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# Carbon-accounting methods and reforestation incentives*

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The emission of greenhouse gases, particularly carbon dioxide, and the consequent potential for climate change are the focus of increasing international concern. 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 the present paper, the economic implications of adopting four of these approaches are evaluated in a normative context. The analysis is based on simulation of Australian farm–forestry systems. Results are interpreted from the standpoint of both investors and landholders. The role of baselines and transaction costs are discussed.

## 1. Introduction

Concerns over global warming have led to proposals for the establishment of markets for greenhouse gas emission reductions. Although formal markets have not emerged, a number of international exchanges have occurred, whereby power companies and other energy-intensive industries have invested in 'green' projects, to partially offset their emissions of carbon dioxide ($CO_2$) and other greenhouse gases (GHG) (Hassall and Associates 1999, p. 23).

The Kyoto Protocol (KP) has provided the context in which much of the policy debate on global warming has occurred. The KP established a commitment period (2008–2012) during which Annex I countries[1] would undertake

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[1] Annex I countries include the Organisation for Economic Cooperation and Development countries (except Mexico and Turkey) and transition economies in eastern Europe.

to reduce their GHG emissions by an aggregate 5 per cent relative to their 1990 emissions.

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

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

2. Article 12 – the Clean Development Mechanism, 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, 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 Certified Emission Reduction.

There has been much debate regarding the kinds of activities that may receive credit under these Articles and the meaning of various definitions (Noble *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 GHG, 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 the present paper, arises because LUCF projects tend to be temporary in nature, as $CO_2$ 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.

The issue 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).

The European Union, Japan and other countries have ratified the KP, whereas the USA and Australia have refused to ratify it. Although the withdrawal of the USA will result in a smaller market for emission offsets, implementation of the Protocol is proceeding. The subject of the present paper has relevance even outside the KP, as it is part of the general issue of valuing environmental services. The analysis presented here also has application to current pilot projects in Australia. The Victorian Government recently implemented a 'BushTender' initiative through which landholders have been paid to conserve areas of native vegetation on their properties. NSW has followed this with an 'Environmental Services Scheme' currently being implemented. Landholders will receive payments for changing their land-use practices and improving the environmental services they provide through their properties.

In the present paper, we review four accounting methods that have been proposed to allow sources and sinks of GHG to be compared. We use the term 'carbon credits' to refer to any exchange mechanism, whether the exchange occurs within an international market or at the national or state level. We develop an economic model for each accounting system considered and use a numerical example, based on simulation of a forest plantation in Australia, to study the economic implications of the different accounting systems. The analysis focuses on the standpoint of an individual landholder, but implications to investors are also discussed. We conclude by discussing the implications of our results from a policy perspective and identify possible obstacles to implementation.

## 2. The role of land-use change and forestry

Although the main focus in the global-warming debate is on emissions (sources), the role of sinks, such as carbon sequestration in trees, has also received attention. Trees remove $CO_2$ from the atmosphere during photosynthesis and store the carbon in wood, leaves and roots; while the oxygen is released back into the atmosphere. When trees die, carbon remains in the litter and dead wood until it decomposes, and some is transferred to the soil (Brown *et al.* 2001). However, if living trees are harvested the fate of the carbon depends on the end use of the forest products. For example, carbon may be stored for many years in durable wood products such as construction timber, but for only a few years in paper and pulp, before being released back into the atmosphere as $CO_2$.

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 term, provided the marginal damage of climate change being offset by the project is high enough. They also point out that temporary sequestration contracts are desirable when the objective is to keep $CO_2$ concentrations below a threshold level. In such cases, 'the sequestration project serves to bridge the "hump" of high energy abatement costs' (Lecocq and Chomitz 2001, p. 21).

## 3. The problem of permanence

Among GHG, $CO_2$ has received the most attention because of its concentration in the atmosphere and because it is the main gas emitted by burning fossil fuels. Gases 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 gases into account.[2] The measurement of $CO_2$ equivalents is based on an arbitrary time period of 100 years; this time frame is determined by policy and is not based on any particular technical criterion.[3] This arbitrary time horizon was used by Moura-Costa and Wilson (2000) and Fearnside *et al.* (2000) to derive an equivalence factor that represents the amount of time temporary carbon must be stored in biomass in order to be considered equivalent to a permanently avoided emission. We apply their concept in the present paper and incorporate it into an economic framework.

Carbon dioxide 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 (Albritton *et al.* 1995, p. 217). To evaluate this decay process the Intergovernmental Panel on Climate Change (IPCC) in their Special Report on Climate Change used a carbon-cycle model that incorporates interactions between the atmosphere, oceans and land systems (the Bern model).

The problem of permanence is illustrated in figure 1. The top panel shows the decay path of a pulse of $CO_2$ emitted into the atmosphere (the revised Bern model, Fearnside *et al.* 2000). The bottom panel shows the sequestration of an equivalent amount of $CO_2$ (i.e. a negative emission). The area between the horizontal axis and the decay curve is a measure of the cumulative effect of the pulse of $CO_2$ emitted in year zero. The tonne-year approach consists of finding the number of years required to make the bottom (rectangular) area equal to the top area (figure 1), thereby making the effect of sequestration equivalent to an avoided emission. This number

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

[3] In many of their analyses the IPCC also uses 20-year and 500-year time horizons.

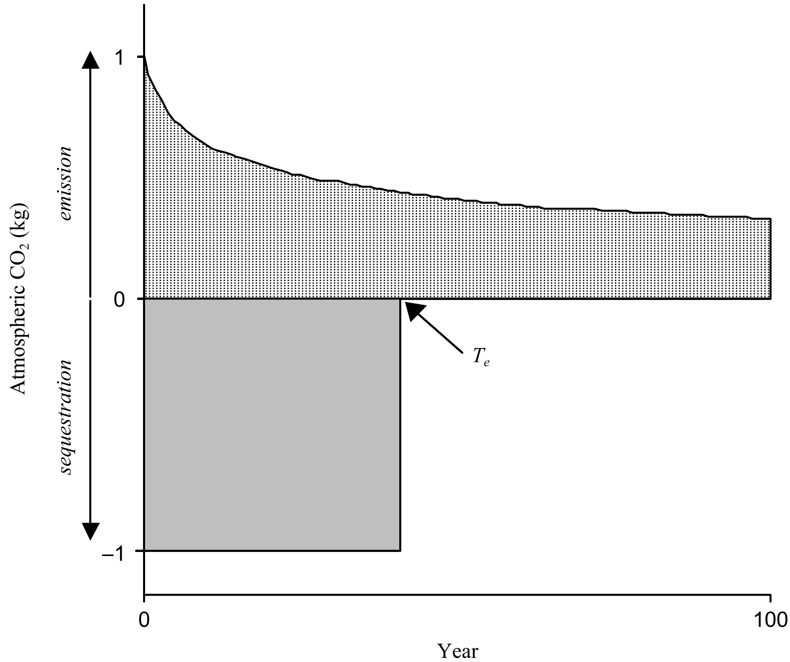


**Figure 1** The permanence problem and equivalence time ($T_e$). The top area is the decay path of atmospheric $CO_2$ based on the Revised Bern Model; the bottom area represents carbon sequestration.

is called the equivalence time ($T_e$) and turns out to be 46 years under the revised Bern model.

Hence, under the tonne-year system a LUCF project has to keep an agreed amount of $CO_2$ out of the atmosphere for 46 years in order to receive the same credit as an energy project that decreases emissions by the same amount. The equivalence time is used to calculate the equivalence factor ($E_f$), given by $1/T_e$ (Moura-Costa and Wilson 2000). The $E_f$ represents the effect of keeping one tonne of $CO_2$ out of the atmosphere for one year.

There is still a great deal of uncertainty in relation to the permanence of $CO_2$ in the atmosphere – consequently the values of the equivalence measures, $T_e$ and $E_f$, are not known with certainty. According to Houghton *et al.* (1995, p. 255), the atmospheric response time of $CO_2$ has the largest scientific uncertainty of the major GHG. This is because the rate of its uptake is a complex process involving the biosphere, oceans, ocean–atmosphere exchange rates, deep ocean sediments, etc. 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 GHG emission reductions. Hence, there is still much room for policy debate.

## 4. Carbon-accounting

In this section we describe four accounting systems that compare sources and sinks of GHG. The first is what we call the ideal system, one where credits and debits accrue in the year they are incurred. The other three systems are based on the tonne-year approach; they use either $T_e$ or $E_f$ and differ from each other in the timing of carbon-credit payments. The three latter approaches have been discussed in the published literature at a general level, but no formal economic analysis has been undertaken previously.

### 4.1 Ideal accounting system

Under the ideal accounting system, payment for carbon sequestration occurs as the service is provided and a debit occurs when carbon is released (i.e. by fire or harvest). Consider the case of a landholder evaluating the prospect of planting trees and an investor who is willing to pay price per tonne ($p_b$) of carbon dioxide sequestered by those trees. The value of a stand of forest in the presence of carbon-sequestration payments and with redemption upon harvest is:

$$\pi_1(T) = v(T) \cdot p_v(d(T)) \cdot [1+r]^{-T} + \sum_{t=0}^{T}\left[\Delta b(t) \cdot \upsilon \cdot p_b \cdot [1+r]^{-t}\right] - c_E - b(T) \cdot \upsilon \cdot p_b \cdot [1+r]^{-T} \tag{1}$$

where $\pi_1(T)$ is the net present value 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 sum of the annual net benefits from carbon sequestered in the interval $(0, \ldots, T)$, $c_E$ is the forest establishment cost, $p_v$ is the price of timber that depends on the average stem diameter ($d$, cm) of the trees at harvest, $\upsilon$ converts biomass carbon into $CO_2$, and $r$ is the discount rate. The state variables $v(t)$ and $b(t)$ are, respectively, the timber (stemwood) volume in cubic meters per hectare ($m^3$/ha), and the carbon stock in forest biomass in tonnes per hectare (tC/ha). The last term in (1) represents the assumption that credits obtained during forest growth have to be fully redeemed upon harvest. The annual rate of carbon sequestration, $\Delta b_t$, is calculated from $b_t$ as explained later in the present report.

The full debit at harvest means that the total amount of carbon credits received during the life of the forest must be paid back to the investor by the landholder. Although not all carbon is released back to the atmosphere upon harvest, because a large proportion may remain fixed in wood products for decades, this model assumes a contract that ends when the carbon sequestered is no longer under the control of the landholder. In other words, the contract between an investor (i.e. a power company) and a landholder to capture and maintain a given amount of carbon out of the atmosphere expires when the forest is harvested. This is because the carbon is no longer under the control of the landholder, who therefore cannot guarantee that the terms of the contract will continue to be fulfilled. Once the contract expires, the investor would have to find an alternative sequestration project, or pay a carbon tax. This scheme is equivalent to the rental carbon market proposed by Marland *et al.* (2001).

### 4.2 Tonne-year accounting

The tonne-year method does not require redemption of carbon credits upon harvest, because payment occurs based only on the 'equivalent' amount of permanently avoided emissions during a given year. Payment is made annually based upon the current stock rather than on the flow of $CO_2$. Under tonne-year accounting with annual payments, the objective function is:

$$\pi_2(T) = v(T) \cdot p_v(d(T)) \cdot [1 + r]^{-T} + \sum_{t=0}^{T} \left[ b(t) \cdot \upsilon \cdot E_f \cdot p_b \cdot [1 + r]^{-t} \right] - c_E \quad (2)$$

The sequestered carbon is credited annually in a similar way to the ideal approach, however, credits are not paid in full. Only a fraction ($E_f$) of the carbon stock receives payment each year. This method has the advantage that no guarantee that the project will last a given number of years is required, as the annual payments are adjusted by the equivalence factor. If the project is abandoned and the carbon is released, the investor does not need to recover payments from the landholder.

### 4.3 Ex-ante full crediting

Another accounting method discussed by Moura-Costa and Wilson (2000) consists of paying carbon credits in full when the project starts. This requires a commitment that the project will last for at least $T_e$ years, the time required to offset a unit of emissions. This means that an up-front payment is made when the project starts for the carbon stock that will be sequestered to year $T$, but only the carbon stock accumulated in the period from year zero to year $T{-}T_e$ receives credit. The objective function is:

$$\pi_3(T) = \begin{cases} v(T) \cdot p_v(d(T)) \cdot [1+r]^{-T} - C_E; & if\ T \le T_e \\ v(T) \cdot p_v(d(T)) \cdot [1+r]^{-T} - C_E + b(T - T_e) \cdot \upsilon \cdot p_b; & if\ T > T_e \end{cases} \quad (3)$$

The value of $T$ must be specified in the contract before up-front payment occurs. If the forest is retained for 46 years or less ($T \le T_e$), timber is the only source of revenue (the top row of equation 3 applies) and the landholder does not participate in the carbon market, so no contract is established and no up-front payment occurs. Carbon payments apply only for the stock of carbon that is retained in the forest for 47 years or longer (the bottom row in equation 3). This method is also based on the tonne-year concept, but it uses the equivalence time ($T_e$) rather than the equivalence factor. This method can provide a strong incentive for forest establishment, because of the large initial carbon-credit payment (the payment is not discounted). However, the cost of providing a guarantee of permanence would reduce the size of the incentive.

## 4.4 Ex-post full crediting

The final accounting method analysed here, also proposed by Moura-Costa and Wilson (2000), consists of paying carbon credits once the project reaches $T_e$ years. The carbon payments are made from year $T_e$ until harvest. The objective function becomes:

$$\pi_4(T) = \begin{cases} v(T) \cdot p_v(d(T)) \cdot [1+r]^{-T} - C_E; & if\ T \le T_e \\ v(T) \cdot p_v(d(T)) \cdot [1+r]^{-T} - C_E + \sum_{t=T_e}^{T} \left[ \Delta b(t - T_e) \cdot \upsilon \cdot p_b \cdot [1+r]^{-t} \right]; & if\ T > T_e \end{cases} \quad (4)$$

As in model (3), under this method carbon payments apply only if $T > T_e$. However, payments are based on annual flows of carbon sequestration (rather than stocks) and they are heavily discounted, as they start in year $T_e$. 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.

## 4.5 Infinite horizon

The profit functions defined account for only one forest cycle, and ignore the profits from future harvests, or the opportunity cost of delaying the harvest. With an infinite planning horizon the profit function for accounting system $j$ becomes:

$$NPV_j = \frac{\pi_j(T)}{1-(1+r)^{-T}}; \quad j \in (1, \dots, 4) \tag{5}$$

Where the numerator is any of the functions defined in (1) to (4). By maximizing (5) with respect to $T$ we find the optimal forestry cycle (in years) for an infinite planning horizon.

To implement this model it is necessary to define tree growth and that determines carbon accumulation, $b(t)$, the volume of timber available for harvest, $v(T)$, and the diameter of trees at harvest, $d(T)$. These functions are defined further.

## 5. Forest growth model

The Chapman-Richards function has been shown to provide a good representation of growth in timber volume, $v(t)$, and basal area, $a(t)$ (Venn *et al.* 2000, p. 75). So the growth of a forest stand can be represented as:

$$v(t) = \theta_v[1 - \exp(-\alpha_v \cdot t)]^{\beta_v} \tag{6a}$$

$$a(t) = \theta_a[1 - \exp(-\alpha_a \cdot t)]^{\beta_a} \tag{6b}$$

where the parameters $\theta$, $\alpha$ and $\beta$ are determined by the species of tree, environmental conditions and forest management. Once parameterised, equation (6a) is used to estimate timber volume at harvest, while equation (6b) is used to estimate the average diameter of the trees as:

$$d(t) = 200 \cdot \sqrt{\frac{a(t)}{\pi \cdot tph}} \tag{7}$$

where *tph* is the number of trees per hectare. This equation is derived from the formula for the area of a circle; the square-root term is multiplied by 100 to convert m to cm and by 2 to convert radius to diameter (hence the 200). The value of $d$ is used to calculate the price received for the timber harvest:

$$p_v = \gamma_0 + \gamma_1 \cdot d(T) \tag{8}$$

If wood density and the proportion of carbon in stemwood biomass are known, the stock of carbon in stemwood biomass ($w(t)$, tC/ha), can be estimated as:

$$w(t) = \delta \cdot v(t) \tag{9}$$

where $\delta$ is the carbon content per cubic meter of stemwood (tC/m$^3$). Because equation (9) accounts only for stemwood, it underestimates the carbon content of the forest. Stemwood represents approximately 70% of forest biomass; the other 30% comprises branches and foliage[4]. The ratio of forest biomass to stemwood biomass depends on the type of tree and its age. Young trees generally have more branches and foliage relative to stem than old trees. This is represented in the following function, derived from the model of Kirschbaum (2000):

$$b(t) = \phi \cdot [(\delta \cdot \theta_v)^{\mu} \cdot w(t)]^{1/(1+\mu)} \tag{10}$$

where $b(t)$ is the total carbon stock in the standing forest biomass (tC/ha), $\phi$ and $\mu$ are parameters determined by tree shape, and the remaining variables have been previously defined. Annual changes in the standing carbon stock can now be estimated by differencing:

$$\Delta b(t) = b(t) - b(t-1) \tag{11}$$

Equations (6a), (8), (10) and (11) are substituted into (1) to (4), as necessary, to represent a given accounting system. Only above-ground biomass carbon has been considered here; $b(t)$ includes stem, branches, and foliage, but not carbon contained in the soil or roots. Including soil and root carbon will increase the stock of carbon that receives payment but will also increase the cost of measuring that carbon; this is discussed by Cacho *et al.* (2002b) and is not considered further in the present paper.

## 6. Land-use scenarios and model calibration

Tree-growth parameters for equations (6a) and (6b) 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 has high rainfall and Site 2 has moderate rainfall.

Observed and predicted timber volumes of *Eucalyptus nitens* for the two sites are presented in figure 2. The analysis of the carbon-accounting methods was performed on both sites to gain insight into the consequences

[4] Roots represent an additional 10–40% of above-ground biomass; soil carbon is not part of forest biomass.

**Table 1** Tree parameter values used in the model, estimated from data reported by Wong *et al.* (2000) with equations (6a) and (6b)

| Parameter | Site 1 | Site 2 |
|---|---|---|
| $\theta_v$ | 842.873 | 262.956 |
| $\alpha_v$ | 0.190 | 0.252 |
| $\beta_v$ | 3.759 | 4.651 |
| $\theta_a$ | 69.540 | 30.124 |
| $\alpha_a$ | 0.139 | 0.383 |
| $\beta_a$ | 1.724 | 5.000 |

**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 (°C) | | |
| January | 10.5–22.2 | 11.4–23.7 |
| July | 3.6–10.0 | 5.1–12.9 |
| Annual pan evaporation (mm) | 1018 | 1262 |
| Slope | Gentle (24–28%) | Gentle |
| Altitude (m) | 380 | 60 |
| Soil type | Sand over medium clay | Structured, clay loam |

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

that differences in soil type and rainfall have on the temporal path of sequestration and the nature of the steady state. It is obvious that the growth function (6a) provides a good fit to the data. However, data were only available for trees up to 10 years of age; this means that predictions regarding the steady state that is reached after year 30 are uncertain. Nonetheless, the predicted maximum volumes (given by $\theta_v$ in table 1) at steady state are plausible (843 $m^3$/ha and 263 $m^3$/ha for sites 1 and 2, respectively).

Base values for other parameters used in the numerical model are presented in table 3. Model runs consisted of estimating function (5) for each of the accounting systems (1) to (4), using the parameter values in table 1 and table 3. The optimal cycle length ($T^*$), timber harvest ($v^*$) and carbon sequestered in biomass ($b^*$) were estimated based on the value of $T$ that maximised equation (5). Then, for each accounting system, the optimal amount of emissions offset ($EO^*$) were calculated as the time-averaged $CO_2$ equivalent stock in above-ground biomass:

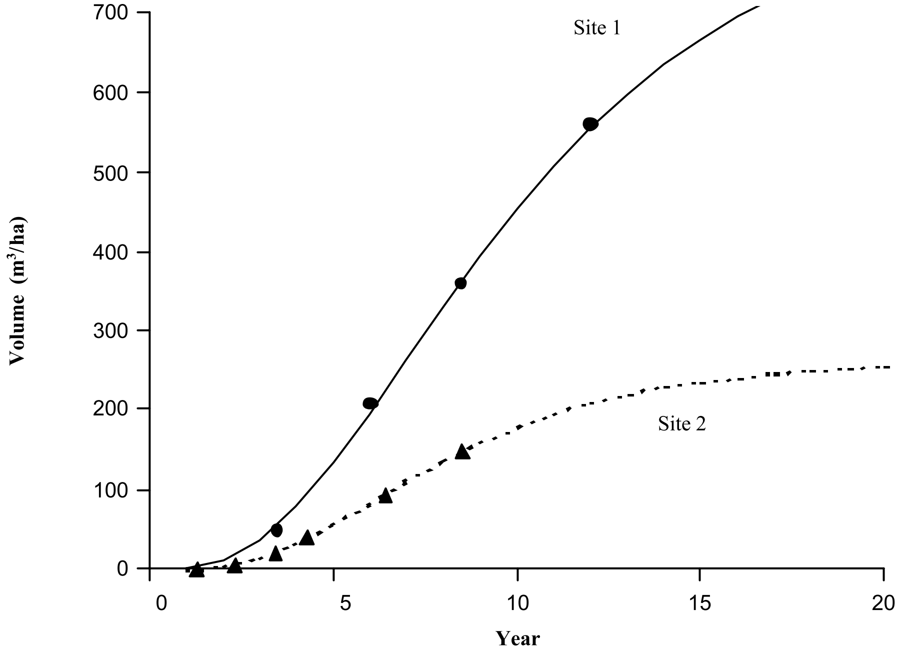


**Figure 2** *Eucalyptus nitens* growth at the two sites. Predicted (lines) and observed values (dots) for Site 1 and Site 2. Data from Wong *et al.* (2000).

**Table 3** Base parameter values

| Parameter | Value | Units | Description | Source |
|---|---|---|---|---|
| $\gamma_0$ | –4.342 | \$ | Timber price intercept | g |
| $\gamma_1$ | 0.936 | \$/cm | Timber price slope | g |
| $p_b$ | 20 | \$/t | Price of $CO_2$ | a |
| $r$ | 6 | % | Discount rate | f |
| $\upsilon$ | 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 |
| $c_E$ | 2300 | \$/ha | Establishment cost | a |
| $T_e$ | 46.4 | year | Equivalence time | c |
| $E_f$ | 0.0215 | 1/year | Equivalence factor | c |
| $\delta$ | 0.378 | t C/m$^3$ | Carbon content of wood | d |
| $\phi$ | 1.429 | * | Biomass in mature forest relative to stemwood biomass | e |
| $\mu$ | 0.2 | * | Forest biomass parameter | e |

*unitless coefficient. Sources: a, Hassall and Associates (1999); b, based on molecular weights of $CO_2$ and Carbon; c, Fearnside *et al.* (2000); d, estimated as wood density × Carbon content of biomass = 0.7 (t/m$^3$) × 0.54; e, calculated from parameters presented by Kirschbaum (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.).

$$EO^* = \frac{\upsilon \cdot \sum_{t=0}^{T^*} b(t)}{T^*} \tag{12}$$

Finally, the actual cost to the investor per emission offset ($C_I^*$), in dollars per tonne of $CO_2$, was calculated as the present value of total carbon-credit payments made by the investor to the landholder minus the present value of credits redeemed, divided by $EO^*$. The difference between the price of carbon dioxide ($p_b$) and the cost to the investor ($C_I^*$) is that the former is the spot price (assumed constant) paid at a given point in time, whereas the latter is the actual cost to the investor of a permanent emission offset measured in terms of present value. $p_b$ was the same for all accounting systems whereas $C_I^*$ was calculated for each accounting system (1) to (4) by applying the infinite-horizon equation for the optimal cycle length given by maximizing equation (5).

## 7. Results

As discussed, the optimal cycle-length for the forest is determined by maximising *NPV* (equation 5) with respect to time. The solution to this problem depends on the accounting method used. By inserting equations (1), (2), (3) or (4) into (5), the problem was solved for each of the four accounting methods described earlier in the present report. Figure 3 shows the objective function (5) plotted for selected accounting systems when applied to growth data for Site 2.

With no carbon credits, it is optimal to harvest the forest after 15 years in Site 2 (figure 3). This value corresponds to the maximum point on the *NPV* curve (figure 3, solid dark line). Under both the tonne-year (2) and ex-post full crediting (4) methods $T^*$ and $NPV^*$ are virtually the same as with no credits, so curves for these accounting methods are not shown in figure 3. With the tonne-year approach, annual returns from carbon credits increases profits slightly, but not enough to provide any incentive to grow trees for longer. With the ex-post approach, carbon payments are too delayed to have any influence on profits, and it is not worthwhile extending the cycle-length beyond that which is optimal when selling timber alone.

When carbon payments occur under either the ideal (1) or the ex-ante full crediting (3) method, $T^*$ and $NPV^*$ both increase relative to the no-carbon-credit case (figure 3). The ideal system causes the objective function to shift up and to the right compared to the no-credits case. The ex-ante system changes the shape of the objective function, that has a local maximum in year 15 and a global maximum in year 73. The function becomes bimodal under ex-ante accounting because the landholder has two choices. If the

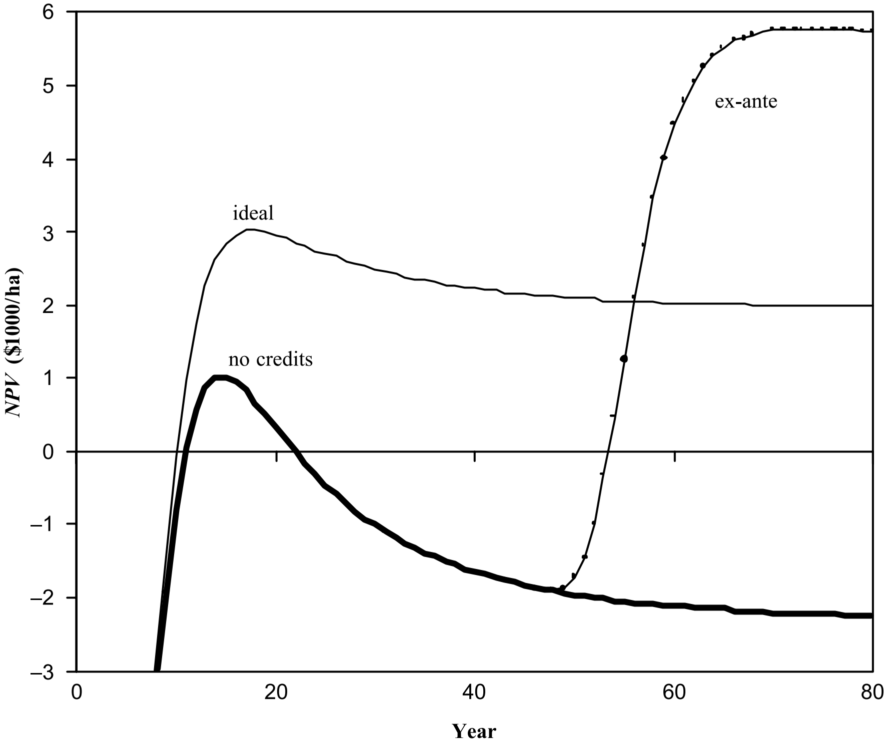


**Figure 3** Trajectories of net present value under three accounting systems in Site 2.

landholder decides to harvest before the equivalence time, no carbon credits are received and profit is the same as for the no-credits case. Carbon payments are received upfront but only after the landholder has agreed to keep each tonne sequestered by the forest for the equivalence time (46 years) or longer, and this would be a binding agreement. Hence, the incentive to provide carbon-sequestration services depends on the relative height of the two peaks in the objective function (figure 3), that in turn depends on the discount rate and on the price of carbon relative to the price of timber.

The ex-ante method provides the greatest incentive to landholders to farm trees for carbon as well as for timber. Optimal cycle-length is longest and profits are highest by a significant margin with this method.

For any given method, the optimal cycle-length is associated with optimal values of timber supply, emission offsets ($EO^*$) and costs to the investor ($C_I^*$). These values are presented in table 4 for both sites.

With no carbon credits, timber supply and $EO^*$ are larger for Site 1 than for Site 2, as a result of the higher productivity of the former (table 4). With the ex-post method, these optimal results are unchanged, because

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

| Accounting System | Site | Cyle length (years) | *NPV* (\$/ha) | Timber supply ($m^3$/ha/year) | *EO** (t $CO_2$/ha) | $C_I^*$ (\$/EO) |
|---|---|---|---|---|---|---|
| No credits | 1 | 16 | 14 290 | 38.0 | 387 | na |
| Ideal | 1 | 18 | 19 707 | 37.7 | 459 | 12.75 |
| Tonne-year | 1 | 17 | 16 467 | 38.0 | 424 | 5.42 |
| ex-ante | 1 | 79 | 23 221 | 10.6 | 1060 | 23.66 |
| ex-post | 1 | 16 | 14 290 | 38.0 | 387 | 0.00 |
| No credits | 2 | 15 | 1026 | 14.4 | 140 | na |
| Ideal | 2 | 18 | 3014 | 13.5 | 176 | 13.06 |
| Tonne-year | 2 | 15 | 1818 | 14.4 | 140 | 5.42 |
| ex-ante | 2 | 73 | 5754 | 3.6 | 340 | 23.41 |
| ex-post | 2 | 15 | 1026 | 14.4 | 140 | 0.00 |

Figures represent optimal values, *EO** = carbon-emissions offset per hectare, $C_I^*$ = net cost to investor per emissions offset (present value); na, not applicable.

delayed payments give no incentive to landholders to provide carbon-sequestration services. Under tonne-year accounting *NPV* increase by 15% (to \$16 467) in Site 1 and 77% (to \$1818) in Site 2 relative to the no-credits case, the investor pays \$5.42 per tonne of $CO_2$ offset, and *T** increases by 1 year (to 17 years) in Site 1 and remains unchanged (at 15 years) in Site 2. In terms of emissions offset, the optimal cycle lengths result in a 9 per cent increase in Site 1 (*EO** increases from 387 t $CO_2$/ha to 424 t $CO_2$/ha) and no increase in Site 2 (140 t $CO_2$/ha) when tonne-year accounting is introduced. Thus the tonne-year approach provides little or no incentive to landholders to sequester any more carbon than the incentive provided by the timber market alone, especially in less productive land.

With the ideal and the ex-ante method *EO** increases relative to the no carbon-credits case, because of the longer cycle-lengths involved. The cost to the investor is higher with the ex-ante method (approximately \$23/t $CO_2$) than with the ideal method (approximately \$13/t $CO_2$). Carbon payments have a much higher proportional effect on *NPV* in Site 2 than in Site 1, indicating that the incentive is stronger in the less productive land, although the carbon sequestration rate is also lower.

### 7.1 Sensitivity analysis

To evaluate the effect of changes in the price of carbon and the discount rate on the supply of emission offsets (*EO**), and the cost to the investor per tonne of carbon sequestered ($C_I^*$), the model was solved for a range of carbon prices (ranging from \$4/t $CO_2$ to \$26/t $CO_2$) and discount rates (2, 6 and 10%). As expected from the base results, only the ideal system and the

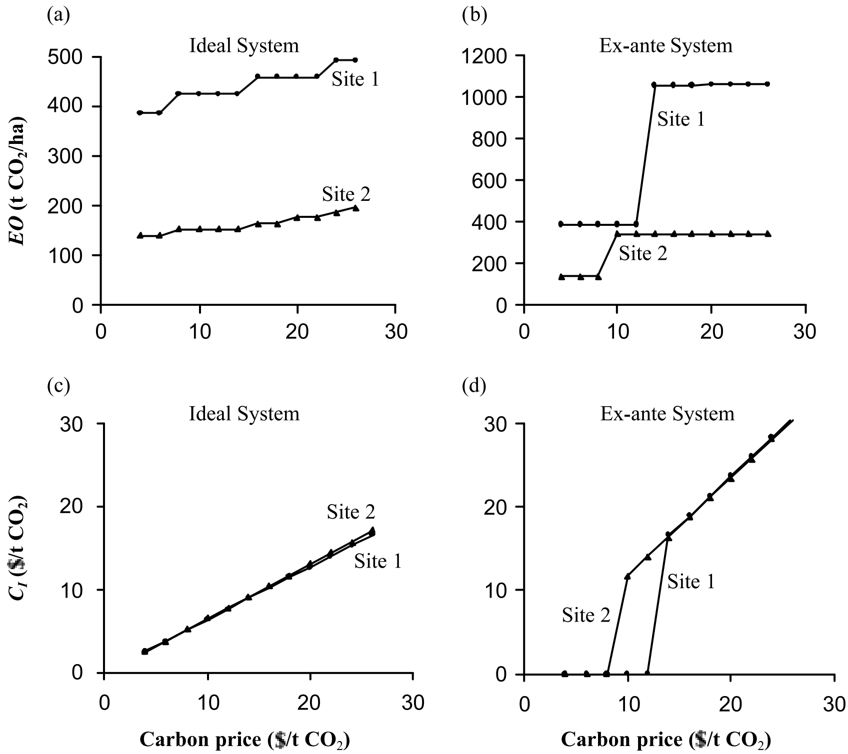


**Figure 4** Effect of carbon price on optimal solutions under the ideal (a and c) and ex-ante (b and d) accounting methods. The top charts are the supply of emission offsets ($EO$*), the bottom charts are cost to investor ($C_I^*$) per tonne of emission offset.

ex-ante system exhibited any significant sensitivity within the ranges tested. Hence the following discussion is limited to these two systems.

Under the ideal accounting system, the supply of emission offsets increases as carbon price increases (figure 4a). The increase is step-wise because it is caused by lengthening the forest cycle, and time is discrete in the model. The elasticity of supply at the base carbon price is 0.25 in Site 1 and 0.41 in Site 2. So an increase in the price of carbon results in almost twofold the response in *EO* supply in the less productive site.

Under the ex-ante method the elasticity of supply is zero at the base carbon price of \$20/t $CO_2$ (figure 4b). However, there is a very large increase in *EO* supply at the 'critical' point at which the landholder enters the carbon market. The switch from timber alone to timber and carbon farming depends on the value of carbon relative to the value of timber (this is the price ratio at which the second peak in figure 3 becomes higher than the first peak). The critical point at which supply jumps to a higher value (figure 4b)

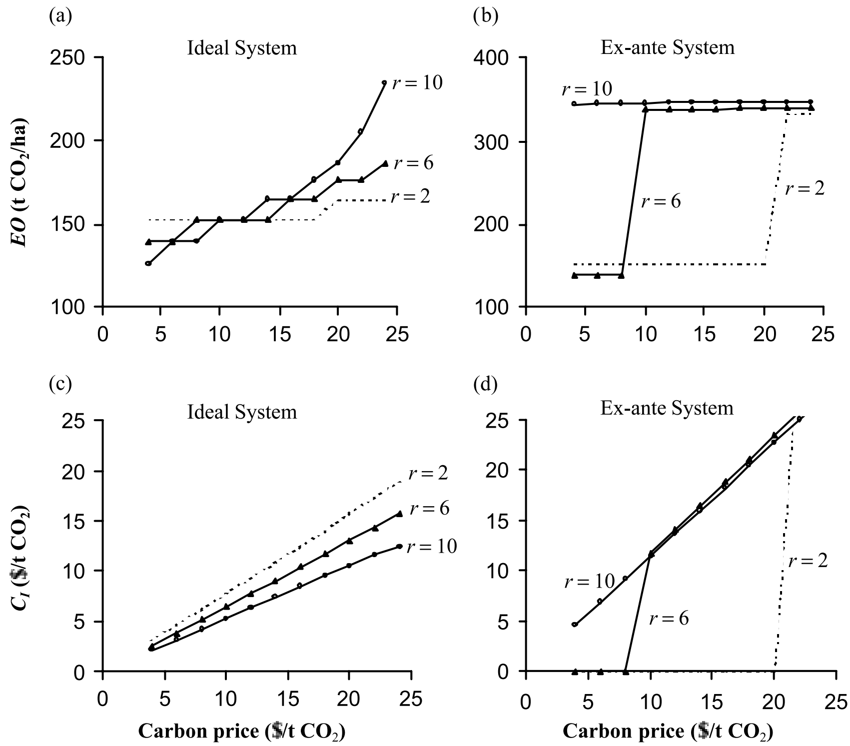


**Figure 5** Effect of carbon price and discount rates on the supply of emission offsets ($EO^*$) and the investor cost ($C_I^*$) under two accounting systems. Results are for Site 2 only.

occurs at a lower carbon price in Site 2 (at \$10 $EO^*$ increases from 140 to 338 tonnes) than in Site 1 (at \$14 $EO^*$ increases from 388 to 1055 tonnes), because the value of timber is lower in the former as a result of lower growth rates.

The investor cost ($C_I^*$) increases with the carbon price for both accounting systems (figure 4c,d). This increase is slower under the ideal system (the slope is 0.65) than under the ex-ante system (the slope is 1.17), because annual payments are discounted under the former but not under the latter. There is a discontinuity in the cost curve for the ex-ante method (figure 4d) corresponding to the critical point described. The cost curves are practically the same for both sites (except for the critical points in figure 4d).

As the supply responses described are the result of the long-term process of carbon sequestration, the discount rate influences these relationships; this is illustrated in figure 5. Under the ideal accounting system the supply response becomes steeper as the discount rate increases (figure 5a). This is because the present value of the timber harvest decreases as the discount rate increases and therefore the stream of carbon payments becomes relatively more attractive. Under the ex-ante method, increases in the discount rate cause the critical point to move to the left (figure 5b). This means that, the higher the discount rate, the lower the carbon price required to entice the landholder to enter the carbon market. At a discount rate of 10% the supply response becomes flat, indicating that the present value of the timber harvest has become negligible relative to the value of carbon.

Increasing the discount rate causes the slope of the investor-cost function ($C_I^*$) to become less steep under the ideal accounting system (figure 5c), but not under the ex-ante method (figure 5d). This occurs because carbon credits are paid at the start of the project and are not discounted under the ex-ante method, whereas under the ideal method the stream of carbon-credit payments is discounted. The lower cost at higher discount rates (figure 5c) occurs because the investor will have to find an alternative project once the forest is harvested (the carbon credits are redeemed by the landholder) and the present value of this future cost is lower at higher discount rates.

## 8. Discussion

An important question raised by the foregoing analysis is: which accounting method is dominant in a Pareto sense? The question cannot be answered unambiguously with the tools developed in the present paper, because additional assumptions must be made regarding the opportunity cost of planting trees and the nature of the contract between landholder and investor, with its associated transaction costs. The results of our analysis, however, can help elucidate the factors that will influence the answer to this question.

The four carbon accounting systems considered in the present paper differ in terms of incentives to the landholder and cost to the investor. From the standpoint of the landholder the ex-ante method dominates in terms of $NPV$, but it is the most expensive to the investor (see $NPV$ and $C_I^*$ columns in table 4). From the standpoint of the investor, the tonne-year approach dominates because it has the lowest cost per tonne of carbon ($C_I^*$ is $5.42), but it provides little or no incentive to the landholder to sequester any more carbon than the incentive provided by the timber market alone, especially in the less productive site (see $EO^*$ in table 4). So the preferred accounting system differs between the investor and the landholder.

### 8.1 Baselines

Under the assumptions of the present study the $NPV$ of planting a forest in the absence of carbon credits was positive for both sites ($14 290/ha in Site

1 and $1026/ha in Site 2), which means that the forestry enterprise would be acceptable to the landholder. However, forestry may not be the most attractive alternative. If the current land use is pasture, and grazing yields an *NPV* greater than $14 290/ha in Site 1 or greater than $1026/ha in Site 2, then the landholder would not enter forestry unless a large enough incentive to change land use is available. If, however, forestry is the best alternative available to the landholder, then the baseline (the without-project scenario) is a forestry rotation of 16 years in Site 1 and 15 years in Site 2 (see the no-credit cases in table 4).

The baseline is critical because only the marginal increase in carbon stocks (carbon with project minus carbon without project) would be credited as an offset to the investor. As an arbitrary example, with a discount rate of 6%, an annual crop or livestock enterprise producing an annual profit of $120/ha will have a *NPV* of $2000/ha. Applying this information to Site 2 we see that a forest for timber only (*NPV* = $1026/ha) or receiving carbon credits under tonne-year accounting (*NPV* = $1818/ha) would not be preferred to agriculture, but carbon farming under the ideal system (*NPV* = $3014/ha) or the ex-ante system (*NPV* = $5754) would be the preferred system. Under the assumptions of the present study, the tonne-year approach would provide an incentive to switch from agriculture to forestry (in Site 2) if the annual profit from agriculture were less than $109 per hectare per year, which results in an *NPV* for agriculture of $1818/ha.

To illustrate the relevance of the baseline, table 5 shows marginal increases in carbon stocks under two different baseline assumptions. In the first case (third and fourth columns in table 5), the baseline is assumed to

**Table 5** Effect of baseline on credited emission offsets and investor cost

| | | Baseline | | | |
|---|---|---|---|---|---|
| | | Pasture | | Forest | |
| Accounting System | Site | $EO^*$ (t $CO_2$/ha) | $C_I^*$ ($/$EO$) | $EO^*$ (t $CO_2$/ha) | $C_I^*$ ($/$EO$) |
| Ideal | 1 | 454 | 13.10 | 72 | 83.01 |
| Tonne-year | 1 | 419 | 5.59 | 37 | 64.01 |
| ex-ante | 1 | 1055 | 23.80 | 673 | 37.33 |
| ex-post | 1 | 382 | 0.00 | 0 | na |
| Ideal | 2 | 173 | 13.52 | 37 | 63.93 |
| Tonne-year | 2 | 137 | 5.80 | 0 | na |
| ex-ante | 2 | 337 | 23.66 | 200 | 39.82 |
| ex-post | 2 | 137 | 0.00 | 0 | na |

na, not applicable.

be a pasture with an average carbon stock of 5 t $CO_2$ equivalents/ha in Site 1 and 3 t $CO_2$ equivalents/ha in Site 2 (to be deducted from the *EO* column in table 4). In the second case (fifth and sixth columns in table 5), the baseline is assumed to be a forestry enterprise managed for timber only, with average carbon stocks of 387 t $CO_2$ equivalents/ha in Site 1 and 140 t $CO_2$ equivalents/ha in Site 2 (based on results in table 4). With a pasture baseline, the investor cost per tonne of $CO_2$ ranges between $5.59 and $23.80 (table 5), whereas with the forest baseline the cost increases to between $37.33 and $83.01. At these costs, the case of a forest baseline would probably not be attractive to the investor, as cheaper alternatives may be available elsewhere.

An interesting result in table 5 is that with a pasture baseline the ideal system has a lower investor cost than the ex-ante system ($13 v $23), whereas the opposite occurs with a forest baseline ($83 v $37). This is because with a forest baseline the marginal increase in carbon stocks under the ideal system is produced by keeping the forest for an additional 2 or 3 years relative to the baseline (18 v 16 years in Site 1 and 18 v 15 years in Site 2) and this occurs when the rate of carbon sequestration by the forest has slowed down. Under the ex-ante system the marginal increase in carbon stocks is caused by keeping the forest for an additional 58–63 years, which allows the forest to reach maturity and the carbon stocks to be maintained for several decades. As $C_I^*$ is calculated by dividing the total cost to the investor by the time-averaged emissions offset, the smaller marginal increase in $EO^*$ under the ideal system results in a higher cost per tonne of $CO_2$ offset.

## 8.2 Transaction Costs

So far the analysis has assumed zero transaction costs, but transaction costs are probably high in carbon sink projects, especially in the initial stages, as parties learn how to implement and manage contracts. Transaction costs are the costs 'of arranging a contract to exchange property rights *ex-ante* and monitoring and enforcing the contract *ex-post*, as opposed to production costs, which are the costs of executing a contract' (Matthews 1986, p. 906). Model results need to be re-interpreted in the presence of transaction costs.

From the standpoint of the landholder who receives a price $p_b$ per tonne of $CO_2$ sequestered, our results implicitly assume that the investor will cover all the transaction costs of participating in the carbon market. So the cost to the investor (the present cost per $CO_2$ emission offset) will be higher than indicated by $C_I^*$. This means that, in deciding whether to invest in a sink project, the investor will have to weigh the total cost (carbon-credit payments plus transaction costs, in present-value terms) against the alternative, such as the cost of an emissions tax or the present value of investing in emission-reduction technology.

From the standpoint of the investor who receives emission offsets at a cost of $C_I^*$ per tonne of $CO_2$, our results implicitly assume that the landholder bears the transaction costs. This can be represented in the model as a lower price received by the landholder than the price paid by the investor, with the difference being the transaction cost per tonne of $CO_2$ sequestered.

Between the two extremes, where all transaction costs are born by either the investor or the landholder, there is an infinite number of possible combinations of shared costs. The sensitivity analyses on $p_b$ can help to illustrate the effect of transaction costs. By either increasing $C_I$ or decreasing $p_b$, the gap introduced by transaction costs can be represented from the standpoint of either the investor or the landholder. This is shown based on the results for the ideal accounting (figure 4a,c) in Site 2. The supply response was converted into a smooth function by fitting a regression line to the step-wise results from figure 4a. The resulting analysis is presented in figures 6 and 7.

Figure 6 shows the effect of transaction costs born by the landholder. The top panel is the cost to the investor ($C_I^*$) and the bottom panel is the

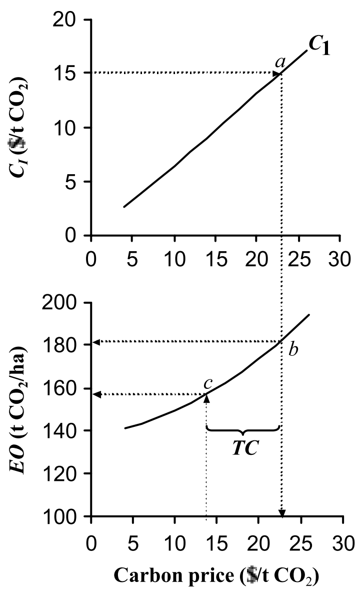


**Figure 6** Effect of transaction costs (*TC*) on the carbon price received by landholders and the supply of emission offsets, when transaction costs are born by the landholder. Results for Site 2.

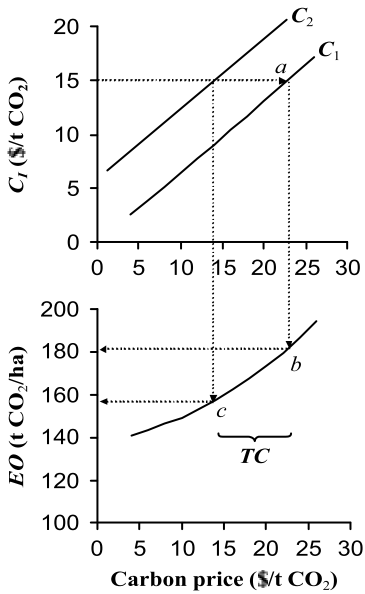


**Figure 7** Effect of transaction costs (*TC*) on the carbon price received by landholders and the supply of emission offsets, when transaction costs are born by the investor. Results for Site 2.

supply of emission offsets by the landholder (*EO**). Assume that the investor is willing to spend a maximum of \$15/t $CO_2$ (i.e. the size of an emission tax); this means that the investor would be prepared to pay up to approximately \$23 per tonne of $CO_2$ under the ideal accounting method (indicated by point a). At this price, the landholder would be willing to supply 180 tonnes of $CO_2$ per hectare, indicated by point *b*. This is the outcome in the absence of transaction costs. If, in order to enter the carbon market the landholder faces transaction costs *TC* (expressed as dollars per tonne of $CO_2$), the effective carbon price received by the landholder would be \$23 minus *TC*, or approximately \$14 in the arbitrary example shown in Figure 6, this corresponds to point *c*, where only approximately 160 t $CO_2$/ha are supplied.

Figure 7 illustrates the effect of transaction costs born by the investor. The top and bottom panel are the same as in Figure 6, but there is an additional cost curve ($C_2$) representing a shift caused by transaction costs. In the absence of transaction costs, curve $C_1$ applies and the outcome (180 t $CO_2$/ha supplied at point *b*) is the same as before. With transaction costs the relevant curve is $C_2$. If, as before, the investor will pay a maximum of \$15 per tonne, the price paid to the landholder will decrease (to approximately \$14 in this example) and the supply of emission offsets will be limited to approximately 160 tonnes. The effect of the transaction cost on the producer price is indicated by *TC* in figure 7. So, when the investor has alternative options for emission offsets (or faces a tax) the effect of transaction costs on the landholder are equivalent, independently of whether those costs are born by the producer or by the landholder.

The fact that the landholder always bears the transaction cost when the investor has other options in the carbon market, does not mean that the transaction costs will be equal whether they are covered by the investor or the landholder. If the investor has better access to information and expertise in carbon monitoring, or if economies of size exist, then it may well be that the total cost of the carbon-offset transaction is lower when the investor pays for participating in the market (i.e. when the cost curve shifts from $C_1$ to $C_2$ in figure 7) than when the landholder pays (as in figure 6). Hence, the design of the 'right' contract between investor and landholder can benefit both parties by reducing total transaction costs. This was pointed out by Dietrich (1994), who stated that transaction-cost savings can result in 'mutual financial advantage' (Dietrich 1994, p. 43).

It is important to note that these results are on a per-hectare basis, so the supply function does not include any possible area response. However, because transaction costs reduce the amount of carbon sequestered per unit area (as illustrated in figures 6 and 7) the investor will need a larger area to offset a given amount of $CO_2$.

To apply our results any further in comparing accounting systems it would be necessary to calculate the transaction costs per emission offset. We do not attempt to provide quantitative estimates of transaction costs, but will discuss how they will probably vary between accounting systems. Brief definitions of transaction costs are presented in the following text, followed by a discussion on how these may differ between accounting systems. Only the ideal, tonne-year and ex-ante methods are considered, the ex-post method is no longer discussed, as it provides no carbon-sequestration incentives.

Transaction costs of carbon-sink projects can be classified into seven categories (Cacho *et al.* 2002a): (i) *search costs* are incurred as investors and hosts (landholders) seek partners for mutually advantageous projects; (ii) *negotiation costs* are the costs of interested partners coming to an agreement; (iii) *verification and certification costs* occur when the negotiated exchange must be approved by an accredited agency, verification refers to checking the validity of the claims of a project, whereas certification occurs *ex post*, once sequestration has occurred (Moura-Costa *et al.* 2000); (iv) *implementation costs* are associated with the resources expended in administering the translation of a project design into practice; (v) *monitoring costs* are incurred to measure the greenhouse-gas abatement actually achieved by the project, as opposed to forecasts; (vi) *enforcement costs* are the expenses of achieving compliance (or obtaining compensation) if monitoring detects divergences from the agreed terms of the transaction; (vii) *insurance costs* arise from the risk of project failure.

The costs most probable to diverge between accounting systems are monitoring, enforcement and insurance costs.

Carbon monitoring costs (in terms of dollars per tonne) are sensitive to project size, the geographical dispersion of project parcels, and the heterogeneity of the environment (Cacho *et al*. 2002b). None of these factors will vary between accounting systems for a given site and size of project. However, the frequency and timing of monitoring costs will differ: the ideal and tonne-year methods require annual measurements of carbon stocks for the duration of the project, whereas the ex-ante method requires measurement only at the end of the project, to verify that the agreed amount of carbon has been stored in the forest. Although some sort of regular monitoring would be desirable in the ex-ante case, to ensure that the land has not been deforested, this could be based on low-cost method such as aerial photographs or satellite images that do not require on-site measurement of carbon stocks. Monitoring costs could be reduced by undertaking actual measurement of forest-carbon stocks at longer intervals (i.e. every 5 years) and using predictive models to set a schedule of annual payments. The payment schedule (and model assumptions) would be adjusted after each monitoring event based on actual outcomes.

The tonne-year system may not require insurance against premature release of $CO_2$, whereas both the ideal and ex-ante systems will. The ex-ante system requires insurance against premature carbon loss for the entire project length, because full payment for sequestration services occurs at the beginning; therefore this system would incur the highest insurance cost. Under the ideal system, credit is assigned when carbon is sequestered and debits accrue when carbon is emitted. In this case, insurance may play a role in hedging against price fluctuations, where the value of debits for premature carbon release is higher than the original value paid for the credits when the carbon was initially sequestered, but the main purpose of insurance would be to ensure that the investor obtains compensation when the forest is harvested (or goes up in smoke). The cost of this insurance is dependent on the future price of carbon, which, because of its uncertainty, will probably make the cost of insurance large.

Insurance and enforcement costs under the ideal system could be reduced by adjusting the payment schedule so as to avoid the need to redeem payments at the end of the project. This could be achieved by finding a factor by which annual payments are reduced, so as to make the $NPV$ of the new system (requiring no carbon-credit redemption) equal to the $NPV$ of the ideal system (requiring redemption at the end of the project). This system would be a hybrid between the tonne-year and the ideal system, with the equivalence factor being based on economic principles.

## 9. Summary and conclusions

The present paper was motivated by the potential of land-use change and forestry projects to benefit from emerging emission-offset markets. The paper presents an analysis of four carbon-accounting methods that have been proposed to deal with the problem of permanence, so as to make temporary carbon sequestration by forests equivalent to permanent emission reductions in the energy sector. The analysis is based on the standard infinite-horizon forestry model, extended to include the value of payments obtained in exchange for carbon-sequestration services. The four accounting methods are compared based on their net-present value from the standpoint of a landholder considering planting trees.

Results of numerical experiments are presented, based on a simple growth model for *Eucalyptus nitens* trees planted in high- and moderate-rainfall areas in south-eastern Australia. The results are used to compare net benefits to landholders and investors in the absence of transaction costs. Sensitivity analysis is undertaken to derive emission-offset supply responses at the firm-level (expressed as tonnes of $CO_2$ offset per hectare) and investor-cost curves (expressed as the present value of payments per tonne of emission offset).

It is shown that the tonne-year approach, a carbon-accounting method that has attracted much interest in the policy debate surrounding the Kyoto Protocol, offers little or no incentives to landholders to plant commercial forests under plausible assumptions regarding tree growth rates, prices, costs and discount rates in Australia. The tonne year approach, however, will probably have lower enforcement and insurance costs than other approaches, and therefore offers some advantages.

Model results are used to explain the importance of the baseline (the 'business as usual' scenario) and the implications of transaction costs. The transaction costs that will vary between accounting methods are identified and suggestions are presented to reduce some of these costs. To carry the present analysis any further requires specific assumptions on project size and details of the contract between investor and landholder, so the per-hectare models developed here would need to be extended to the project level, involving a large area of land under the management of one or more landholders.

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