A Bioeconomic Analysis of Soil Carbon Sequestration in Agroforests[1]

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Abstract

Agroforestry can help in the battle to control global warming by sequestering atmospheric CO_2. Most attention so far has been on the carbon sequestered in trees, but soils can also contain considerable amounts of carbon, some of which is released upon harvest. There has been little quantification of the impact of different land-uses on soil carbon levels due to the high costs and lengthy time periods required to accurately measure soil carbon fluctuations, within and across sites, and over an entire project lifespan. This study attempts to quantify soil carbon changes under agroforestry systems using a modeling approach. The net effects on carbon storage of implementing agroforestry depend on the carbon content of the land-use practices that are replaced. Also, agroforestry projects will impact upon soil carbon levels by preventing land clearing and by maintaining carbon already in the soils. These issues are evaluated from the standpoint of individual landholders, and implications for management of agroforestry systems are discussed.

Keywords: Agroforestry, bioeconomics, soil carbon, global warming.

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[1] Working paper CC02. ACIAR project ASEM 1999/093, http://www.une.edu.au/febl/Econ/carbon/
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Introduction

The Greenhouse effect is a naturally occurring process whereby gases, with the ability of preventing infrared radiation from escaping the earth's atmosphere, cause global temperatures to rise. This process is essential to the creation and continuing existence of life on earth. However, over the last one and a half centuries, this process has been exacerbated by increasing quantities of greenhouse gasses (GHG) emitted into the atmosphere. It is believed that enhancing the Greenhouse effect will result in global climate change, which in turn, will lead to many socio-economic and environmental consequences (IPCC, 2001a).

The higher levels of atmospheric GHGs experienced over the last 150 years are primarily due to anthropogenic activities, including fossil fuel burning and land use change and forestry activities (LUCF), such as deforestation. These activities have either increased emissions from global carbon stocks and/or decreased the capacity of global carbon sinks to absorb these gases.

There are several greenhouse gases, including Methane (CH_4), Nitrous oxide (NO_x) and Carbon dioxide (CO_2). CO_2 is the focus of this study, since it is the main gas emitted by burning of fossil fuels and is the gas captured by growing forests.

CO_2 is emitted from and absorbed by three main global carbon stocks: the oceans, fossil fuels, and terrestrial biomass and soils.

Although the bulk of policies and legislation on greenhouse gasses are likely to focus on carbon emissions, reflecting the dominant role of emissions, carbon sinks can contribute considerably to reducing net emissions. According to IPCC (2001b) terrestrial ecosystems have the potential to offset between 10% and 20% of the CO_2 emissions expected between now and 2050. Hence, any legislation or policy framework designed to stabilize the level of GHGs in the atmosphere should focus on both reducing emissions from sources and enhancing absorption by sinks.

Exchanges between the atmosphere and terrestrial biomass and soils occur during the biochemical processes of photosynthesis and respiration. In photosynthesis, plants and trees use carbon dioxide, water and minerals to produce biomass. It is during this process that carbon is captured (sequestered) from the atmosphere and 'fixed' in biomass. Respiration is the chemical reaction that occurs during the decomposition or burning of biomass, where oxygen is used to break down biomass and carbon dioxide is released into the atmosphere as a waste product. The net flow of carbon from terrestrial biomass into the atmosphere becomes negative when biomass production (carbon sequestration) exceeds biomass destruction (carbon emissions).

Thus far, most studies of carbon exchanges between the atmosphere and terrestrial carbon stocks have focused on exchanges between terrestrial *biomass* and the atmosphere (e.g. Grist *et al.,*1999a; Ley and Sedjo, 1997; Kirschbaum, 1995). Little attention has been given to carbon fluxes between soils and the atmosphere.

The paucity of research on the impact of land-uses on soil carbon levels is partly due to the high costs and long time periods required to accurately measure soil carbon fluctuations within and across sites, and over an entire project lifespan. The difficulty of detecting small changes in soil carbon because of the generally high background levels and natural soil variability is also a factor.

The purpose of this study is to assess the economic consequences of accounting for soil carbon in climate mitigation policy. The paper starts by presenting a brief overview of the global carbon cycle, followed by a glance at the carbon cycle within soils. An economic model is then presented, which accounts for marketable outputs (firewood) as well as carbon sequestration services by soil and biomass. A numerical model is presented and calibrated for a *Gliricidia sepium* plantation in the uplands of Sumatra, Indonesia. An agroforestry simulation model (WaNuLCAS) is used to obtain biophysical results, under 27 different scenarios, for a period of 25 years. These results are then subjected to economic analysis under four different carbon-payment mechanisms, and the best management strategies are identified within the set of results available. The paper ends with a discussion of implications for management of agroforestry systems under carbon-sequestration payments.

The Global Carbon Cycle

Atmospheric carbon levels are determined by fluxes between the atmosphere and three main carbon pools: oceans, terrestrial ecosystems and fossil fuel stocks (see Figure 1). The contribution of each carbon pool to the global carbon cycle has been quantified by IPCC (2000, pp. 30). Over the period 1989 – 1998, activities in the energy and building sectors of the global economy increased atmospheric carbon levels by 6.3 Gigatonnes of carbon per year[2] (Gt C yr^{-1}). LUCF activities released 1.6 Gt C yr^{-1} into the atmosphere and absorbed 2.3 Gt C yr^{-1} with a net effect of decreasing atmospheric carbon levels by 0.7 Gt C yr^{-1}. Oceans removed about 2.3 Gt C yr^{-1} from the atmosphere. The net result of these fluxes over the last 10 – 15 years, is that atmospheric carbon levels have increased by about 3.3 Gt C yr^{-1}.

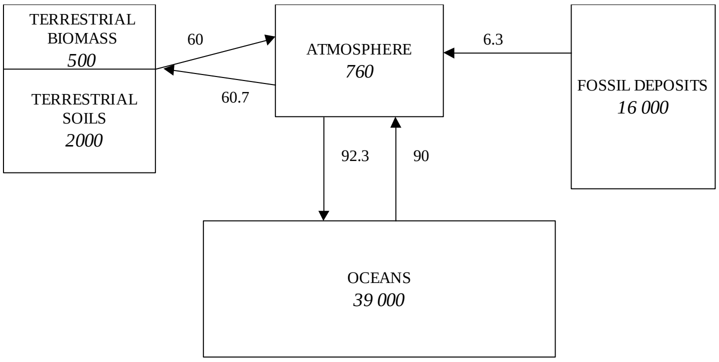

Figure 1. Global carbon stocks, numbers show the sizes of carbon pools (Gt C) and fluxes (Gt C yr^{-1}), source: IPCC (2000, pp. 30)

The Soil carbon cycle

'Soil carbon' is defined as 'all non-living, below-ground carbon, including roots and charcoal' (Polglase *et al.,* 2000). It is the sum of all the organic and inorganic (carbonates and charcoal) fractions of carbon found in the top one meter of soil. Litter (residue input), however, is defined as a discrete entity and is counted separately from soil carbon.

For modeling purposes, soil organic matter (SOM) is divided into different fractions or pools based on the rate of decomposition or turnover time. The CENTURY model (Parton *et al.,* 1987) for example, divides SOM into three different pools – active, slow, and passive. The 'Active pool' has a rapid turnover rate of one to five years and consists of live microbes and microbial products along with SOM. The 'Slow pool' is the fraction with an intermediate turnover time (20-40 years), where the SOM is physically and/or chemically protected and therefore more biologically resistant to decomposition. The lignin fraction of the litter goes directly into this pool. The third pool is the 'Passive pool'. This pool has the longest turnover time (200 – 1500 years) and represents the stabilised, recalcitrant organic matter.

The level of carbon in soils is determined by the net balance between SOC aggrading and degrading processes. The processes that enhance soil carbon include plant biomass production (litter and roots),

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[2] A gigatonne is 10^9 tonnes.

humification, aggregation[3] and sediment deposition. The processes that degrade SOC include soil erosion, leaching, and soil organic matter decomposition (due to respiration in the turnover process). Turner and Lambert (2000, p232) state that “at any time, the quantity of organic matter in the soil will be a balance of losses due to decomposition and inputs from roots and litter”.

Figure 2 describes the dynamics of soil carbon fluxes between, and within, the two carbon pools of the residue layer and the three soil organic carbon pools as defined in the CENTURY model. As the litter is broken down, carbon is transferred into the active and slow soil carbon pools, and some is emitted as CO_2. Fluxes of carbon also occur between each of the three soil carbon pools during decomposition (the sizes of these fluxes are shown in the diagram), with CO_2 emitted as a waste product.

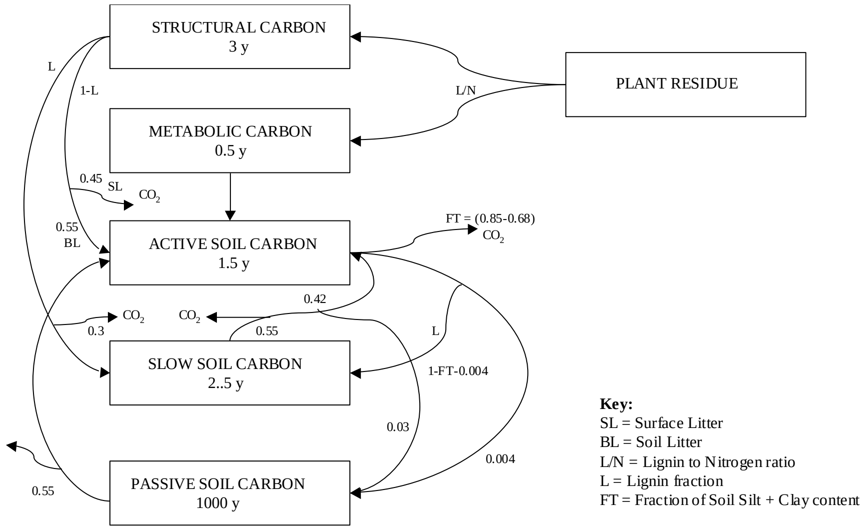

Figure 2: Flows between soil carbon pools (Sitompul, 1999).

The rate at which carbon is accumulated or lost from soils depends upon many factors, as outlined in Table 1. The most relevant factors in this study are previous land use, residue management, species type and soil type.

To a large degree, previous land use determines soil fertility and soil carbon level, which in turn affects the potential of different land-use types to accumulate carbon. The effect of different initial soil carbon levels on carbon accumulation is investigated in this study.

The effects of harvest and pruning regimes on total carbon stocks are also investigated in this study. Turner and Lambert (2000, p. 242) state that “input of carbon from litter appears to be relatively low and that the observed accumulation of carbon in the soil is predominantly through an alternative source, presumably root production and loss”.

Species type determines net primary productivity (NPP) and hence carbon accumulation; it also determines residue quantity and quality. The productivity of a given species is not only a function of genotype but it is also “a function of soil type and site management factors such as fertiliser application, weed control and slash management” (Polglase et al, 2000). A single tree species is simulated in this study.

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[3] Aggregation is the formation of stable aggregates which provide physical protection of SOC against microbial decomposition and thus prevent carbon from being broken down Lal *et al.* (1998, p6).

Table 1. Factors and processes relating to LUCF activities that impact upon soil carbon levels.

Factor	*Reason (Process)*	*Effect on Soil Carbon*	*Source*
Previous Land Use	Improved Pasture: high carbon content, susceptible to losses.	-	a
	Cropping: lower carbon content, stable humus resistant to breakdown.	+	a
Residue Management	Depends on the frequency and quantity of pruning and harvesting of pruned material.	- or +	b
	Quality of residue (lignin content and carbon/nitrogen ratio).	- or +	c
	Relative contribution of roots and litterfall to total residue.	+	b
Site preparation (establishment)	Tilling, ripping and mounding increase aeration and alter soil microclimate, accelerate decomposition.	-	a
	Clearing of original vegetation &/or burning of vegetation.	-	a
	Grasses and weeds, if left, provide inputs and buffer against soil carbon loss.	+	a
Species type (growth rate)	Affects the temporal pattern of inputs of litter and root residues.	- or +	a
	Affects the quality of residue inputs through its allocation of nutrients to different components of the plant.	- or +	a
Final harvest	Depends on the techniques used, frequency (rotation length) and clearing.	- or +	a
Soil type	Texture, clay/silt/sand content, nutrient status – all affect the aggrading and degrading processes described above.	- or +	a

Sources: a: Polglase *et al.* (2000); b: Turner & Lambert (2000, pp. 242); c: Ghidey & alberts (1993) in Potter *et al.* (1997, pp. 146);

ECONOMIC MODEL

Consider a landholder who is assessing the possibility of planting trees in the presence of payments for carbon sequestration i.e. carbon credits. The profit function faced by the landholder over a planning horizon of T years is:

$$V_T = \sum_{t=0}^{T} \left[(\Delta S_t + \Delta B_t) P_C + H_t P_H - CM_t \right] (1+r)^{-t} - CE \qquad (1)$$

Where S_t is soil carbon content and B_t is above-ground biomass in year t, both measured in tonnes of carbon per hectare (t C/ha), and Δ represents annual changes. H_t is the amount of products harvested during year t. P_C is the price of carbon and P_H is the price of harvested products. CM_t are annual maintenance costs and CE are establishment costs.

The units of H_t depend on the type of output. In this paper we assume only firewood is harvested, but H_t can be expanded to represent a vector of outputs, including products such as fruits, oils or latex. Annual costs may include any soil tests and other carbon-monitoring expenses required to receive carbon payments. It is important to note that both ΔS_t and ΔB_t can be negative. This is particularly important in the last year of the planning horizon (T), when total harvest may occur, thereby reducing standing biomass and requiring the landholder to pay back some of the carbon credits previously received.

The changes in soil and biomass carbon depend on biophysical processes and management regimes. These changes are defined as:

$$\Delta S_t = Sa_t - Sr_t \tag{2}$$

$$\Delta B_t = Ba_t - Br_t \tag{3}$$

Where Sa and Ba represent additions to the soil and biomass carbon pools, and Sr and Br represent removals from the soil and biomass carbon pools, respectively.

Ba_t results from photosynthesis, which in turn depends on solar radiation, leaf area, temperature, soil type and tree species among others. Br_t represents any biomass removed by pruning, harvest and fire. Sa_t is the result of additions of organic matter to the soil. This may happen naturally through falling leaves and branches, but it can be managed by pruning mulching, and controlled burning. Hence, high values of Br_t may be associated with high values of Sa_t if prunings are added to the soil rather than taken away as harvest. Finally, Sr_t may be caused by disturbances that increase the rate of oxidation of organic matter and release as CO_2 by the soil (i.e. tilling) and by soil erosion.

For a given set of environmental variables, the rates of carbon additions and removals can be represented as functions of management variables (X) and the state of the system, as represented by soil and biomass carbon. So we have:

$$Sa_t = fa(X, S_t) \tag{4}$$

$$Sr_t = fr(X, S_t) \tag{5}$$

$$Ba_t = ga(X, B_t) \tag{6}$$

$$Br_t = gr(X, B_t) \tag{7}$$

This model assumes that S_t does not directly affect the net rate of biomass accumulation (ΔB_t), and B_t does not directly affect the net rate of soil carbon accumulation (ΔS_t). However, these variables are indirectly related through the effect of the management variables, represented by the vector X:

$$X = [u, v] \tag{8}$$

where u is the pruning rate and v is the harvest rate, both expressed as percentages. The decision variables also affect biomass harvest rates, hence we can write:

$$H_t = h(X, B_t) \tag{9}$$

For any given set of prices, costs and management variables, the model can be solved by substituting equations (4) and (5) into (2), and (6) and (7) into (3), and then substituting (2), (3) and (9) into the objective function (1). The trajectories of the state variables S_t and B_t, and hence profit, depend partly on the initial state (S_0, B_0).

The processes represented in equations (4) to (7) are quite complex and subject to many types of interactions. Rather than explaining them in detail, we implement a numerical solution based on an existing simulation model. The model can later be extended to maximise (1) by setting the optimal levels of X for given prices and environmental conditions.

NUMERICAL MODEL

As stated previously, the processes of biomass and soil carbon accumulation were represented by a simulation model: WaNuLCAS (Water Nutrient and Light Capture in Agro-forestry Systems).

WaNuLCAS is based on the CENTURY model but has a spatial dimension and other features. The model concentrates on below-ground interactions where competition for water and nutrients (Nitrogen and Phosphorous) is based on the effective root-length densities of crops and trees, the current demand factors of crops and trees, and the supply of nutrients and soil-water content (van Noordwijk and Lusiana, 2000). The model does this by dividing the soil vertically into four user-defined layers and horizontally into four user-defined spatial zones. Each layer and spatial zone (i.e. 16 blocks) can be characterized according to initial water and nitrogen contents; clay and silt content; bulk density of the soil and soil type. Above-ground interactions such as competition for sunlight, and management effects such as planting density, species selection, pruning regime and fertiliser application, are also simulated by WaNuLCAS. The outputs most relevant to this study include total aboveground biomass and carbon, soil carbon levels, and harvested biomass and carbon.

Model Calibration

WaNuLCAS has parameter values and input data for *Gliricidia sepium* and it has been calibrated to different soils types in Indonesia. For the purposes of this study the model was calibrated to the climatic and environmental conditions typical of the Jambi[4] province of south Sumatra.

Jambi is situated in the middle of Sumatra – one of the largest islands of the Indonesian Archipelago. A large part of Jambi is covered by Sumatra's broad 'peneplain' agro-ecological zone. This region is divided into a *lowlands area* (10%), which is less than 200m above sea level, and is made up of river levees and flood-plains with fertile alluvial soils, and an *uplands area* (90%) with altitudes greater than 200m above sea level, slopes of 5-17% and mostly red-yellow podzolic soils, which fall under the soil order 'Ultisols' (Tomich *et al.*, 2001). The rainfall in the region exceeds 1500mm per year with up to four dry months. The shifting cultivation practice that typifies the upland areas is upland rice with *Imperata* fallow (*Imperata* is a pandemic, perennial grass found throughout the tropics and is characterized as having a spreading habit). Medium-textured, free draining soils with clay and silt contents of 25%, pH values of between 4.5 and 5.5, and topsoil bulk density values of between 1.2 and 1.4 gcm^{-3} were used in this study.

WaNuLCAS uses a modified version of the CENTURY model to simulate soil carbon fluxes. Instead of the SOM and the residue inputs being fractionated into three and two carbon pools respectively, as in the CENTURY model, they are divided into five pools each: structural, metabolic, active, slow and passive. The same processes of litter and SOM decomposition and carbon flow modelled in the CENTURY model are used in WaNuLCAS, but the latter simulates these processes on a daily rather than monthly scale and therefore requires more detailed fractionation. In this study, soil carbon is the sum of the five SOM pools used in the WaNuLCAS model, down to a depth of one meter.

In order for the model to simulate carbon accumulation and decomposition, the initial nitrogen and carbon values for each of the five pools in the litter and soil are required. Such data are not readily available in the literature so default values determined within WaNuLCAS were used. The climatic data used are mostly default values supplied within WaNuLCAS, except rainfall data where average monthly rainfall data from Muller (1982, pp. 136) were used.

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[4] Compiled from a range of sources which include: Menz and Grist (1999, pp15), Hardiyanto *et al.* (1999), Kirschbaum (1999) and WaNuLCAS V2.1 (van Noordwijk and Lusiana, 2001)

Agroforestry System

Gliricidia sepium is a single or multi-stemmed tree with a medium crown and a deep root system. It is a fast-growing, small tree and can grow to a maximum height of about 15m. *Gliricidia's* natural habitat is in early and middle successional vegetation types, on disturbed sites such as coastal sand dunes, riverbanks, floodplains and fallow land.

The characteristics of *Gliricidia sepium* which make it suitable as a productive, sustainable agroforestry system in Indonesia include:

- It grows well on disturbed sites under a wide variety of conditions. It is suited to the climate and acidic soils typical of S.E. Asia and, more specifically, the Jambi province (Grist *et al.*, 1999b).
- It has been cultivated in Indonesia since the early 1900s therefore the know-how and infrastructure are present and in practice.
- It has many commercial and subsistence outputs such as firewood, cabinet timber and panelling, fencing, mulch, fodder, shade and shelter, honey, and medicine.
- It provides environmental services such as shading and suppressing *Imperata* grasses (due to its ability to grow fast), and cycling nitrogen through the system (by producing mulch with a high nutrient value).

The system simulated in this study is a 25-year rotation of a *Gliricidia sepium* plantation, adapted from the *Gliricidia* systems simulated by Grist *et al.* (1999b) and Nelson *et al.* (1998). Preparing the land for *Gliricidia* involves removing existing vegetation (usually by burning) and then ploughing the site. Cuttings are then collected and planted. A planting density of 10000 trees per hectare was used. *Gliricidia* cuttings are quick to establish, and once established require little maintenance, including no weeding. Fertiliser is applied at a rate of 60 kg/ha/yr for the first four years. To maximize nutrient recycling, pruning is done frequently. In WaNuLCAS, pruning events are based on canopy density, where pruning only occurs when the total tree leaf area index (LAI) exceeds a user-defined critical value. The critical value for LAI, for a frequently pruned tree species such as *Gliricidia*, suggested by van Noordwijk and Lusiana (2000, pp. 98) is 0.1[5]. When harvesting this pruned material the wood, twigs and leaves are removed from the system.

WaNuLCAS was used to simulate the effects of different pruning and harvesting regimes at three different levels of initial soil organic matter (carbon). A total of 27 experimental scenarios were simulated. The different combinations of harvesting and pruning regimes are detailed in Table 2.

Table 2. Scenarios simulated in the numerical model, figures identify scenarios by their 'treatment no. '

	Harvesting (%)		
Pruning (%)	***100***	***50***	***25***
75	1	2	3
50	4	5	6
25	7	8	9

The scenarios are referred to by their number followed by the letter H, M or L to represent high medium or low initial soil carbon. For example 5H represents the scenario where 50% of the tree

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[5] Tree prune limit (T_PrunLimit) is expressed as 'tree biomass per unit field area' (van Noordwijk and Lusiana, 2000, pp. 98).

canopy is pruned and of this pruned material 50% is harvested, starting the simulation with a high soil carbon level.

The three initial soil carbon levels were determined using the second of the three options for initializing soil organic matter pools provided within WaNuLCAS. The size of all pools (C_{org}) are stated relative to a forest soil (C_{ref}) that is calculated from soil texture data, elevation and pH (van Noordwijk *et al.,* 2000, pp. 156; and van Noordwijk and Lusiana 2001). The equation used to calculate C_{ref} will vary depending on the soil type and forest type. The example given by van Noordwijk *et al.* (2000, pp. 156) is for an Andisol soil and a swamp forest.

The size of the high, medium and low initial soil carbon pools given by this method were: 58.37 t C/ha, 32.43 t C/ha and 16.21 t C/ha respectively. These values represent arbitrarily chosen C_{org}/C_{ref} ratio values of 1.8, 1, and 0.5 respectively. Although the high soil carbon level may not occur naturally in the region, we were interested in exploring the behaviour of the model under extreme conditions.

Table 3. Base parameter values

Parameter	Value	Units	Description	Source
P_{FW}	75 000	Rp/t	firewood price	b
P_C	100 000	Rp/t	price of carbon	f
P_S	150	Rp/seedling or cutting	price of seedlings	a
r	15	%	discount rate	c & e
C_F	400	Rp/kg	price of fertiliser	a
C_L	6000	Rp/day	price of labour	e
C_E	$S_{est} * P_S$	Rp	establishment costs	
C_M	$C_L + C_F$	Rp	annual maintenance costs	
Lest	80	days/yr	labour for establishment	d
Lann	1	days/t DM/ha/yr	labour requirements	d
Fa	60	kg/ha/yr	fertilizer application rate	a
S_{est}	10 000	seedlings	planting density	d
phw	70	%	% harvest sold as fuelwood	
δ	0.42	-	carbon content of wood	e

Sources: a: Grist *et al.* (1999c, pp.171), b: CESERF (1999), c: midway between the 10% used by Menz and Magcale-Macandog (1999, pp10) and the 20% used by Tomich *et al.* (1998, pp63), d: adapted from Grist *et al.* (1999b, pp. 135), e: van Noordwijk and Lusiana (2001), f: Grist *et al.* (1999a, pp. 257) use $US 5, $US 10 and $US 20/t of carbon sequestered.

The soil carbon (S_t) and biomass carbon (B_t) results obtained from each 25-year simulation were substituted into equation (1) and net present values were calculated under the base parameter values presented in Table 3. Labour requirements, and therefore annual costs, depend on the level of pruning and harvesting.

The labour requirements were calculated in terms of days required to prune and harvest one tonne of biomass. Grist *et al.* (1999b, pp. 135) state that 20 days per hectare per year are required to prune and harvest a *Gliricidia* plantation and that the average quantity of material pruned per hectare per year is 21 tonnes. Hence the labour requirements are 20 (d/ha/yr) / 21(t/ha/yr) which equals 0.95 d/t. This was rounded up to 1.0 d/t.

BIOPHYSICAL RESULTS

Average Carbon Stocks

The results of the 27 treatments are presented in Table 4. Figures represent the average amount of carbon in soil and standing biomass (t C/ha) and the average amount of biomass harvested as firewood (kg DM/ha) per year. These figures were estimated as:

$$Y_{ij} = \frac{\sum_{t=1}^{25} Y_{ijt}}{25}$$

Where the Y_{ijt} represents annual output i under treatment j, where i= soil carbon (S_t), biomass carbon (B_t), or firewood harvested. Hence these results measure average annual stocks over the planning horizon and do not reflect any differences in the time paths of biomass accumulation. Selected treatments are studied in more detail later by examining time paths.

The advantage of the summary results in Table 4 is that overall differences between treatments can be identified and cases for further analysis selected.

Harvest has significant effects on soil carbon and harvested biomass, with very small effects on standing biomass; in contrast, pruning has small effects on soil carbon and harvested biomass, and a more pronounced effect on standing biomass (Table 4). These patterns generally hold for all initial soil carbon (S_0) levels, except for the case of low initial soil carbon and high harvest, where the system is obviously not sustainable. These results are explained in more detail below.

Table 4. Average carbon stocks in soil and biomass, and average annual harvest of firewood

	High initial soil carbon				Medium initial soil carbon				Low initial soil carbon			
	Harvest				Harvest				Harvest			
Pruning	100%	50%	25%	Mean	100%	50%	25%	Mean	100%	50%	25%	Mean
					Soil carbon (t C/ha)							
75%	34.79	43.78	48.24	42.27	21.21	30.19	34.66	28.69	12.08	20.98	25.47	19.51
50%	34.80	43.55	47.91	42.09	21.19	31.11	34.33	28.88	12.08	20.72	25.08	19.29
25%	34.81	43.20	47.37	41.79	21.23	29.62	33.79	28.21	12.09	20.34	24.55	18.99
Mean	34.80	43.51	47.84	42.05	21.21	30.31	34.26	28.59	12.08	20.68	25.03	19.26
					Standing biomass carbon (t C/ha)							
75%	23.68	24.68	24.68	24.35	23.36	24.68	24.68	24.24	14.25	24.53	24.63	21.14
50%	26.14	27.51	27.51	27.05	28.35	29.68	27.51	28.51	15.07	27.24	27.35	23.22
25%	32.91	34.41	34.41	33.91	32.40	34.40	34.41	33.74	19.15	34.05	34.18	29.12
Mean	27.58	28.87	28.87	28.44	28.04	29.59	28.87	28.83	16.16	28.61	28.72	24.49
					Harvested biomass (t DM/ha/yr)							
75%	25.42	13.25	6.62	15.10	25.02	13.25	6.62	14.97	15.79	13.16	6.60	11.85
50%	25.13	13.08	6.54	14.92	24.88	13.08	6.54	14.84	15.73	12.96	6.51	11.73
25%	24.44	12.71	6.36	14.50	24.06	12.71	6.36	14.37	15.57	12.54	6.31	11.48
Mean	25.00	13.01	6.51	14.84	24.66	13.01	6.51	14.73	15.70	12.89	6.47	11.69

The effects of pruning regime on carbon stocks can be analysed by comparing the rows in Table 4. For any given value of S_0 and harvest regime, an increase in pruning level, has a small effect on soil carbon, effects range between 1% and 3% as pruning increases from 25% to 75%. As would be expected, pruning affects standing biomass. Depending on initial soil carbon, an increase in pruning (from 25% to 75%) causes average standing biomass to decrease by between 27% (from 33.9 to 24.4 tC/ha with high S_0) and 28% (from 29.1 to 21.1 t C/ha with low S_0).

The effects of harvest regime on carbon stocks can be analysed by comparing the columns in Table 4. As harvest increases from 25% to 100%, average soil carbon decreases by 27% (from 47.8 to 34.8 tC/ha) with high S_0, and by 51% (from 25.0 to 12.1 tC/ha) with low S_0. The same increase in harvest causes average standing biomass to decrease by only 4% (from 28.9 to 27.6 t/ha) at high S_0, but by 44% (from 28.7 to 16.2 tC/ha) at low S_0. These results clearly illustrate that harvest regime has more pronounced effects on carbon stocks in poor soils than in rich soils.

Harvest is inversely related to soil carbon, because biomass that is pruned but not harvested is added to the soil, whereby it is decomposed and contributes carbon and nutrients (mainly N and P) to the soil. Biomass harvested per year ranges between 6.5 t/ha and 25 t/ha depending on harvest regime (see last row of Table 4).

Figure 3 represents the time trajectory of carbon stocks over 25 years for selected scenarios. The darker-shaded area in each figure represents the soil carbon stock (S_t) and the lighter-shaded area represents standing biomass (B_t). The scenarios presented in this figure range from high-pruning, high-harvest (1) to low pruning, low harvest (9), as defined in Table 2.

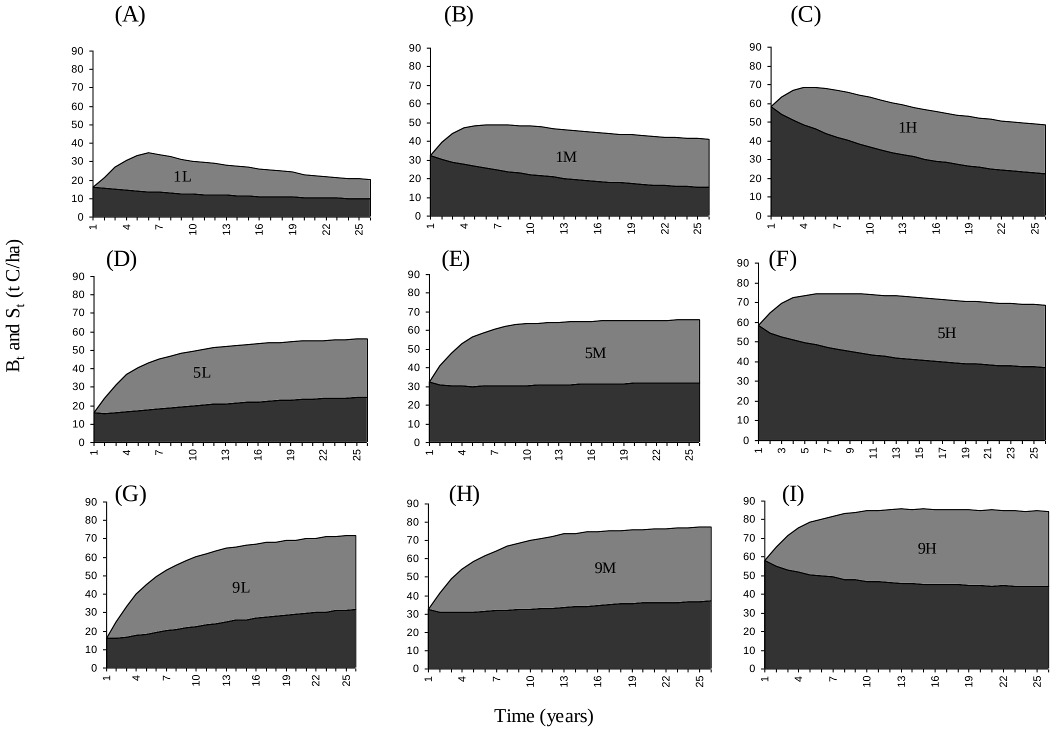

Figure 3. Time-trajectory of carbon stocks in above-ground biomass (light) and soils (dark) under low (A,D,G), medium (B,E,H) and high (C,F,I) initial soil carbon levels.

Each row represents a different combination of pruning and harvesting regimes and each column represents a different initial soil carbon level. On initial inspection, for any given combination of pruning and harvesting level, the higher the initial soil carbon level the larger the total carbon stock. This is most clearly evident when comparing the three figures in column three (Figure 3 C, F and I) with the three figures in column one (Figure 3 A,D and G). This pattern gives the impression that in order to have higher total carbon stocks it is better to have high initial carbon levels. This may be true if we are concerned only with total stocks, with no regard for the baseline. From a policy perspective, however, baseline is critical. What matters is how much carbon is sequestered relative to what would have occurred in the absence of the project.

Carbon Stocks Relative to the Baseline

When one considers the change in carbon stock over the 25 years, relative to the initial carbon stock (the baseline), a very different picture emerges. This is best shown using the average carbon stock relative to initial carbon values (C_j) summarized in Table 5.

Table 5. Average biomass and soil carbon stock above baseline (t C/ha).

	Pruning			Harvest		
S_0	75%	50%	25%	100%	50%	25%
H	8.3	10.8	17.3	4.0	14.0	18.3
M	20.5	25.0	29.5	16.8	27.5	30.7
L	24.4	26.3	31.9	12.0	33.1	37.5

The values in Table 5 were calculated as

$$C_j = \frac{\sum_{t=1}^{25} S_{jt} + B_{jt}}{25} - S_{j0}$$

Where: C_j represents the average carbon stock above the initial value (baseline) for treatment *j*, and S_j and B_j represent soil carbon and biomass carbon for scenario *j*, respectively.

The entries in Table 5 show a larger net increase in carbon stock with low initial soil carbon compared with high initial soil carbon, and this occurs for all pruning and harvesting strategies.

For any given pruning regime a decrease in initial soil carbon has a substantial positive effect on average carbon stock of the project. A decrease in initial soil carbon from a high level (*H*) to a low level (*L*) increases average carbon stock between 294% (from 8.3 to 24.4 t C/ha) when the pruning regime is high, and 184% (from 17.3 to 31.9 t C/ha) when the pruning regime is low.

For any given harvesting regime a decrease in initial soil carbon also has a substantial positive effect on average carbon stock. Changes in average carbon stock when the initial soil carbon level decreases from *H* to *L*, are always positive and range between 300% (from 4.0 to 12.0 t C/ha) when harvesting regime is high, and 205% (from 18.3 to 37.5 t C/ha) when harvesting regime is low.

In summary, average carbon stocks, relative to the baseline, are very sensitive to changes in initial soil carbon level. Increases in C_j range between 184% and 300% depending on harvesting and pruning regime. The effect is slightly greater under higher pruning or harvesting regimes than with low pruning or harvest regimes.

Figure 4 shows the trajectory of total carbon stock (including soil and standing biomass carbon) relative to baseline at varying levels of pruning and harvest. The trajectories in this Figure support the general findings from the data in Table 5 but contribute more detailed information on the effects of initial carbon stock on total carbon stock fluctuations over the entire rotation.

At both low and medium initial soil carbon levels, the total carbon stock increases rapidly for the first seven or so years, reaches a maximum, and then levels out for the rest of the rotation. This is the case for all the scenarios depicted in Figure 4 except when the harvest regime is high. With a high harvest regime, however, the total carbon stock increases rapidly in the first seven years or so and then decreases over the remaining 18 years. This indicates that such a system is unsustainable.

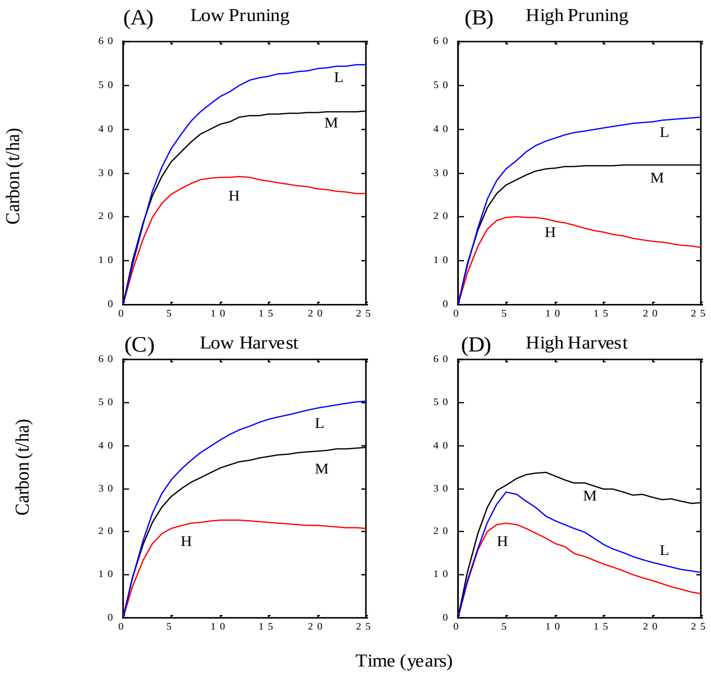

Figure 4: The effect of different initial soil carbon levels on carbon stock (includes soil and standing biomass) relative to baseline, at varying pruning and harvesting levels.

When the initial carbon stock is high, the total carbon stock increases rapidly for the first few years, reaches a maximum, and then gradually decreases over the remaining years of the rotation. This occurs irrespective of the harvest and pruning regimes, but is most pronounced when the harvest regime is high.

Harvested Biomass

Table 6 shows the average carbon harvested annually for firewood from the *Gliricidia* plantation over the 25-year rotation. It is clear that the harvest regime has a significant effect on the quantity of carbon harvested, whereas pruning level has a small impact upon annual harvested carbon. For example, as pruning increases from 25% to 75%, average annual harvested carbon increases by 3% (from 6.1 to 6.3 t C/ha/yr) with high initial soil carbon, and by 4% (from 4.8 to 5.0 t C/ha/yr) with low initial soil carbon.

Table 6. Average carbon harvested for firewood annually (t C/ha/yr).

	Pruning			Harvest		
S_0	75%	50%	25%	100%	50%	25%
H	6.3	6.2	6.1	10.5	5.5	2.8
M	6.3	6.2	6.1	10.4	5.4	2.7
L	5.0	4.9	4.8	6.6	5.4	2.8

In contrast, as harvest increases from 25% to 100%, average annual harvested carbon increases by 73% (from 2.8 to 10.5 t C/ha/yr) for high initial soil carbon, and by 58% (from 2.8 to 6.6 t C/ha) for low initial soil carbon. These results confirm that high harvest regimes and low initial soil carbon are an unsustainable combination. Under these conditions the soil becomes exhausted, since no nutrients are being returned to the system, and biomass production decreases with time.

Figure 5 shows the trajectories associated with selected results from Table 6. The two graphs show the effect of increasing harvest on harvested carbon. As harvest level increases the amount of harvested carbon also increases, except when harvest is 100% and initial soil carbon is low. The decrease in harvested biomass beyond year 5 (Figure 5B, line L) presents a clearer picture of the unsustainability argument above.

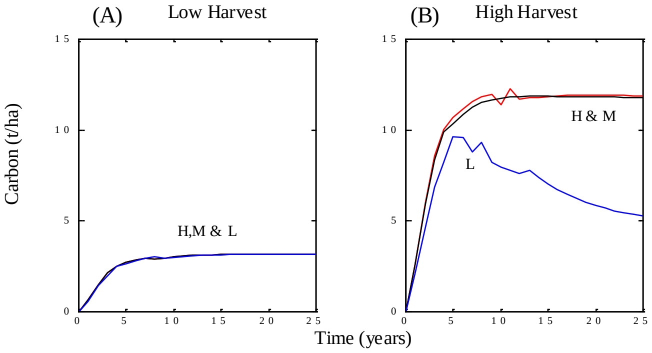

Figure 5: The effect of different initial soil carbon levels on harvested carbon at two harvesting levels and a 50% pruning regime.

ECONOMIC ANALYSIS

The economic performance of the management scenarios discussed in the previous section depends on the prices of firewood and carbon, establishment costs and discount rate. Economic performance will also be affected by the carbon-credit regime; in particular, the carbon pools that are eligible for payment will influence the financial attractiveness of the project. Three pools may be eligible: standing biomass, soil carbon and harvested biomass. Standing biomass is fairly easy to measure and any carbon-credit regime would include this pool. Soil carbon is more difficult to measure and there may be arguments against including this pool based on monitoring costs. Harvested biomass would be included only if it can be shown that the biomass burned is replacing fossil fuels as a source of energy, thereby decreasing net emissions. Four accounting methods are considered in the economic analysis that follows:

1. No carbon credits
2. Carbon credits on standing biomass only
3. Carbon credits on standing biomass and soil carbon
4. Carbon credits on standing biomass, soil carbon and harvested biomass.

Only the nine scenarios with low initial soil carbon are considered in this section, as it is unlikely that clearing land containing high carbon stocks to establish an agroforestry operation would be acceptable in a carbon-credit scheme.

Base-Case Results

The net present values (NPV) of the nine scenarios with a low initial soil carbon and using four different accounting procedures are presented in Table 7. NPV is greatest when harvest regime is 100% and decreases as the harvest regime decreases. This pattern occurs for all accounting procedures. A similar pattern applies to the different pruning regimes. NPV is largest at high (75%) pruning and decreases as the pruning level decreases. NPV becomes negative at low (25%) harvest regimes when no carbon payments occur. Results indicate that the land-use system simulated in this study might be worth investing in, provided harvesting is undertaken at 50% or more of biomass pruned.

Table 7: Net Present Values (Rp '000/ha) for each of the nine scenarios, for base parameter values, using different accounting systems.

	Accounting System[2]			
Scenario[1]	1	2	3	4
1 *(75/100)*	2,595	3,877	3,633	6,557
2 *(75/50)*	1,152	2,929	3,144	5,128
3 *(75/25)*	-399	1,402	1,852	2,855
4 *(50/100)*	2,516	3,887	3,643	6,515
5 *(50/50)*	1,049	2,967	3,165	5,077
6 *(50/25)*	-444	1,500	1,923	2,891
7 *(25/100)*	2,266	3,911	3,668	6,377
8 *(25/50)*	854	3,147	3,313	5,087
9 *(25/25)*	-535	1,788	2,166	3,063

[1] numbers in brackets indicate pruning/harvest levels (%)

[2] Accounting systems: 1, no carbon credits; 2, credits on standing biomass only; 3, credits on standing biomass and soil carbon; 4, credits on standing biomass, soil carbon and harvested biomass.

For each of the four accounting systems, the largest NPV is always attained with a high harvest / high pruning regime (Scenario 1). When carbon payments are introduced (accounting systems 2, 3 and 4), the NPVs are higher and the relative rankings of management scenarios remain the same (Table 7).

It is interesting to note that when soil carbon payments are introduced (accounting system 3), the NPVs increase relative to the biomass-only payments (accounting system 2) except when the harvest regime is 100%. In these cases (scenarios 1, 4 and 7) NPV actually decreases. This occurs because soil carbon stock decreases when no pruned biomass is returned to the system.

Larger NPVs occur when all pools, including harvested carbon, are eligible for payment (accounting system 4), and the largest NPV (Rp 6,557,000/ha) occurs with the high pruning/high harvest regime. It is debatable whether harvested carbon should be included when accounting for carbon stocks. Harvested wood is sold as firewood and this carbon will be released back into the atmosphere when burned. This issue is discussed in more detail later.

Investing in agroforestry or plantation forestry projects will only occur if the expected returns exceed the opportunity cost of the funds if they were invested elsewhere. The opportunity cost of capital in the base case is 15%, but this may not be enough for smallholders facing high interest rates. Table 8 lists the internal rates of return (IRR) corresponding to the scenarios and accounting systems of Table 7.

Table 8: Internal rates of return (%) for nine scenarios and four accounting systems, using base parameter values and low initial soil carbon.

	Accounting System[2]			
Scenario[1]	1	2	3	4
1 *(75/100)*	29.2	41.9	40.0	51.4
2 *(75/50)*	21.0	36.5	37.4	45.2
3 *(75/25)*	12.7	28.6	31.8	37.1
4 *(50/100)*	28.4	41.9	40.1	50.7
5 *(50/50)*	20.3	36.6	37.3	44.5
6 *(50/25)*	12.4	29.4	32.2	37.1
7 *(25/100)*	26.7	41.9	40.1	49.7
8 *(25/50)*	19.2	37.7	38.1	44.4
9 *(25/25)*	12.1	31.7	33.9	38.0

[1] numbers in brackets indicate pruning/harvest levels (%)

[2] Accounting systems: 1, no carbon credits; 2, credits on standing biomass only; 3, credits on standing biomass and soil carbon; 4, credits on standing biomass, soil carbon and harvested biomass.

IRRs are above 15% for all cases except when no carbon payments occur and harvest level is low (scenarios 3, 6 and 9). The general pattern is that, as more carbon pools are included in the accounting systems, the rate of return increases, except at high harvest when soil carbon is included (accounting system 3).

When biomass carbon is included the IRRs increase by between 13% (from 29.2% to 41.9% at high harvest / high pruning) and 20% (from 12.1% to 31.7% for low harvest / low pruning). The increases in IRR when biomass carbon is included are greater as the harvest regime decreases, for each of the three pruning regimes. When soil carbon is included (accounting method 3) the IRRs do not increase significantly (the greatest increase being 3.2% for scenario 3). In fact, at the high harvest regime (100%), the IRRs decrease slightly when soil carbon is included.

Effects of Establishment Cost

The base-case assumption for the establishment cost is that the price of seedlings is Rp150. For 10000 seedlings, this makes the establishment cost Rp 1,500,000/ha. There is uncertainty regarding this seedling price, which was based on the cost of collecting jungle rubber seedlings, but may be too high for *Gliricidia* seedlings. Therefore the effect of lower establishment costs are investigated in this section. The effects of halving establishment costs are presented in Table 9.

Comparing the IRR between Table 9 and Table 8, it is clear that an agroforestry system such as this is more profitable and more attractive to investors for all the different scenarios and under every accounting system, when establishment costs are halved. In fact, comparing the accounting systems (moving from left to right) in Table 9, increases in IRR of between 5% (for scenario 1 using the accounting system 2) and 19% (for every scenario using the accounting method 4) are seen. The effect of harvest regime and pruning regime on IRR's follow the same patterns as those highlighted in Table 8.

Table 9: Internal rates of return (%) for nine scenarios and four accounting systems, with low seedling price.

	Accounting System\2			
Scenario\1	1	2	3	4
1 *(75/100)*	40.0	60.0	57.3	70.4
2 *(75/50)*	28.7	54.5	55.2	63.9
3 *(75/25)*	17.9	46.7	50.2	55.8
4 *(50/100)*	38.6	60.0	57.4	69.3
5 *(50/50)*	27.7	54.4	54.9	62.8
6 *(50/25)*	17.5	47.6	50.4	55.5
7 *(25/100)*	36.2	60.0	57.4	68.0
8 *(25/50)*	25.9	55.8	55.8	62.6
9 *(25/25)*	16.7	50.2	52.1	56.4

\1 numbers in brackets indicate pruning/harvest levels (%)

\2 Accounting systems: 1, no carbon credits; 2, credits on standing biomass only; 3, credits on standing biomass and soil carbon; 4, credits on standing biomass, soil carbon and harvested biomass.

Effects of Firewood Price

The pre-crisis, 1997 price for firewood in South Sumatra was Rp 27,000 (CESERF,1999). The base case price for firewood in this study has been set at approximately three times this price. Firewood is the main output of the plantation simulated in this study, therefore the sensitivity of this system to changes in the price of firewood needs to be investigated. The IRR for each of the nine scenarios and the four accounting systems under a low firewood price of Rp 40,000 are listed in Table 10.

When only firewood is accounted for, a low firewood price leads to decreases in IRR of between 13% and 6% (for scenarios one and nine, respectively) as compared with the base case. The largest decreases in IRR occur when the harvest regime is 100%. This is expected since in these cases there is more firewood being sold.

Table 10: Internal rates of return (%) for nine scenarios and four accounting systems, with low firewood prices.

	Accounting System[2]			
Scenario[1]	1	2	3	4
1 *(75/100)*	16.0	28.7	26.4	42.2
2 *(75/50)*	11.6	27.3	**28.7**	38.8
3 *(75/25)*	6.1	21.8	26.2	32.8
4 *(50/100)*	15.7	29.4	27.1	42.1
5 *(50/50)*	11.4	28.1	**29.3**	38.6
6 *(50/25)*	6.1	23.3	27.1	33.1
7 *(25/100)*	14.9	30.8	28.5	41.9
8 *(25/50)*	10.9	30.6	**31.3**	39.3
9 *(25/25)*	6.2	26.9	29.7	34.6

[1] numbers in brackets indicate pruning/harvest levels (%)

[2] Accounting systems: 1, no carbon credits; 2, credits on standing biomass only; 3, credits on standing biomass and soil carbon; 4, credits on standing biomass, soil carbon and harvested biomass.

The only scenarios in column two of Table 10 that have IRR's greater than the social interest rate of 15% are scenarios 1, 4 and 7. The rest of the scenarios have IRR's ranging between 13% and 6%. These scenarios have gone from being profitable at a high firewood price to being unprofitable at a low firewood price. This indicates that the profitability of such plantation systems is sensitive to decreases in firewood price.

When carbon credits are included in the accounting procedures, the IRR for all scenarios, although lower than for the base case by between 5% and 13%, still exceed the social rate of interest and are therefore attractive for investment. The main difference between these results and those in the base case is that the relative rankings of scenarios under accounting system 3 change. In this case, it becomes more profitable to undertake moderate harvest (50%) rather than high harvest (100%) and this is true for all three pruning levels (see bold figures in table 10). This is because soil carbon becomes more valuable relative to firewood than in the base case.

Effects of Carbon Price

If the price of carbon were to halve from the A$20 assumed in the base case, the profitability of the system (as measured by the IRR), would obviously only be affected if carbon sequestration payments were included (accounting systems 2, 3 and 4).

Table 11 summarises the IRR's for each of the nine scenarios under the four accounting systems for a low carbon price, with all other parameters at their base values. The IRR's for all nine scenarios using accounting systems 2, 3 and 4 all remain greater than the social rate of interest indicating that the attractiveness in investing in such a project is not overly sensitive to drops in the price of carbon.

Although decreases in the IRR of between 7% and 12% under accounting system 2, 6% and 13% under accounting system 3, and 11% and 14% under accounting system 4, are evident, these are not large enough to make the project unprofitable. The effect of harvest and pruning regime on IRR's follow the same patterns as those highlighted in Table 8.

Table 11: IRR's (%) for nine scenarios and four accounting systems, using a low carbon price.

Scenario[1]	Accounting System[2] 1	2	3	4
1 *(75/100)*	29.2	35.1	34.2	40.5
2 *(75/50)*	21.0	27.8	28.3	32.8
3 *(75/25)*	12.7	18.9	20.5	23.7
4 *(50/100)*	28.4	34.6	33.8	39.7
5 *(50/50)*	20.3	27.4	27.9	32.1
6 *(50/25)*	12.4	19.1	20.6	23.6
7 *(25/100)*	26.7	33.7	32.8	38.3
8 *(25/50)*	19.2	27.3	27.6	31.5
9 *(25/25)*	12.1	19.8	21.1	23.7

[1] numbers in brackets indicate pruning/harvest levels (%)

[2] Accounting systems: 1, no carbon credits; 2, credits on standing biomass only; 3, credits on standing biomass and soil carbon; 4, credits on standing biomass, soil carbon and harvested biomass.

DISCUSSION

Overall, results show that the *Gliricidia* system is profitable under most circumstances, except when harvest regime is low and no carbon-credit payments occur. In general, the most attractive management strategy, from the landholder perspective, is to follow a high-pruning, high-harvest regime. Unfortunately, this strategy is unsustainable as shown by the drop in biomass production after year 5. This decrease in productivity does not offset the extra profit obtained by selling firewood, partly because of the high discount rate (15%).

The use of harvested biomass (firewood) and/or wood residues at processing plants to produce energy may have positive effects on rural poor populations of many developing nations. Some of these benefits may include value-added to the raw materials, a more stable wood-processing industry, and a cheaper source of rural electrification (Gowen *et al.,* 1994, pp. 27). Other benefits might be derived from the alleviation of environmental problems caused by using fossil fuels at the processing plants and by preventing wood residues at processing plants from being dumped in landfills or burned in the open air (Gowen *et al.,* 1994, pp. 27).

With relevance to this study, if it can be shown that the harvested biomass sold as firewood substitutes for fossil fuel use – and therefore permanently decreases net carbon emissions – then the carbon in the firewood would be eligible for inclusion in a carbon-credit scheme and should therefore be accounted for when calculating the total amount of carbon sequestered by such a system. In this study we used a simplified procedure, by assuming that a unit of carbon from firewood is equivalent to one unit of carbon from fossil fuel. However, if the energy released by burning one unit of fossil-fuel carbon is higher than the energy released by burning one unit of firewood carbon, then a larger amount of firewood carbon would be required to substitute for a given level of energy production. In other words, the calorific values of both firewood and the fossil fuel need to be taken into account. This is an important topic for future research.

Under the assumptions of this paper, and given the simulation results obtained from an existing model, we found that a profit-maximising landholder would prune and harvest as much firewood as possible– at least in the short term. Pruned biomass, however, has an important role to play when considering longer-term sustainability, productivity and profitability. By not harvesting all of the pruned biomass, but returning some to the system as mulch, carbon and nutrient levels can be maintained. This maintains, if not increases, the quality and productivity of the soil and ensures a more sustainable land-use practice. Doing this, however, will involve trade offs between short-term profitability and long-term sustainability, and raises the question of whether a carbon-credit scheme that allows for biomass energy production should include sustainability constraints.

SUMMARY AND CONCLUSIONS

This paper presents an analysis of the economic consequences of accounting for soil carbon in climate mitigation policy. The analysis is based on the growth of a *Gliricidia* plantation under different pruning and harvesting management regimes and different initial soil carbon levels.

The profitability of the system is evaluated under four accounting methods, including no carbon payments, payments for accumulation of carbon in biomass and soils, and payments for carbon stocks and flows under a scheme where firewood substitutes for fossil fuels. It is shown, for each of the four accounting procedures used, that the system is profitable under most pruning and harvesting regimes, except when no firewood harvest occurs in the absence of carbon credits. Under the assumptions used in this study, it is also shown that in order to maximise profit over a single 25-year rotation, a landholder will prune and harvest as much biomass as possible. In other words, under base prices, the benefits from harvesting biomass exceed the benefits foregone if some of the biomass had been returned to the system as mulch to increase or maintain soil carbon levels - at least in the short-term. In the longer-term, however, productivity and profitability will not be sustained under such management practices. Therefore, in order to ensure that sustainability is achieved landholders would need to decrease their harvest and return some of the pruned biomass to the system.

In summary, the trade offs involved between short-term profitability and long-term sustainability are clearly illustrated by our results. The question of whether carbon schemes for biomass energy production should be subject to sustainability constraints is raised by this study and remains an important area for future research and debate.

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