responsive to fertiliser use whereas trees are not.

When not receiving C payments, and when the fertiliser price is low or subsidised (Figure 2 A, C, E, G; dashed lines), it is optimal to plant the entire smallholding 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) and to avoid using fertiliser by returning 80% of pruned biomass to the soil as residues (Figures 2 E and G, respectively). This combination of decisions maximises profits while ensuring that the state of the land improves over time. It is optimal to grow trees at s_t values less than 17.5 Mg C ha^{-1} 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 use a high fertiliser regime because larger profits are made and maize yields can be sustained.

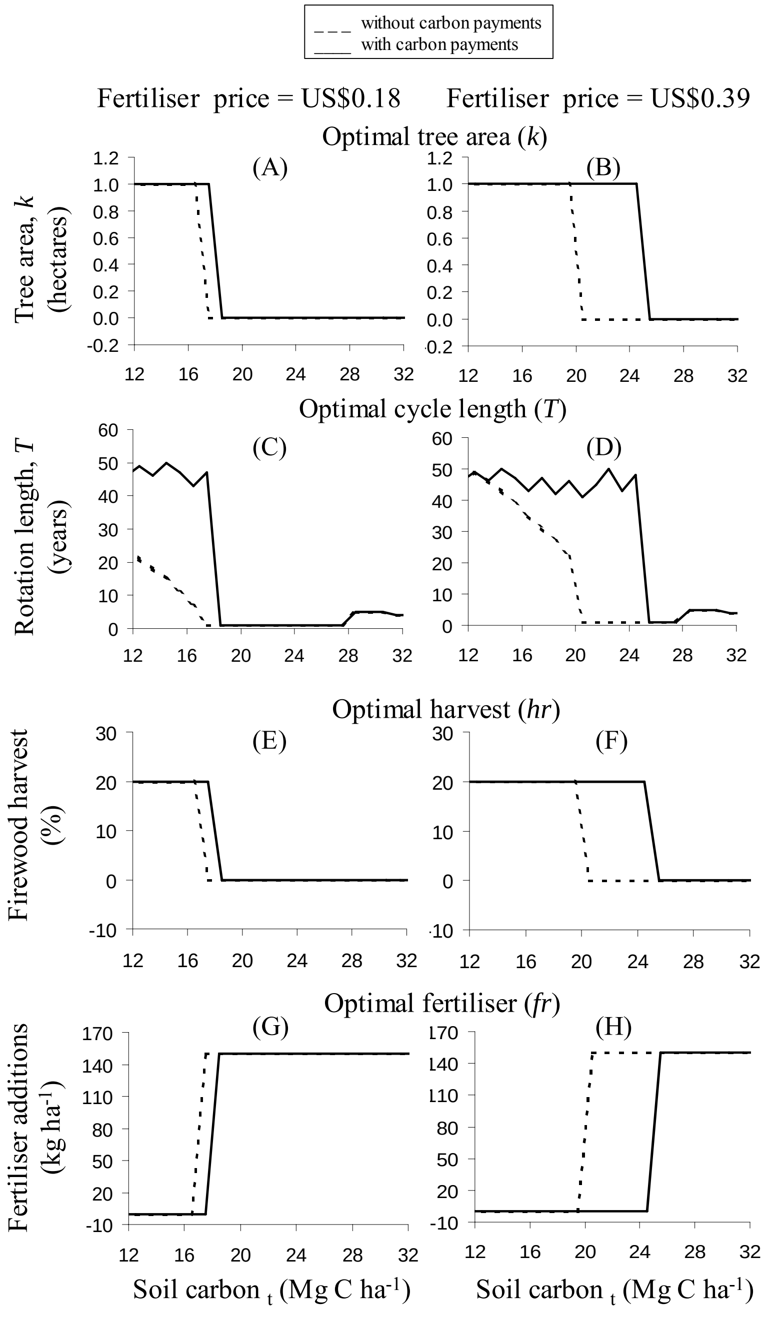

Figure 2. Optimal management regimes obtained by solving the Dynamic-Programming model for four combinations of fertiliser and carbon prices at a discount rate of 15%.

A similar optimal-decision rule (k^*, T^*, hr^*, and fr^*) is observed when the fertilizer price is unsubsidised (US$0.39) and C-sequestration payments are not being received (Figure 2 B, D, F, H; dashed lines). But, because fertiliser is more expensive, the dashed lines shift to the right because a more productive soil is required for maize to be more profitable than trees (i.e., s_t must now exceed 20.5 Mg C ha^{-1} instead of the 17.5 Mg C ha^{-1} at low p^f). Hence, growing trees (k = 1) and only removing a small fraction of the pruned biomass (hr = 20%) is optimal for all s_t values ≤ 20.5 Mg C ha^{-1} (Figure 2B & F). The optimal cycle length also increases to between 22 and 48 years at a higher p^f, depending on the initial amount of C in the soil (Figure 2 D). Longer tree cycles are required 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.

The effect of C payments on the optimal management of the system can be seen by comparing the solid lines with the dashed lines within the graphs of Figure 2. Carbon-sequestration payments increase the profitability of trees relative to crops. This makes it optimal to grow trees for s_t values up to 18.5 for the low p^f and up to 25.5 Mg C ha^{-1} for the high p^f (up from the 17.5 and 20.5 Mg C ha^{-1} without C payments). Carbon payments also make it optimal to increase tree-cycle length to between 43 and 50 years at low p^f and between 41 and 50 years at high p^f. In other words, C payments give incentives to landholders to increase C stocks by keeping trees for longer. The critical value of s_t at which it becomes optimal to switch from trees to crops increases in the presence of C-sequestration payments because a more productive soil is required to make the cropping system more profitable than trees.

3.2.2 Optimal state transitions

The state transitions – the changes in the C content of the soil (s_n to s_{n+1}) – that result from applying the optimal-decision rules are depicted in Figure 3. The 45-degree line dividing each graph in Figure 3 represents the steady state of the system where the soil-C stock does not change ($s_n = s_{n+1}$). A constant soil-C stock implies a stable and sustainable system and represents the 'target' soil-C level in the long run. The intersection of the optimal-state transition with the steady-state line marks the long-run target soil-C stock for the given scenario. Figure 3 shows that a range of target s_n values exists, illustrated by points on the reference line. The upper value of this range is 27.8 Mg C ha^{-1} for all p^f and p^c tested. The lower value of this range varies positively with changes in p^f and p^c. For example, the target s_t varies between 17.5 and 18.5 Mg C ha^{-1} when p^f is low (Figure 3 A & C) and between 20.5 and 25.5 Mg C ha^{-1} when p^f is high (Figure 3 B & D), for the without and the with C-payment scenarios, respectively. This is explained in the previous section and occurs because trees are grown at low s_n to build soil-C stocks up to target levels that can be maintained with cropping and fertiliser. In many soils, growing crops continuously even when using fertiliser can deplete the soil of its C and essential nutrients unless organic matter is added to the system. This does not happen here because, in the underlying SCUAF simulations of this system, organic residues from the leaf and root component of the crop are returned to the soil.

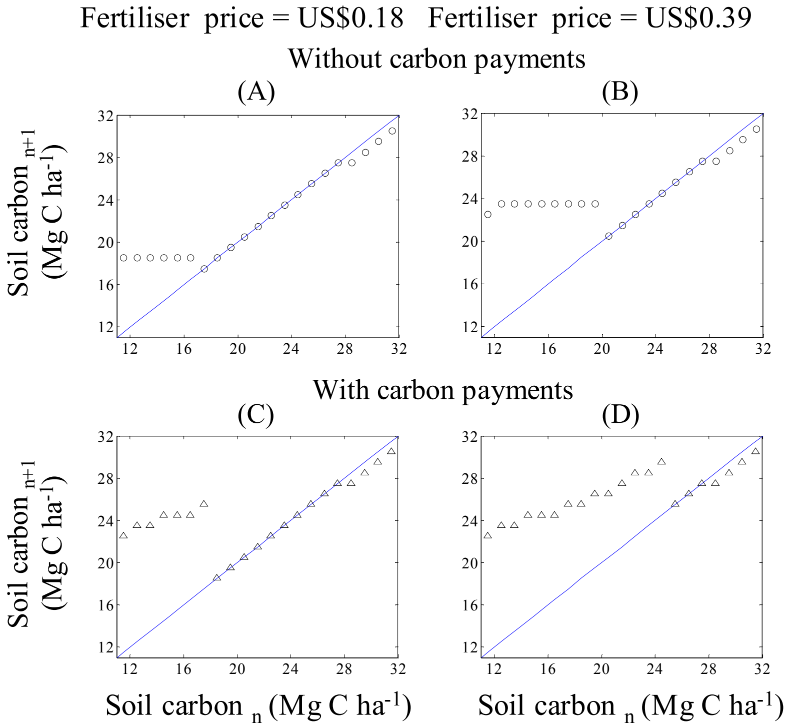

Figure 3. Optimal state transitions associated with the optimal management decisions in Figure 2 for each of the four combinations of fertiliser and carbon prices, for a 15% discount rate.

3.2.3 Optimal-state and optimal-decision paths

The trajectories of the state variable (s_t) that result from applying the optimal-decision rules over a period of 150 years for the four scenarios in Table 5 and at two initial soil-C values are plotted in Figure 4. If the initial soil quality is relatively good (s_0 = 33 Mg C ha^{-1}) it is optimal to exploit the system and reduce soil C for 57 years until it reaches an equilibrium value of 27.8 Mg C ha^{-1}. In this scenario, it is optimal to use intensive cropping to run the system down, and then to change to a less intensive cropping regime able to maintain s_t constant for the remaining 93 years of the simulation. This is discussed in more detail later in relation to Table 6. If, however, 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 of 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. The levels at which s_t plateaus correspond to the end of a period in which trees are grown, where it becomes optimal to replace trees with continuous cropping.

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 soil-C path because they have no effect on the optimal decision rule. When the system is relatively degraded (s_0 = 12 Mg C ha^{-1}), however, it is optimal to improve soil-C content first by growing trees and returning 80% of all pruned biomass to the soil. The level to which the soil-C stock is built depends on the relative profitability of trees and crops. Increasing the soil-C stock is relatively costly and requires large amounts of time so it is optimal to switch to crops as soon as the soil is of sufficient quality to grow crops more profitably than trees. The higher the price of C and the more costly fertiliser, the greater must be the soil-C stock before crops can be grown. This is reflected in the different levels to which soil C increases in each of the graphs in Figure 4.

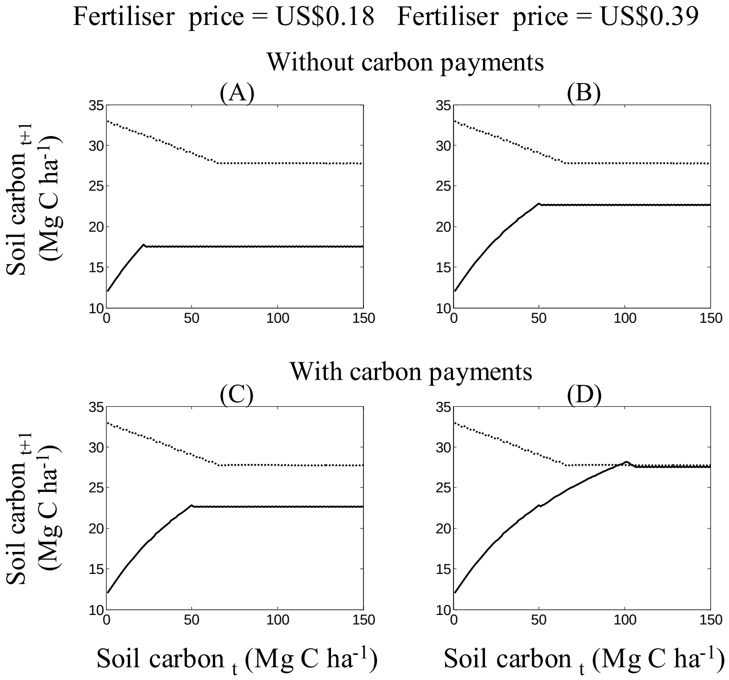

Figure 4. Optimal state paths associated with the optimal management decisions obtained by solving the dynamic-programming model for four combinations of fertiliser and carbon prices and two levels of initial soil carbon, using a discount rate of 15%.

The initial state of the soil (s_0) has a significant influence on the optimal path of the state variable over the first 50 to 100 years (Figure 4). Eventually however, the optimal paths for different initial states converge and fall within a range of target s_t values (as shown in Figures 3 and 4). It is interesting that the optimal paths for the different initial soil-C levels do not converge to the same target s_t value. Soil quality is expensive to improve so it is generally not optimal to increase it to the same level as that of the good quality soil. In fact, only when a high fertiliser price is combined with C payments does it become optimal to build the soil-C stock to almost the same level as that of the equilibrium or target level reached at high s_0.

The optimal decisions (for the first five cycles only) causing the state paths depicted in Figure 4 are presented in Table 7. The decisions that cause s_t to increase involve one or two cycles of growing trees (*k = 1*) for cycle lengths (*T*) of between 21 and 50 years, using no fertiliser, and harvesting only 20% of pruned biomass (columns 2 to 5, Table 7). The cycle length of the tree plantation varies depending on p^c and p^f as described above – increasing from 21 years in the case of scenario 2 to 49 years for scenarios 1 and 4, and to 99 years (involving two cycles) for scenario 3. When it is optimal to deplete the soil of C (high s_0), the optimal land-use practice to adopt involves intensively growing crops in periods of four or five years and to use 150 kg ha^{-1}yr^{-1} of fertiliser (columns 6 to 9, Table 7). The management regime that maintains s_t at its target level involves growing maize annually, provided that 150 kg ha^{-1}yr^{-1} of fertiliser is used.

Table 7. Optimal-decision rules over five cycles for four fertiliser- and carbon-price scenarios, 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	1	2	3	4
1	1	1	1	1	0	0	0	0
2	0	0	1	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
	Optimal cycle lenth (T, yrs)*							
	Scenario				Scenario			
	1	2	3	4	1	2	3	4
1	49	21	49	49	4	4	4	4
2	1	1	50	1	4	4	4	4
3	1	1	5	1	4	4	4	4
4	1	1	1	1	4	4	4	4
5	1	1	1	1	4	4	4	4
	Optimal harvest (hr, %)*							
	Scenario				Scenario			
	1	2	3	4	1	2	3	4
1	20	20	20	20	0	0	0	0
2	0	0	20	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
	Optimal fertiliser (fr, kg ha^{-1} yr^{-1})*							
	Scenario				Scenario			
	1	2	3	4	1	2	3	4
1	0	0	0	0	150	150	150	150
2	150	150	0	150	150	150	150	150
3	150	150	150	150	150	150	150	150
4	150	150	150	150	150	150	150	150
5	150	150	150	150	150	150	150	150

The cumulative NPV associated with the optimal decisions are presented in Table 8. These are calculated by solving equation (6) for the scenarios in Table 6, where $n = 6$. The cumulative NPVs increase at a decreasing rate with each cycle because of discounting. At low s_0, cumulative NPV stops increasing after the fourth cycle whereas at high s_0, the value of future cycles becomes negligible from cycle 10 onwards. This is because at low s_0 the first four cycles represent 25 to 100 years, whereas at high s_0 each cycle represents 4 or 5 years only.

Comparing the results between the two initial soil-C levels, the cumulative NPVs at high s_0 clearly exceed those at low s_0 for scenarios 1, 2 and 4 (by US$ 158.2, US$ 296.7 and US$ 87.4 ha^{-1}, respectively) and give an indication of the economic value of having better quality land (higher soil C). In the case of scenario 3 the cumulative net returns when s_0 is low are greater than those when s_0 is high because of the C-sequestration payments and the high fertiliser price. At low s_0 the C payments internalise the environmental benefits provided by the trees and therefore increase NPV from -US$ 64.49 ha^{-1} without C payments (scenario 4) to US$61.47 with C payments (scenario 3). In contrast, at high s_0 the C payments internalise the environmental costs of the crops depleting the soil-C stock and therefore decrease the present value of net revenues from US$20.59 ha^{-1} without C payments (scenario 4) to US$7.99 with C payments (scenario 3). In other words, C payments promote the restoration of degraded land (with low s_0) and penalise the exploitation of good land.

Table 8. Cumulative net revenues associated with the optimal decisions for six cycles at a discount rate of 15%. The first five NPV values correspond to the optimal decisions listed in Table 7.

Cycle	Low initial soil carbon ($s_0 = 12$ Mg C ha^{-1})				High initial soil carbon ($s_0 = 33$ Mg C ha^{-1})			
	Cumulative NPV (US$ ha^{-1})							
	Scenario				Scenario			
	1	2	3	4	1	2	3	4
1	61.41	-64.50	61.41	-64.50	88.70	94.34	-1.23	4.41
2	61.44	-64.40	61.47	-64.50	142.05	150.88	0.69	9.53
3	61.47	-64.32	61.47	-64.50	173.92	184.58	3.17	13.83
4	61.49	-64.25	61.47	-64.49	192.87	204.55	5.31	16.99
5	61.51	-64.18	61.47	-64.49	204.07	216.33	6.90	19.16
6	61.53	-64.13	61.47	-64.49	210.66	223.26	7.99	20.59

3.2.4 Sensitivity of optimal-decision paths to changes in discount rate

The sensitivity of the optimal-state paths and decision rules to a lower discount rate is investigated by re-running the DP-model for the four scenarios in Table 6 at a discount rate of 5%. It is found that the optimal-decision rules and optimal-state paths do not change when the discount rate decreases from 15 to 5% except when s_0 is low and C payments are not being received (compare scenarios 2 & 4 in Table 7 with Table 9). Only the optimal decisions for the low s_0 scenarios are given in Table 9 and the changes in optimal management are highlighted in bold. In each case, the change in optimal management involves growing trees for longer. The changes, however, do not have a significant effect on NPV so are not shown.

At low s_0, the cumulative NPVs for scenarios 2 and 4 are negative over the entire 150-year simulation for both discount rates (Tables 8 and 10). This indicates that, under the assumptions of these scenarios, the land-use options simulated are unsuitable for adoption and that alternatives might be worthwhile investigating or government-support programs might be appropriate to implement.

Table 9. Optimal decisions over five cycles for four fertiliser- and carbon-price scenarios, at a low initial soil-carbon level only, and a discount rate of 5%.

Cycle	Low initial soil carbon ($s_0 = 12$ Mg C ha^{-1})							
	Optimal tree area (k)*				*Optimal cycle length (T*, yrs)*			
	Scenario				Scenario			
	1	2	3	4	1	2	3	4
1	1	1	1	1	49	**31**	49	49
2	0	0	1	**1**	1	1	50	**11**
3	0	0	0	0	1	1	5	1
4	0	0	0	0	1	1	1	1
5	0	0	0	0	1	1	1	1
	Optimal harvest (hr, %)*				*Optimal fertiliser (fr*, kg ha^{-1} yr^{-1})*			
	Scenario				Scenario			
	1	2	3	4	1	2	3	4
1	20	20	20	20	0	0	0	0
2	0	0	20	**20**	150	150	0	**0**
3	0	0	0	0	150	150	150	150
4	0	0	0	0	150	150	150	150
5	0	0	0	0	150	150	150	150

3.2.5 Total certified emission reductions

Soil-C stocks and flows have been the focus of this paper thus far because this is the variable defining the state of the system. However, tree biomass contributes more to CERs than does soil C. Hence, it is informative to investigate the trajectories of the total eligible-C stock associated with the optimal-decision paths, as this reflects the cumulative stream of annual C payments to landholders.

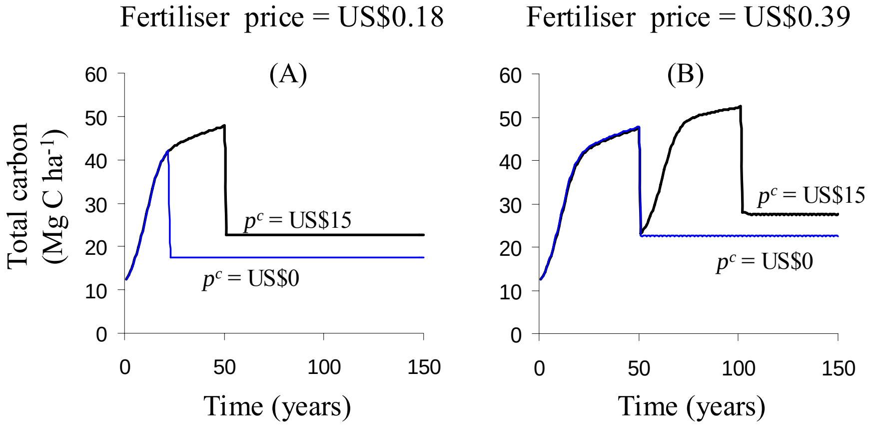

Figure 5. The trajectory of the eligible-carbon stock associated with the optimal management regimes for the different prices of carbon and fertiliser for a poor quality soil presented in Table 9.

For C stocks to be eligible for sale in the C market they must be shown to be above the baseline. The baseline therefore has a significant effect on the quantity of C that is eligible for payment. The implications of baselines on eligible C stocks are investigated by Wise and Cacho (2005b) and are not discussed further here. For the sake of this discussion the baseline-C stock is assumed to be stable and representative of grassland. The trajectories of eligible C stock for the optimal-decision paths at low s_0 (columns 2, 3, 4, 5 in Table 7) are presented in Figure 5. The equivalent trajectories of eligible-C stock when s_0 is high are not plotted as they involve soil C only and are identical to the optimal-state paths in presented in Figure 4.

The averages of the C-stock trajectories in Figure 5 are listed in Table 11. Both the trajectories and the averages 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.

Table 11. The effect of carbon price (p^c) and fertiliser price (p^f) on the average eligible-carbon stock (Mg C ha^{-1}) of an agroforestry system grown on a smallholding with low soil quality.

	$p^c = 15$	$p^c = 0$
$p^f = 0.18$	12.79	4.19
$p^f = 0.39$	21.62	12.79

In summary, it is only optimal to plant trees for C-sequestration purposes and to participate in a C-sink project when the quality of the land is poor (low s_0). If fertiliser subsidies are removed an incentive is created for landholders to plant a second rotation of trees (Figure 5), as crops can no longer compete financially with trees at the low levels of s_t.

4. DISCUSSION AND CONCLUSIONS

Where interdependencies exist between choices made in the present and outcomes in the future a dynamic-decision framework able to incorporate feedbacks between these decisions and outcomes is required to determine optimal decisions through time. A deterministic, dynamic-programming (DP) model was developed in this study to determine optimal management of a tree/crop system over many cycles when in the presence of payments for certified emission reductions (CERs). The DP model was designed to interact with a numerical simulation model developed to mimic soil-tree-crop processes of tree plantations and agroforests under various management regimes. The biophysical data simulated by the numerical model were used in an economic model of a hectare of homogenous land in southern Sumatra, Indonesia to calculate net present values for various simulated scenarios.

The management options investigated include: area planted to trees and crops, firewood-harvest regime, fertiliser-application rate and tree-rotation length. Optimal values of each of these variables were estimated for a range of assumptions regarding fertiliser price, C price and discount rate. The effect of land quality on optimal management was also investigated by solving the model for a good quality and a poor quality soil, as defined by the C content of the land. The terms 'good' and 'poor' are not absolute terms but are used in the relative sense as they describe the 'high' and 'low' soil-C levels simulated in this paper.

It was found that the optimal-decision path depends on the initial C content of the soil (s_0). If the land is of relatively good quality, it is optimal to only grow crops, to apply 150 kg of fertiliser per ha per year, and not to participate in the C market. The intensive cropping regime initially depletes 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 the profitability of the system because landholders are required to pay for the C lost from the soil during the first 56 years, until a steady state is reached. In other words, based on the assumptions of this paper, incentives do not exist for landholders to participate in C-sink projects under the Clean Development Mechanism of the Kyoto Protocol when the quality of the land is relatively good. This is especially true when fertiliser prices are subsidised, making cropping more competitive than trees.

If the initial soil quality is poor the results are quite different. Optimal management involves planting the entire area to trees for cycles of between 20 and 100 years and returning 80% of pruned biomass to the soil to replenish soil C and soil nutrients (a 20% harvest regime). 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 a cropping system and to use fertiliser to help maintain the soil-C stock at its target level. The optimal number of tree cycles and their optimal length depend on C and fertiliser prices. Payments for C make it optimal to lengthen the tree cycle from 21 years to 49 years. When C payments are combined with a high fertiliser price (i.e. fertiliser is unsubsidised) it becomes optimal to delay the planting of crops even more by establishing a second tree cycle of 50 years.

An important finding in this analysis is that it is optimal not to build poor quality soils (with 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 feasible to build a low s_0 up to the same target steady state as that reached for soils with a high s_0. The reason for this is because it is expensive (in terms of the forgone crop revenues) to do so. Therefore, as soon as the soil is good enough to grow crops more profitably than trees, the switch from trees to crops is made.

Optimal management is only found to be sensitive to fertiliser prices when the land quality is poor. The removal of fertiliser subsidies makes cropping less profitable and results in the optimal tree phase being lengthened by 28 years (from 21 to 49 years) in the absence of C payments and by 78 years (with a second 50-year tree phase) in the presence of C payments.

Some of the findings of this paper have identified issues requiring further investigation. The use of soil C as a measure for soil quality and soil sustainability, for example, may be improved by including nitrogen (i.e., use a carbon/nitrogen ratio instead) since the productivity of agricultural systems seems to be more responsive to changes in nitrogen availability than to changes in soil-C stock. Secondly, the DP model determined that the optimal management of poor quality soils is to grow tree plantations for long time periods (20 to 100 years) in order to improve soil quality, and then to convert the land to input-intensive continuous-cropping. Committing an entire landholding to trees for 20 to 100 years has implications for landholder food security and for traditional practices based on growing food crops. Therefore, it may be unlikely that farmers will adopt such practices. Also, the risk associated with growing trees (such as poorly defined property rights) is a factor likely to make their long-term adoption unlikely. A way of overcoming these issues might be to adopt a landscape approach to land management, which will allow some areas to be planted to trees while others are planted to crops. Thirdly, the economic and management implications of including payments for emission reductions generated when firewood substitutes for fossil fuels requires investigation. Fourthly, the biophysical parameter values used in the numerical model are specific to the system simulated in this paper. The model, however, can be applied to a range of agricultural practices. Of particular interest might be a system in which the interactions between the soil, trees and crops are more responsive to management than those presented here. And finally, it is apparent from the corner solutions predicted by the model that many of the environmental services provided by trees have not been comprehensively 'picked up' by the numerical model. Some of these might include the beneficial effects that trees provide by shading weeds, protecting crops, providing fodder for livestock and herbs for subsistence use. These may lead to different tree-crop combinations being optimal.

5. REFERENCES

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