Carbon-accounting methods and reforestation incentives

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Contributed Paper to the 46th Annual Conference of the Australian Agricultural and Resource Economics Society
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ABSTRACT

The emission of greenhouse gases, particularly carbon dioxide, and the consequent potential for climate change are the focus of increasing international concern. Eventually, an international agreement will likely be enacted to reduce greenhouse gas emission levels and assign rules for emission trading within and between countries. Temporary land-use change and forestry projects (LUCF) can be implemented to offset permanent emissions of carbon dioxide from the energy sector. Several approaches to accounting for carbon sequestration in LUCF projects have been proposed. In this paper, the economic implications of adopting some of these approaches are evaluated in a normative context, based on simulation of Australian farm-forestry systems.

Keywords: climate change, carbon accounting, reforestation, bioeconomics

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INTRODUCTION

Concerns over global warming have led to proposals for the establishment of markets for greenhouse gas emissions. Although formal markets have not emerged, a number of international exchanges have occurred, whereby power companies and other energy-intensive industries have invested on "green" projects, to partially offset their emissions of carbon dioxide (CO_2) and other greenhouse gasses (GHG).

Until recently, the Kyoto Protocol (KP) has provided the context within which much of the policy debate on global warming has occurred. The KP established a commitment period (2008 to 2012) over which Annex I countries[1] would undertake to reduce their greenhouse gas emissions by an aggregate 5 percent relative to their 1990 emissions. The recent collapse of the KP, caused by the withdrawal of the USA, means that the first commitment period and other rules set by KP may not stand. However, global warming processes will continue to operate and, eventually, some sort of international agreement will have to be ratified. Such an agreement is likely to contain provisions for exchange of greenhouse-gas emission permits. Over the last decade or so, a large amount of high-quality scientific contributions have been made to the United Nations Framework Convention on Climate Change (UNFCCC), particularly through the Intergovernmental Panel on Climate Change (IPCC), which has produced a number of technical reports. Many of these contributions will influence the shape of the agreement that may eventually be reached to replace the KP.

The KP contains two articles of special relevance to this paper:

Article 6 states that "any Party included in Annex I may transfer to, or acquire from, any other such party emission reduction units resulting from projects aimed at reducing anthropogenic emissions by sources or enhancing anthropogenic removals by sinks of greenhouse gasses in any sector of the economy", subject to certain provisos. This mechanism covers the so-called activities implemented jointly (AIJ). The proposed medium of exchange under this Article is the ERU (Emission Reduction Unit).

Article 12, The Clean Development Mechanism (CDM), has the purpose of assisting " Parties not included in Annex I in achieving sustainable development and in contributing to the ultimate objective of the Convention,

[1] Annex I countries include the OECD countries (except Mexico and Turkey) and transition economies in eastern Europe.

and to assist Parties included in Annex I in achieving compliance with their quantified emission limitation and reduction commitments...”. The proposed medium of exchange under this Article is the CER (Certified Emission Reduction).

We use the term “carbon credits” to refer to both exchange mechanisms throughout this paper. There has been much debate regarding the kinds of activities that may receive credit under these Articles and the meaning of various definitions (e.g. see Watson *et al.* 2000). Much of the controversy has been in regard to land-use change and forestry (LUCF) activities. Forestry and other land-use activities act as sinks of greenhouse gasses, particularly CO_2. Growing forests contribute to the reduction of net CO_2 emissions by fixing carbon in wood, leaves and soil. Some Parties (particularly the European Union) are opposed to the eligibility of LUCF projects for carbon credits, while other Parties (particularly the USA) argue in their favour. The problem of *permanence*, which is the focus of this paper, arises because LUCF projects tend to be temporary in nature, since CO_2 captured during forest growth is released upon harvest. In contrast, projects in the energy sector that reduce emissions are permanent, in the sense that an avoided emission will never reach the atmosphere.

So, in comparing sources and sinks, the duration of a carbon sequestration project is important because, whereas technological advances in the energy sector have a permanent mitigation effect, forestry projects will release carbon upon harvest. Smith *et al.* (2000) point out that "non-permanent forestry projects slow down the build up of atmospheric concentrations, unlike energy projects, which actually reduce emissions. Non-permanent forestry projects should therefore be regarded as an intermediate policy option".

The problem of permanence must be addressed before LUCF projects are acceptable in a carbon-credit market. Proponents of LUCF projects point to several advantages of temporary sequestration; such as (i) some proportion of temporary sequestration may prove permanent, (ii) deferring climate change has benefits, (iii) temporary sequestration ‘buys time’ while affordable energy technologies are developed, and (iv) temporary sequestration projects have value in saving time to gain information on the process of global warming (Lecocq and Chomitz 2001).

In this paper, we review four accounting methods that have been proposed to allow sources and sinks of greenhouse gasses to be compared and measured by a common unit of exchange. We use a numerical example to show the economic implications of these different accounting methods from the standpoint of an individual firm. We then discuss the implications of our results from a policy perspective and identify possible obstacles to implementation.

THE ROLE OF LAND-USE CHANGE AND FORESTRY

Although the main focus in the battle against global warming is on emissions (sources), sinks, such as carbon sequestration, have also received considerable attention. Through the process of photosynthesis trees absorb large quantities of CO_2 from the atmosphere. CO_2 remains fixed in wood and other organic matter in forests for long time periods, and hence trees are a convenient way of sequestering carbon from the atmosphere to reduce net emissions.

A forest will fix carbon while it grows, but it will release CO_2 after harvest. The fate of harvested forest products may influence the choice of systems considered efficient for greenhouse gas control. Depending on harvest techniques, a substantial amount of CO_2 may be released back to the atmosphere within a decade after harvest occurs. Also, the merchantable portion of trees releases some CO_2 during processing, but a considerable portion of carbon remains fixed in timber products for a long time.

Lecocq and Chomitz (2001) use an optimal control model of global mitigation strategies to show that temporary sequestration projects can be cost effective in the short to medium run provided the marginal damages of climate change are high enough. They also point out that temporary sequestration contracts make sense when it is desirable to keep CO_2 concentrations below a threshold, then “the sequestration project serves to bridge the “hump” of high energy abatement costs” (Lecocq and Chomitz 2001, p. 21). In this case sequestration follows a bang-bang optimal dynamics.

If the incentives are right, the physical environment may be radically affected by changed patterns of land use associated with the emergence of carbon markets. Surface flora and fauna, both in and adjacent to new forests, is likely to change as land uses evolve to incorporate incentives arising from the carbon markets. Trees provide environmental benefits such as soil erosion control and fertility maintenance in addition to carbon-sequestration services. In Australia, for example, there is a sizeable dryland salinity problem, which can be partially controlled through tree planting. However, there is generally no private incentive to address the problem because (downstream) landholders who benefit from tree planting are often not the same as those (upstream) who incur the cost of planting the trees. Hence, incentives for increased tree production to control global warming may have secondary benefits in the form of reduced land degradation.

RADIATIVE FORCING AND GLOBAL WARMING

The impact of a greenhouse gas (GHG) on global warming depends on the amount of heat that is blocked from escaping into space (Fearnside *et al.* 2000). This is explained by the concept of *radiative forcing*.

On average over a year, about a third of solar radiation entering Earth is reflected back to space; the remainder is absorbed by land, ocean and ice surfaces, as well as by the atmosphere. The solar radiation absorbed by the Earth surface and atmosphere is balanced by outgoing (infrared) radiation at the top of the atmosphere. Some of the outgoing radiation is absorbed by naturally occurring greenhouse gasses and by clouds. A change in average net radiation at the top of the troposphere is known as *radiative forcing*. An increase in atmospheric GHG concentration leads to a reduction in outgoing infrared radiation and hence to positive radiative forcing, which tends to increase global temperatures (IPCC 1995).

Although there are several greenhouse gases, CO_2 has received the most attention, because of its concentration in the atmosphere and because it is the main gas emitted by burning fossil fuels. Gasses differ in their capacity to cause global warming, and their resident times in the atmosphere also vary. Greenhouse gas emissions are measured in CO_2 equivalents, a measure that takes the warming potential of individual gasses into account[2]. The measurement of CO_2 equivalents is based on an arbitrary time period of 100 years. This arbitrary time horizon was used by Moura-Costa and Wilson (2000) and Fearnside at al. (2000) to derive equivalence factors between temporary sequestration and emission reductions, and we apply their techniques in this paper.

The approach proposed by Moura-Costa and Wilson (2000) is based on the concept of absolute global warming potential (*AGWP*), which is defined as the integrated radiative forcing of the gas in question (Houghton *et al.* 1995):

$$AGWP(x) = \int_0^T a_x \cdot F[x(t)]dt \qquad (1)$$

where T is the time horizon (years), a_x is the climate-related radiative forcing caused by a unit increase in atmospheric concentration of gas x and $F(\bullet)$ is the time decay of an emitted pulse of x.

CO_2 added to the atmosphere follows a complex decay path. There is an initial fast decay caused by uptake by the biosphere over the first 10 years or so; followed by a gradual decay over the next 100 years or so reflecting transfer to the ocean and, finally a very slow decline occurs over thousands of years as carbon is transferred to deep ocean sediments (Houghton *et al.* 1995, p. 217). To evaluate this decay process, the IPCC Special Report on Climate Change used a carbon-cycle model that incorporates interactions between the atmosphere, oceans and land systems (the “Bern model”). A simplified fractional CO_2 decay function was then derived to crudely characterize the CO_2 removal processes by biosphere and oceans (Houghton et al, 1995, p. 218). This function was used by Moura-Costa and Wilson (2000) to derive their equivalence factor between sequestration and emission reduction.

The ‘revised Bern model’, which incorporates greater uptake by the biosphere and hence increases the value of temporary sequestration of CO_2, was later used by Fearnside *et al.* (2000). The function is:

[2] Other important greenhouse gasses in the context of land use are methane and nitrous oxide, which have 21 and 310 times the warming potential of CO_2, respectively.

$$F[CO_2] = 0.175602 + 0.137467\exp\left(-t/421.093\right) + 0.185762\exp\left(-t/70.5965\right) + 0.242302\exp\left(-t/21.42165\right) + 0.258868\exp\left(-t/3.41537\right) \quad (2)$$

This function is plotted in Figure 1 and compared with the original function used by Moura–Costa and Wilson (2000) to derive their "tonne-year approach". Substituting equation (2) for $F[x(t)]$ into equation (1), and setting $a_x = 1.0$ and $T = 100$, results in a value of *AGWP* of 46.4. This means that a LUCF project would have to keep the agreed amount of CO_2 off the atmosphere for 46 years in order to receive the same credit as an energy project that decreases emissions by the same amount. This value is the *Equivalence Time* (T_e), assuming a linear relationship between the residence of CO_2 in the atmosphere and its radiative forcing effect over the time horizon *T*. The *Equivalence Factor* (E_f) is $1/T_e$ (Moura-Costa and Wilson 2000) and estimates the effect of keeping 1 t CO_2 out of the atmosphere for 1 year. Given equations (1) and (2), $E_f = 1/46.4 = 0.0215$. This factor is used below to derive a profit function under tonne-year accounting.

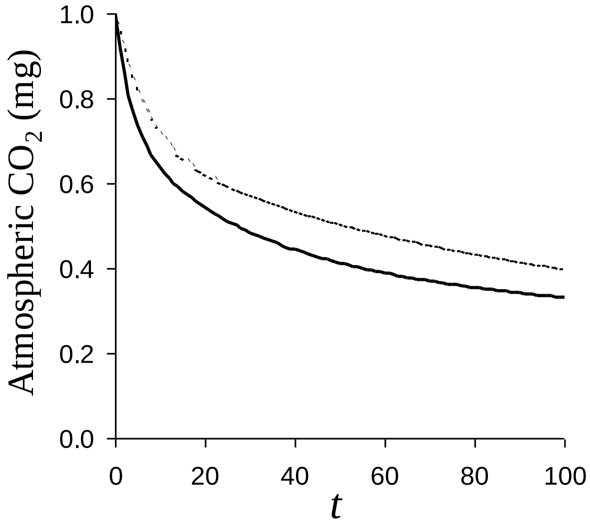

Figure 1. Alternative decay functions for one unit of CO_2 emitted to the atmosphere. Dashed line is the function used by Moura-Costa and Wilson (2000), solid line is the revised Bern model reported by Fearnside *et al.* (2000).

ALTERNATIVE CARBON-ACCOUNTING SYSTEMS

The theoretically-ideal accounting system

From an economic standpoint, the theoretically correct way of accounting for carbon-sequestration payments is to estimate the stream of sequestration services provided in perpetuity. Payment for carbon sequestration must occur as the service is provided and, when the forest is harvested, the value of the carbon released back into the atmosphere must be paid back by the forest owner (eg. some credits would be redeemed). The need for using an infinite time horizon arises when we wish to compare energy projects (or forest conservation projects) against forestry projects, because the former have a permanent effect on atmospheric carbon stocks, while the latter exhibit periods of slow carbon accumulation followed by periods of quick release of carbon to the atmosphere. Although such a detailed accounting system is not possible in practice, the scheme discussed below represents the ideal situation against which alternative policies for actual implementation of the system should be compared.

Consider the case of a landholder evaluating the prospect of planting trees. The value of a stand of forest in the presence of carbon-sequestration payments and with redemption upon harvest can be represented as:

$$\pi(T) = v(T) \cdot p_v \cdot e^{-rT} + \int_0^T \dot{b}(t) \cdot \upsilon \cdot p_b \cdot e^{-rt} dt - c_E - b(T) \cdot \upsilon \cdot p_b \cdot e^{-rT} \qquad (3)$$

where $\pi(T)$ is the net present value (NPV) of a forest harvested in year T after planting. The first term on the right-hand side represents the value of the timber harvest, the second term represents the value of the total flow of carbon sequestered in the interval (0, ...,T), c_E is the establishment cost, p_v and p_b are the prices of timber and biomass carbon respectively, υ converts biomass carbon into CO_2 units, and r is the discount rate. The state variables $v(t)$ and $b(t)$ are, respectively, the timber volume in cubic meters per hectare (m^3/ha) and the carbon contained in forest biomass in tonnes per hectare (t/ha), at time t. The last term in (3) represents the assumption that credits obtained during forest growth have to be fully redeemed upon harvest (at time T). Timber yield at harvest is estimated by solving the differential equation:

$$\dot{v}(t) = \frac{dv}{dt} = f\left(v(t)\right) \qquad (4)$$

This function is then used to estimate carbon sequestration, $\dot{b}(t)$, as explained below. The profit function defined in (3) accounts only for one forest cycle, and ignores the profits from future harvests. To account for multiple cycles the profit function becomes:

$$NPV = \pi(T) + \frac{\pi(T)}{e^{rT} - 1} \qquad (5)$$

where the last term on the right-hand side represents the opportunity cost of delaying the harvest. By maximising (5) with respect to T we find the optimal forestry cycle-length for an infinite planning horizon.

The objective function (5) allows comparison between emission reductions in the energy sector and sequestration in the forestry sector, as it accounts for an infinite planning horizon. This approach may not work in practice because (i) the cost of accurately measuring annual carbon flows may be too high, especially in remote locations; and (ii) the risk of a forestry project defaulting on its "permanent capture" commitment may be unacceptable. How can we guarantee that the forestry cycle will continue in perpetuity? The problem is compounded by the possibility that future rotations may not be as productive as the first, because of soil exhaustion, and so the carbon stock may be eroded over time unless measures are taken to maintain soil productivity.

It must also be noted that this mechanism may be too harsh because, whereas the total amount of credits are redeemed upon harvest, not all carbon is being released back to the atmosphere. The amount of biomass carbon released depends on the final use of the harvest (consider firewood as compared to construction timber). However, it may not be economically feasible, or desirable, to track the fate of forest products after harvest.

Tonne-Year Accounting

An alternative to the method described above is to use the equivalence factor derived from the *AGWP* for CO_2. This method does not require redemption of carbon credits upon harvest. Under this accounting method the objective function becomes:

$$\pi_E(T) = v(T) \cdot p_v \cdot (1+r)^{-T} + \sum_{t=0}^{T} \left[\dot{b}(t) \cdot \upsilon \cdot E_f \cdot p_b \cdot (1+r)^{-t} \right] - c_E \qquad (6)$$

This method has the advantage that no guarantee is required to ensure that the project will last T_e years, as the annual payments are adjusted by the equivalence factor. If the project is abandoned and the carbon is released there is no need to recover payments.

Ex-Ante Full Crediting

Another accounting method discussed by Moura-Costa and Wilson (2000) consists of awarding carbon credits in full when the project starts. This requires a commitment that the project will last for T_e years after the agreed-upon forest carbon stock has been reached. The objective function becomes:

$$\pi_A(T+T_e) = v(T+T_e)\cdot p_v \cdot (1+r)^{-(T+T_e)} + b(T)\cdot \upsilon \cdot p_b - c_E \qquad (7)$$

Under this method the fate of the carbon sequestered in year t is irrelevant after $t+T_e$ years from an accounting standpoint. This method will provide strong incentives for forest establishment, because of the large initial carbon-credit payment, provided that the cost of providing a guarantee of permanence is not too high.

Ex-Post Full Crediting

The final accounting method analysed here, also proposed by Moura-Costa and Wilson (2000), consists of a full carbon-credit payment when the project reaches T_e years. The objective function becomes:

$$\pi_P(T+T_e) = v(T+T_e)\cdot p_v \cdot (1+r)^{-(T+T_e)} + \sum_{t=0}^{T} \dot{b}(t)\cdot \upsilon \cdot p_b \cdot (1+r)^{-(t+1+T_e)} - c_E \qquad (8)$$

Although this method does not require a guarantee, the delayed payment eliminates the incentive provided by a cash flow in the early years of the project; discounting also reduces the attractiveness of the final payment.

A NUMERICAL EXAMPLE

The growth of a forest stand can be represented by Chapman-Richards functions (Harrison and Herbohn 2000, p. 75), for timber volume (*v(t)*) and basal area (*a(t)*), respectively:

$$\frac{dv}{dt} = \alpha_v \cdot v(t)^{\beta_v} - \gamma_v \cdot v(t) \qquad (9a)$$

$$\frac{da}{dt} = \alpha_a \cdot a(t)^{\beta_a} - \gamma_a \cdot a(t) \qquad (9b)$$

The α, β and γ parameters in (9a) and (9b) are specific to a given tree species and may be affected by climatic and soil characteristics. Equation (9a) was substituted into equation (4) to implement the ideal accounting method.

The solutions for the differential equations (9a) and (9b) are, respectively:

$$v(t) = \theta_v \left[1-\exp\left(-\gamma_v(1-\beta_v)\cdot t\right)\right]^{1/1-\beta_v} \qquad (10a)$$

$$a(t) = \theta_a \left[1-\exp\left(-\gamma_a(1-\beta_a)\cdot t\right)\right]^{1/1-\beta a} \qquad (10b)$$

where the maximum values at steady state are given by the θ parameters, as follows:

$$\theta_v = \left(\frac{\alpha_v}{\gamma_v} \right)^{1/1-\beta_v} \tag{11a}$$

$$\theta_a = \left(\frac{\alpha_a}{\gamma_a} \right)^{1/1-\beta_a} \tag{11b}$$

Equations (10a) and (10b) are useful to estimate parameter values from data. Equation (9a) is useful to estimate the annual carbon sequestration rate, and equation (10b) is useful to estimate the average diameter (cm) of individual trees in the forest stand, as explained below.

If wood density and the carbon content of biomass are known, the stock of carbon in stemwood at any time is:

$$w(t) = \delta \cdot v(t) \tag{12}$$

where *w(t)* is the biomass content of the stemwood in tonnes of carbon per hectare (tC/ha) and δ is the carbon content per cubic meter of wood (tC/m^3). Equation (12) considers only stemwood and underestimates the carbon content of the forest, as *w(t)* may represent up to about 70 percent of the biomass contained in a forest, which also includes branches, foliage and soil carbon. The ratio of forest biomass to stemwood biomass depends on the type of trees and on the age of the trees. Young trees generally have more foliage and branches relative to stem than old trees. Based on the paper by Kischbaum (2000) we derived the function:

$$b(t) = \phi \cdot \left[(\delta \cdot \theta_v)^{\mu} \cdot w(t) \right]^{1/1+\mu} \tag{13}$$

where *b(t)* is standing biomass in terms of carbon (t C/ha), ϕ and μ are parameters determined by tree shape, and the remaining variables have been previously defined. Note that *b(t)* includes timber and branches but not carbon contained in soil and roots.

The average diameter (*dbh*, cm) of individual trees in the forest stand at any time is given by:

$$dbh(t) = 200 \cdot \sqrt{\frac{a(t)}{pi \cdot tph}} \tag{14}$$

where *pi* is 3.1416 and *tph* is the number of trees per hectare.

Land-use Scenarios and Model Calibration

Any carbon-accounting method must consider the baseline. That is, the stocks and flows of carbon under the present land use, or under “business as usual”, must be evaluated. Only the carbon sequestered in the project above that which would have been sequestered without the project would receive credits. For simplicity we assume a baseline of zero.

Table 1. Tree parameter values used in the model, estimated from data reported by Wong *et al.* (2000).

Parameter	Site 1	Site 2
α_v	4.279	3.880
β_v	0.734	0.785
γ_v	0.713	1.171
α_a	2.810	3.784
β_a	0.420	0.800
γ_a	0.240	1.915

Tree-growth parameters for equations (9a) and (9b) are presented in Table 1 for two sites in south-eastern Australia. These parameters were estimated statistically based on values reported by Wong *et al.* (2000) for *Eucalyptus nitens* (commonly known as Shining Gum). The two sites are described in Table 2. Site 1 is a high-rainfall site and Site 2 is a moderate-rainfall site.

Table 2. Site Characteristics.

	Site 1	Site 2
Site code	VRV140	EP205
Location	Gippsland, VIC	Mount Gambier, SA
Date Planted	August 1986	July 1988
Previous Land Use	Improved Pasture	Pasture
Annual Rainfall (mm)	1212	766
Average Temperature (^{o}C)	January: 10.5 – 22.2 July: 3.6 – 10.0	January: 11.4 – 23.7 July: 5.1 – 12.9
Annual Pan Evaporation (mm)	1018	1262
Slope	Gentle (24 – 28 percent)	Gentle
Altitude (m)	380	60
Soil Type	Sand over medium clay	Structured, clay loam

Source: Wong *et al*. (2000).

Observed and predicted values for timber volume for *E. nitens* for the two sites are presented in Figure 2. Both sites were selected to perform the analysis of carbon-accounting methods to gain insight into the consequences of differences in the temporal path of sequestration to reach a given steady state.

Base values for other parameters used in the numerical model are presented in Table 3. Note that the price of timber is a function of tree diameter. The price of carbon and discount rate are subject to sensitivity analysis later on. Results of running the models represented by equations (3), (6), (7) and (8) with the parameters in Table 3 for trees at both sites (Table 1) are presented in the next section.

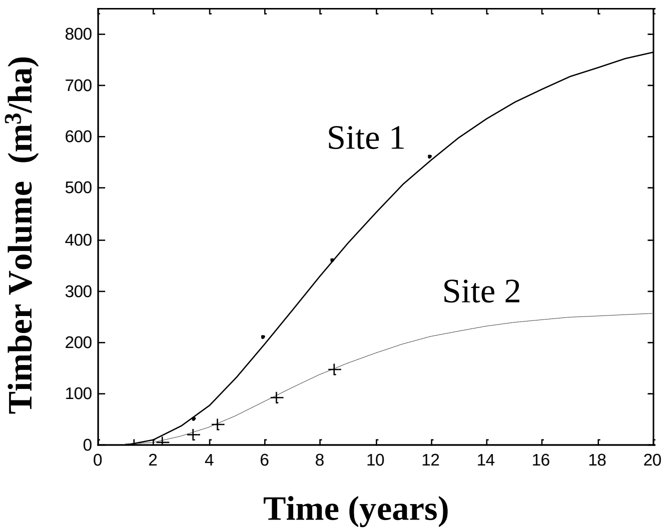

Figure 2. *Eucalyptus nitens* growth at the two sites. Predicted and observed values for Site 1 (solid line and dots respectively) and Site 2 (dashed line and plus-mark respectively). Data from Wong *et al*. (2000).

Table 3. Base parameter values.

Parameter	Value	Units	Description	Source
p_v	0.936*dbh*-4.342	$/m^3	timber price net of harvest costs, $0 \leq p_v \geq 70$	g
p_b	20	$/t	price of CO_2	a
r	6	%	discount rate	f
υ	3.67	t CO_2/t C	CO_2 absorbed per unit of carbon fixed in the forest	b
tph	250	trees/ha	tree density	h
c_E	2,300	$/ha	establishment cost	a
T_e	46.4	yr	equivalence time	c
E_f	0.0215	1/yr	equivalence factor	c
δ	0.378	t C /m^3	carbon content of wood	d
ϕ	1.429	*	biomass in mature forest relative to stemwood biomass	e
μ	0.2	*	forest biomass parameter	e

* unitless coefficient.

Sources: a: Hassall and Associates (1999); b: based on molecular weights of CO_2 and C; c: Fearnside *et al.* (2000); d: estimated as wood density × C content of biomass = 0.7 (t/m^3) × 0.54; e: calculated from parameters presented by Kirchbaum (2000); f: arbitrary value subject to sensitivity analysis; g: linear approximation to assumed data following discussions with Signor (2001, pers. comm.); h: assumed value following discussions with Signor (2001, pers. comm.).

RESULTS

Carbon sequestration in the standing biomass (t CO_2/ha/year) of the forest is presented in Figure 3. For both sites the sequestration rate increases after planting as the forest grows and a higher portion of carbon is fixed in the stemwood of the trees relative to their foliage and branches. The sequestration rate reaches a maximum and then declines as the trees mature. For Site 1, sequestration peaks in year 10 when it reaches 102 t CO_2/ha/year. For Site 2, sequestration peaks a year earlier, in year 9 when it reaches 41 t CO_2/ha/year.

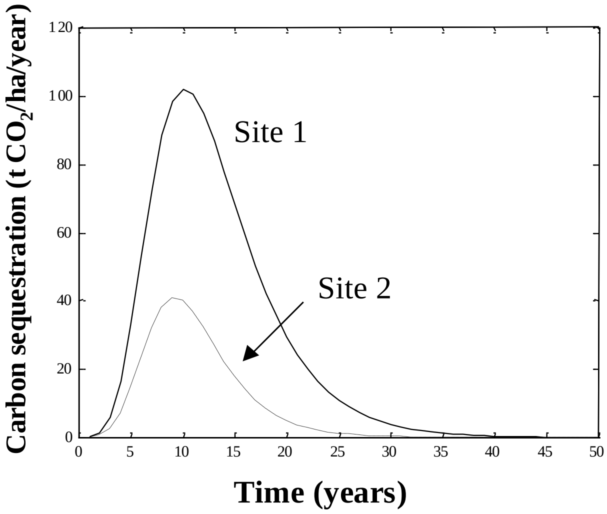

Figure 3. Carbon sequestration for Site 1 (solid line) and Site 2 (dashed line).

Total carbon stocks (t CO_2/ha) corresponding to the sequestration rates discussed above are presented in Figure 4 (A) for both sites. Carbon stocks follow the expected sigmoid pattern, being initially low and then increasing towards a maximum as the trees grow. They are highest for Site 1, tending towards a maximum of 1252 CO_2/ha after 58 years. For Site 2, carbon stocks tend towards a maximum of 395 t CO_2/ha after 62 years.

Optimal model results are presented in Table 4 for cycle-length (T^*), present value of profits (NPV^*), stemwood volume (v^*), standing biomass (b^*), carbon-emissions offset by the farm-forestry project per hectare (EO^*) and per year (EOA^*), and the net carbon payment for emissions offset (CEO^*) for both sites. EO^* takes into account both the carbon sequestration rate, and the number of years for which each annual increment in the carbon stock is stored, adjusted by the equivalence time between LUCF and energy projects. EO^* is therefore a measure of the amount of carbon emitted from an energy project that is permanently offset by the farm-forestry project.

With no carbon sequestration credits, it is optimal to harvest the forest after 16 years for Site 1 and 15 years for Site 2. These values correspond to the maximum points on the graphs in Figure 4 (B). Even though T^* is very similar for both sites, v^* and b^* are larger for Site 1 due to more growth, and the corresponding carbon-emissions offset over the optimal life of the project ($E0^*$) are threefold those for Site 2. On an annual basis, carbon-emissions offset ($E0A^*$) for Site 1 are over twofold those for Site 2.

With the inclusion of carbon sequestration credits, T^* is unchanged for both sites when carbon-sequestration payments are accounted using the tonne-year and ex-post full crediting methods. This is illustrated in Figures 4 (D) and (F). Hence, v^* , b^*, $E0^*$ and $E0A^*$ are also unchanged. For the ex-post full-crediting method, profits are the same as for the no-carbon credits case. This result clearly demonstrates that delayed payment provides no incentive to landholders to undertake farm forestry for carbon-sequestration objectives. Profits increase slightly with the tonne-year method but not enough to encourage landholders to farm trees for carbon. With this method it actually costs \$2/t CO_2 offset ($CE0^*$) at both sites, yet the same carbon emissions would have been offset with no carbon payment.

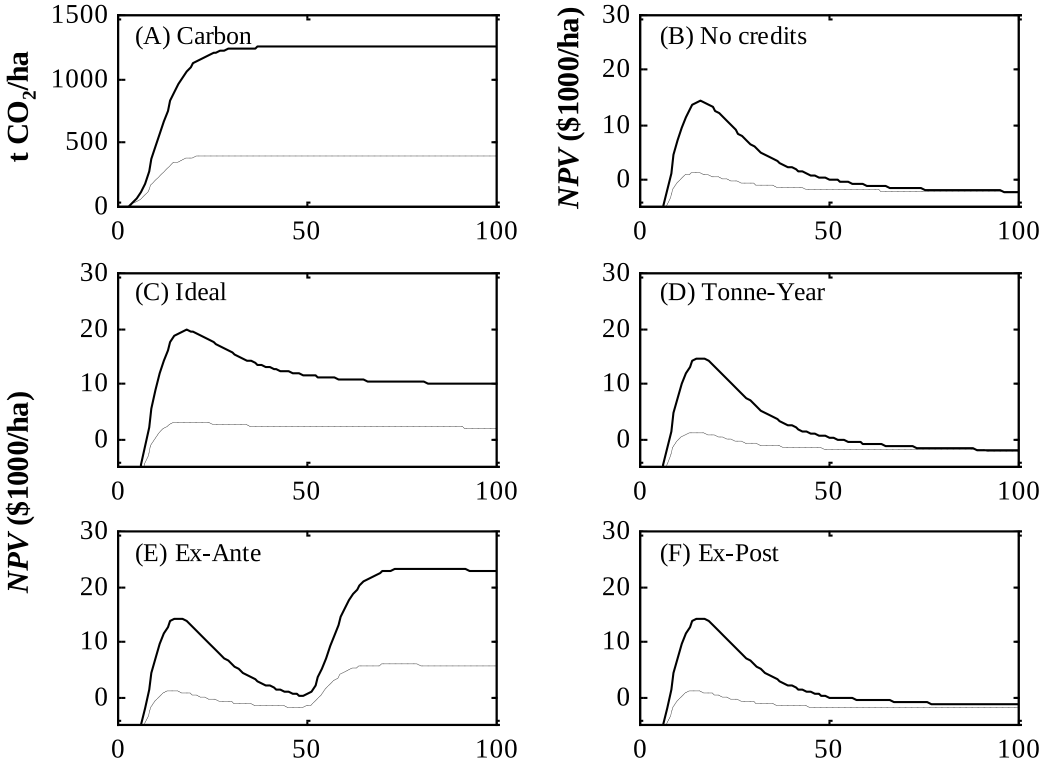

Figure 4. Carbon stocks and present value of profits for Site 1 (solid line) and Site 2 (dashed line).

Table 4. Optimal results for Site 1 and Site 2.

	Site	T^* (years)	NPV^* ($/ha)	v^* (m^3/ha)	b^* (t C/ha)	$E0^*$ (t CO_2/ha)	$E0A^*$ (t CO_2/ha.yr)	$CE0^*$ ($/t CO_2 offset)
No credits	1	16	14290	607	262	134	8	0
Ideal	1	18	19707	678	287	178	10	22
Tonne-Year	1	16	14666	607	262	134	8	2
Ex-Ante	1	79	23221	834	341	1804	23	14
Ex-Post	1	16	14290	607	262	134	8	0
No credits	2	15	1026	216	91	45	3	0
Ideal	2	18	3014	242	100	68	4	22
Tonne-Year	2	15	1168	216	91	45	3	2
Ex-Ante	2	73	5754	263	108	534	7	15
Ex-Post	2	15	1026	216	91	45	3	0

When carbon-sequestration payments are accounted using the theoretically-ideal system and the ex-ante full crediting method, T^* and NPV^* increase for both sites, compared to their no-carbon-credit case values. This is also illustrated in Figures 4 (C) and (E) for the respective accounting systems. v^*, b^* $E0^*$ and $E0A^*$ also increase due to the longer cycle-lengths involved.

With the ex-ante method, payment for carbon sequestration when the project starts provides the greatest incentive to landholders to farm trees for carbon. Optimal cycle-length is longest and profits are highest by a significant margin with this method. T^* increases by five times for both sites, while NPV^* increases by 1.6 times for Site 1, and 5.6 times for Site 2, compared to their no-carbon-credit case values. $E0^*$ and $E0A^*$ are also considerably higher with this accounting method; they are highest for Site 1 because growth is better than at Site 2. With this method, *CE0** is \$14/t CO_2 offset and \$15/t CO_2 offset for the respective sites.

Sensitivity Analysis

To evaluate the effect of changes in the price of carbon and the discount rate on the optimal cycle-length (T^*), carbon-emissions offset per year (EOA^*, t CO_2/ha.yr) and net carbon payment (CEO^*), the model was solved for six carbon prices (from 5 to 30 \$/t CO_2 at \$5 intervals) and ten discount rates (from 1 to 10 percent at 1 percent intervals), for both sites. As expected from the base results, only the ideal system and the ex-ante system exhibited any sensitivity within the range tested. Hence the following discussion is limited to these two systems (see Figures 5 and 6).

With the ideal-accounting system the price of carbon has only a small effect on optimal rotation length (Figure 5A). With the ex-ante method, there is a significant incentive for landholders to farm trees for carbon at Site 1 when P_b increases above \$10/ t CO_2, and at Site 2 when P_b increases above \$5/ t CO_2; at these prices the optimal cycle-length increases well above the equivalence time (Figure 5B). The switch from timber to carbon farming depends on the value of carbon relative to the value of timber. Carbon farming becomes desirable at Site 2 at a lower carbon price than at Site 1, because the value of timber is lower in the former, due to lower growth rates.

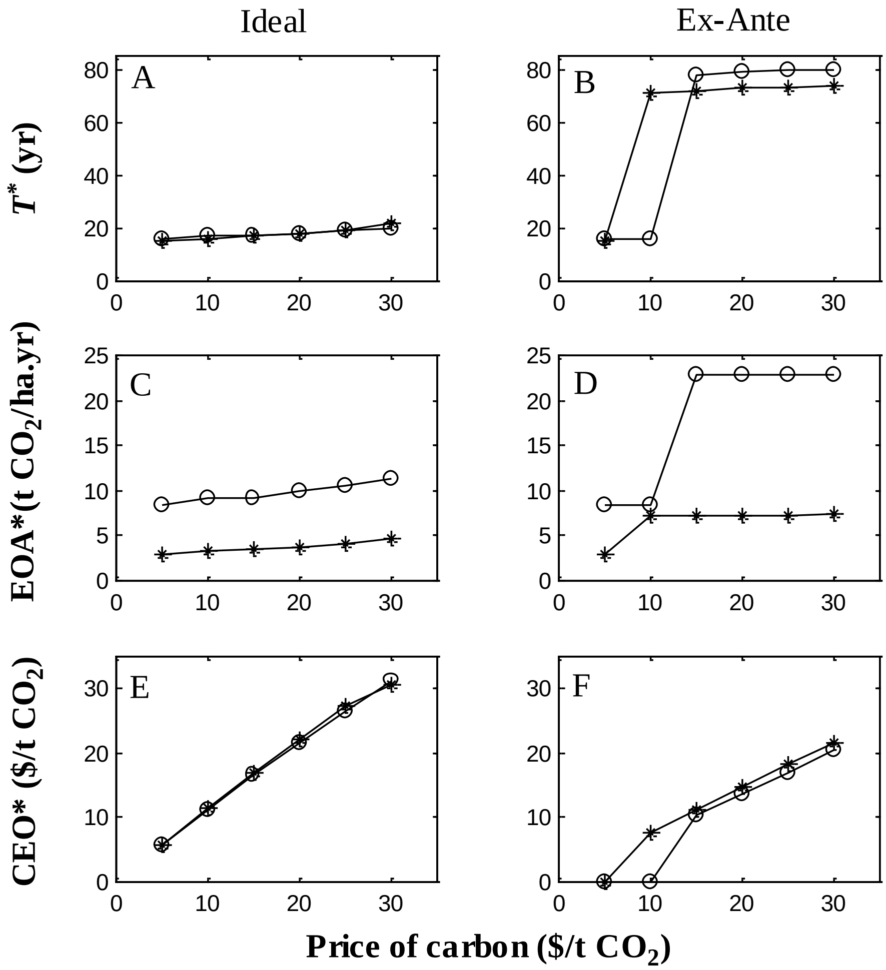

Figure 5. Sensitivity of optimal cycle-length (T^*), carbon-emissions offset (EO^*) and carbon payments (CEO^*) to changes in the price of carbon for Site 1 (circles) and Site 2 (stars).

For both accounting methods, annual emissions offset (EOA^*) increase with P_b, as the optimal cycle-length increases (Figure 5C and 5D). The greatest impact occurs with the ex-ante method at Site 1 when P_b increases from 10 to 15 \$/ t CO_2, because there is a significant jump in T^*. There is a similar but lower impact at Site 2 when P_b increases from 5 to 10 \$/ t CO_2, because even though there is a significant jump in T^*, carbon-sequestration rates are lower in this site. The net carbon payment (CEO^*) increases with the carbon price for both accounting systems (Figure 5E and 5F).

The discount rate has a considerable impact on cycle-length under the ex-ante method (Figure 6B). With this method, the incentive for carbon farming at Site 1 is eliminated at discount rates below 5 percent, as T^* falls significantly below the equivalence time. For Site 2, the incentive is eliminated below 3 percent.

The effect of the discount rate on EOA^* (Figure 6C and 6D) is related to the optimal cycle-length. The greatest impact is felt with the ex-ante method for which the discount rate has the most impact on T^*. EOA^* is highest for Site 1 due to the higher carbon-sequestration rates.

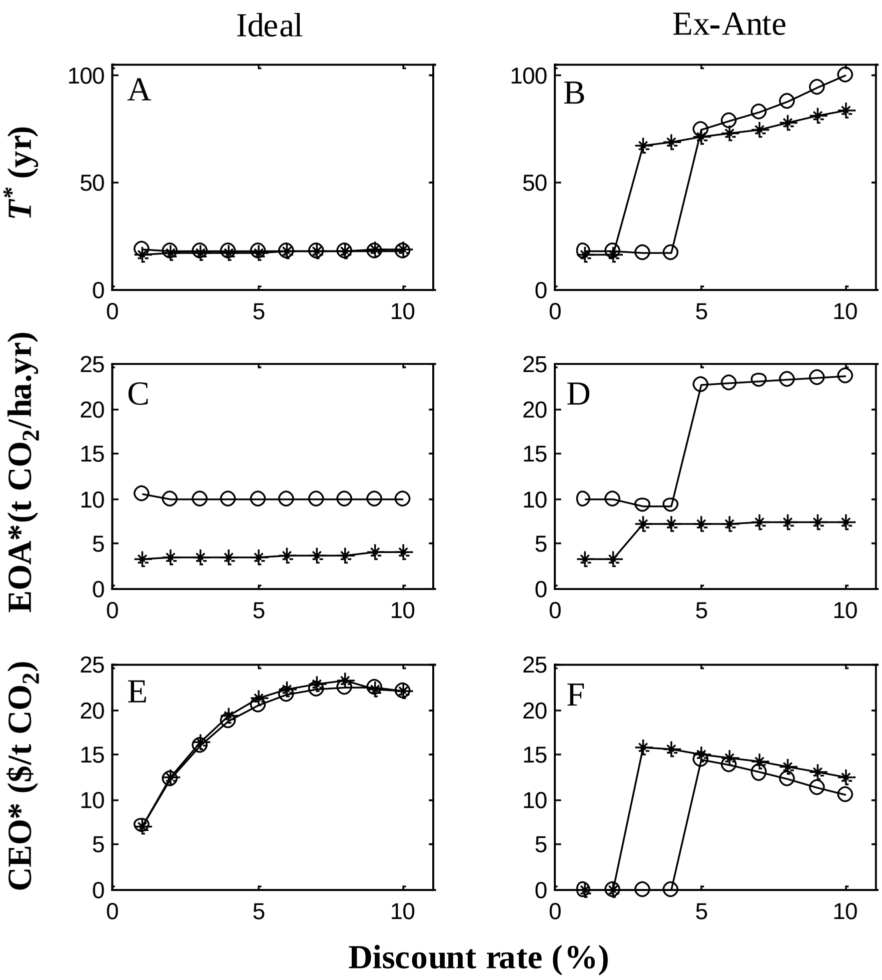

Figure 6. Sensitivity of optimal cycle-length (T^*), carbon-emissions offset (EO^*) and carbon payments (CEO^*) to changes in the discount rate for Site 1 (circles) and Site 2 (stars).

Obviously, the discount rate affects the cost to the investor of making carbon payments. For the theoretically-ideal system, CEO^* increases at a decreasing rate with increases in r (Figure 6E). Although the gross carbon payment decreases with increases in r, the value of the redeemed credits decreases to a greater extent. Hence, the net carbon payment (ie. gross carbon payment less the value of the redeemed credits) increases. For the ex-ante system, CEO^* is zero for low rates of discount, because there is no incentive for carbon farming (Figure 6F). CEO^* becomes sensitive to the discount rate once r reaches 3 percent for Site 2 and 5 percent for Site 1when it becomes desirable to farm trees for carbon.

DISCUSSION

Tonne-year accounting has the advantage that it removes the uncertainty related to the long-term permanence of forests and the need for long-term guarantees (Moura-Costa and Wilson 2000), as well as eliminating concerns about loss of sovereignty caused by CDM projects that require permanent or very long-term sequestration strategies (Chomitz 1998). However, this method provides no incentive to plant forests or keep trees standing longer than is optimal with no carbon credits (16 years for Site 1 and 15 years for Site 2). The optimal emission reductions per year are also the same (8 t CO_2/ha for Site 1 and 3 t CO_2/ha for Site 2), hence it is not rational for a policy maker to pay for sequestration using a tonne-year approach, when the same service would be provided for free by the timber market.

Other than the theoretically-ideal accounting method, only the ex-ante method provides an incentive to plant trees and keep them longer (79 years for Site 1 and 73 years for Site 2). The optimal amount of emission reductions under this method is 23 t CO_2/ha/yr for Site 1 and 7 t CO_2/ha/yr for Site 2. This is a threefold increase over the no-incentive case for Site 1 and more than a twofold increase for Site 2. The disadvantages of this approach are that it requires large up-front payments by the party purchasing the service, and that a guarantee is required regarding the length of time the carbon will remain out of the atmosphere. This guarantee may be expensive and raises the issue of liability should the project fail before meeting its commitment.

A different approach was proposed by Fearnside *et al.* (2000), whereby the benefit of delayed emissions was represented as the difference in the integrals of the revised Bern model (see Figure 1), one starting in year zero and the other starting when the forest is harvested, and both ending in year 100. This method was not evaluated here, but given it is more stringent than the tonne-year approach, it will provide no incentive for farm forestry.

An issue that was not explored in this paper, but which is relevant to the debate on permanence, is that of discounting carbon emissions, so that delaying emissions becomes more attractive. Arguments in favour and against discounting carbon are discussed by Fearnside *et al.* (2000). In short, postponing emissions will postpone some radiative forcing, which has a cumulative effect on climate, so temporary sequestration that shifts downward the future time path of temperature increases has value provided society has a positive discount rate, ie. postponement of damages has value (Chomitz 2000).

Fearnside *et al.* (2000) support discounting future carbon emissions, not just because it delays damage, but because it saves lives. They argue that each million tonne of avoided emission results in the saving of 16.4 human lives (p. 255).

A plantation that eventually reaches a steady-state equilibrium (harvest and planting of stands is even) will obtain no more carbon credits, but the role of carbon credits in helping establish the plantation can be very important. In the long run the problem is complicated by population increases coupled with reduced land available (tied up in forestry) which may drive land prices up to a level that encourages deforestation over sequestration.

Finally, it must be mentioned that not all carbon is released back into the atmosphere upon harvest, since carbon may remain in timber for centuries, but also CO_2 is emitted during harvest and timber processing. A complete accounting system should account for both these factors, but the practical obstacles may be insurmountable.

SUMMARY AND CONCLUSIONS

This paper presents an analysis of some of the accounting methods that have been proposed to deal with the problem of permanence, so as to allow temporary carbon sequestration by forests to be compared to permanent emission reductions in the energy sector. The analysis is based on the growth of a *Eucalyptus* species planted in high- and moderate-rainfall areas in south-eastern Australia.

It is shown that the tonne-year approach, which has attracted much interest in the policy debate surrounding the Kyoto Protocol, does not offer incentives to plant commercial forests under plausible assumptions regarding tree growth rates, prices, costs and discount rates in Australia. Of the accounting systems studied, only two provide forest establishment incentives: a theoretically-ideal system based on infinite forest cycles with redemption of credits after each harvest, and an ex-ante payment scheme that requires a guarantee that the forest will stand for 46 years (the equivalence time) after it reaches its private-optimal level of carbon sequestration. This applies to both sites considered here, but the incentives are much greater in the lower-rainfall area.

As pointed out by Chomitz (2000), there is no unique way to determine the conversion rate between tonne-years and perpetual tonnes; the choice from a set of scientifically sound approaches is a policy decision. It is possible that the decision will take environmental and social objectives into account in addition to net greenhouse-gas emission reductions. Hence there is still much room for policy debate.

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