AN EQUIVALENCE FACTOR BETWEEN CO_2 AVOIDED EMISSIONS AND SEQUESTRATION – DESCRIPTION AND APPLICATIONS IN FORESTRY

PEDRO MOURA COSTA and CHARLIE WILSON
EcoSecurities Ltd, 45 Raleigh Park Road, Oxford OX2 9AZ, UK; E-mail: uk@ecosecurities.com

(Received 31 May 1999; accepted in final form 13 December 1999)

Abstract. Concern about the issue of permanence and reversibility of the effects of carbon sequestration has led to the need to devise accounting methods that quantify the temporal value of storing carbon that has been actively sequestered or removed from the atmosphere, as compared to carbon stored as a result of activities taken to avoid emissions. This paper describes a method for accounting for the atmospheric effects of sequestration-based land-use projects in relation to the duration of carbon storage. Firstly, the time period over which sequestered carbon should be stored in order to counteract the radiative forcing effect of carbon emissions was calculated, based on the residence time and decay pattern of atmospheric CO_2, its Absolute Global Warming Potential. This time period was called the *equivalence time,* and was calculated to be approximately 55 years. From this equivalence time, the effect of storage of 1 t CO_2 for 1 year was derived, and found to be similar to preventing the effect of the emission of 0.0182 tCO_2. Potential applications of this tonne.year figure, here called the *equivalence factor*, are then discussed in relation to the estimation of atmospheric benefits over time of sequestration-based land use projects.

Keywords: carbon accounting, carbon sequestration, carbon sinks, carbon storage, equivalence time, equivalence factor, permanence, tonne.year

1. Introduction

Increased rates of greenhouse gas (GHG) accumulation in the atmosphere, due mainly to anthropogenic activities related to fossil fuel utilization and land use change, are heightening concern over possible climatic changes with unpredictable and negative effects on society. In recent years, this has led 176 countries to ratify the United Nations Framework Convention on Climate Change (UNFCCC), and 84 countries to sign the Kyoto Protocol to the UNFCCC whose central objective is the limitation of GHG concentrations in the atmosphere.

The Kyoto Protocol acknowledges the role played by terrestrial carbon sinks in absorbing and storing CO_2 from the atmosphere, as well as the principle that sinks can be used to counter or ‘offset’ anthropogenic GHG emissions, resulting in reduced net emissions (Kyoto Protocol 1997). At the project-level, activities that result in additional GHGs being actively sequestered from the atmosphere and stored in sinks can generate carbon offsets[1], which may be used to offset GHG emissions at source. However, for this offsetting to occur, the net effect of sequest-

Mitigation and Adaptation Strategies for Global Change **5:** 51–60, 2000.

ration has to be identical to that of avoiding emissions. This raises an important question as to how long carbon sequestered in biomass must be stored, given that vegetation has a finite lifetime. The Kyoto Protocol simply requires 'long-term' benefits, but does not define this length of time. Nor is guidance given as to whether projects which actively sequester and store CO_2 over a finite timeframe should be eligible for carbon offsets.

The key issue, therefore, is to determine the timeframe over which a project has to store actively sequestered carbon in order to reach an equivalence with avoided emissions. This need for a quantification method that addresses the temporal dimension of carbon storage has been expressed by many authors (Moura-Costa 1996; Fearnside 1997; Greenhouse Challenge Office 1997; Chomitz 1998; Tipper and De Jong 1998; Dobes *et al.* 1999; Fearnside *et al.* 2000). Some of these have proposed the use of an equivalence factor between the sequestration and emission of CO_2. This paper describes a methodology for deriving such an equivalence factor and its use in the quantification and temporal allocation of carbon offsets for sequestration-based land use projects.

Although outside the scope of this paper, it should be noted that avoided (or delayed) CO_2 emissions from carbon conservation practices such as reduced impact logging and averted deforestation are assumed to be directly equivalent to avoided (or delayed) CO_2 emissions from industrial sources, for example, through fossil fuel displacement by renewable energies (Fearnside *et al.* 2000). Carbon accounting systems for the two types of avoided (or delayed) emissions should therefore be commensurable.

2. Global Warming Potentials & Radiative Forcing

The approach proposed here is to determine a sequestration-based equivalence factor to the Absolute Global Warming Potential (AGWP) of CO_2. AGWP is defined as the cumulative radiative forcing potential of a unit mass of CO_2 during its residence in the atmosphere over a defined time horizon (Wigley 1994), and calculated according to the following equation (IPCC 1994):

$$AGWP(CO_2) = \int_0^{TH} a_x \bullet [CO_2(t)]dt \qquad (1)$$

where *TH* is the time horizon, a_x is the climate-related radiative forcing due to a unit increase in atmospheric concentration of CO_2, and $[CO_2(t)]$ is the time-decaying abundance of a pulse of emitted CO_2 (Houghton *et al.* 1990). Currently, the best known CO_2 decay function is represented within the Bern model (Houghton *et al.* 1994), which shows that the fraction of a pulse emission of CO_2 remaining in the atmosphere decreases rapidly over the first decades after the emission, followed by a more gradual decrease thereafter. As a workable proxy to the Bern model, this paper uses the parameterized decay function described in IPCC 1990 and 1992 Reports and described in Houghton *et al.* (1994), as follows:

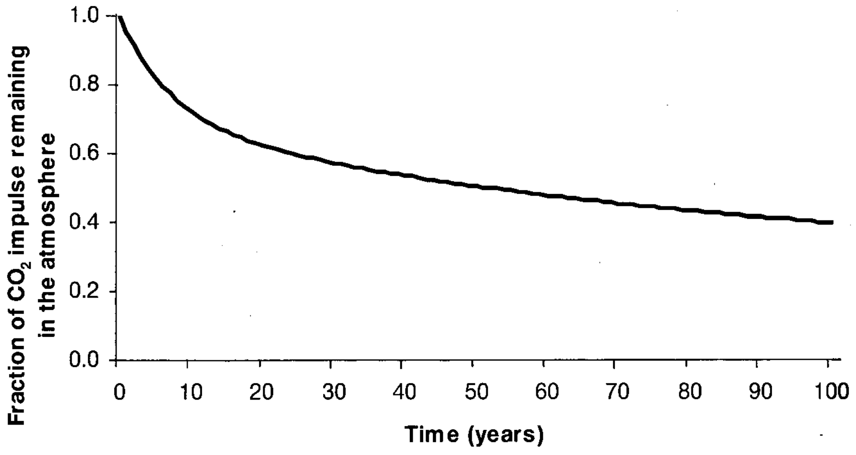

Figure 1. Decay pattern of a pulse emission of CO2 to the atmosphere over a 100-year timeframe, calculated according to IPCC's parameterized decay function (Equation 1).

$$F[CO_2(t)] = 0.30036\exp(-t/6.6993) + 0.34278\exp(-t/71.109) \\ +0.35686\exp(-t/815.727) \qquad (2)$$

This decay pattern is illustrated by the curve in Figure 1. Unlike the Bern model, the parameterized function used does not take into account the effects of atmospheric CO_2 concentrations on the decay profile.

3. Deriving the Equivalence Time Period

Assuming a constant[2] radiative forcing factor (a_x), the integral of the decay curve (Figure 1) is proportionate to the cumulative radiative forcing exerted by a unit of CO_2 released to the atmosphere, as given by its AGWP (see Equation 1). In operationalising the AGWP concept, the Kyoto Protocol sets 100 years[3] as the reference time frame over which cumulative radiative forcing is to be measured. Over this 100-year period, the decay curve integral is equivalent to the forcing effect of approximately 55 tonne.years of CO_2 (54.79119, from Equation 2). Hence, we can infer that removing 1 t CO_2 from the atmosphere and storing it for 55 years counteracts the radiative forcing effect, integrated over a 100-year time horizon, of a 1 t CO_2 pulse emission (Figure 2).

Under the terms of the Kyoto Protocol, the $AGWP_{100}$ of CO_2 represents the radiative effect of a pulse emission which any sequestration-based activity is designed to counteract (or indeed, any emission reduction activity is designed to avoid or delay). In effect therefore, as understood by the Protocol, carbon sequestered at $t = 0$ and stored until $t = 55$ is directly equivalent to an avoided emission at $t = 0$ and could be credited accordingly. Any new emission from the subsequent release of the stored carbon at $t = 55$ would not be deemed to have caused any

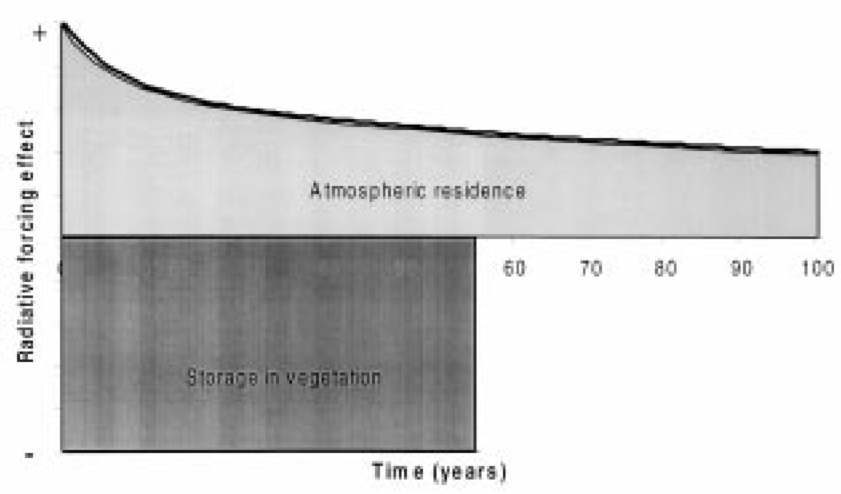

Figure 2. The radiative forcing profile of a pulse emission of a unit of CO2 (with the area under the curve proportionate to cumulative radiative forcing or $AGWP_{100}$) and the necessary timeframe of carbon storage of a similar unit of CO_2 to prevent the same radiative forcing effect (grey area under the X axis), assuming a constant radiative forcing factor (a_x) and a time horizon of 100 years. The area under the curve and the rectangle are the same.

additional radiative forcing effects to those which characterized the start point of the project, measured over the 100-year reference period from the point of emission/sequestration. This timeframe of equivalence between sequestered and emitted CO_2 is here called the '*Equivalence Time'* (T_e). The re-emission of sequestered carbon after its storage for $t = T_e$ does not affect this equivalence.

4. Illustrating Equivalence

To illustrate this equivalence concept, let us assume an atmospheric system that, initially ($t = 0$), contains 2 units, A and B, of recently-emitted CO_2. In a 'business-as-usual' scenario, no action is taken, and both units A and B exert a radiative forcing effect which gradually decreases over a 100-year period, and then, as understood by the Protocol (see above), ceases to contribute further to global warming. Compare this with a 'sequestration' scenario in which trees are planted so as to sequester 1 of these units (say unit B) and store it as biomass for 55 years. The radiative forcing effect of unit A left in the atmosphere, as in the first scenario, will decrease to zero by $t = 100$. However, as there is only one unit, this effect will be half that of the 'business-as-usual' scenario (simplistically assuming linearity between concentration and effect), and the sequestration of unit B can be rewarded as an offset of 1 unit of avoided CO_2 emission.

This offset equivalence at $t = 55$ for the sequestered unit B corresponds to the counteracted radiative forcing *measured over 100 years*. What underpins or allows this temporal equivalence is that, had unit B been left in the atmosphere, it would have been decaying and not held constant like the sequestered carbon (see Figure 2). The release of sequestered unit B at $t = 55$ therefore adds nothing to the radiative forcing effect exerted by unit A left in the atmosphere, *measured over a 100-year timeframe* from the point of sequestration/emission. As this forcing effect is half that of the ‘business-as-usual’ scenario, the net result is that unit B sequestered and stored for a 55-year period is directly equivalent to an avoided emission, irrespective of whether it is released at the end of this 55-year storage period.

5. From Equivalence Time to an Equivalence Factor

The equivalence time, T_e, can therefore be considered as a workable definition of ‘long-term’ as required for the storage of sequestered carbon in the Kyoto context. Moreover, if a linear relationship is assumed between the residence of CO_2 in the atmosphere and its radiative forcing effect *over the 100-year reference time period*, the effect of keeping 1 t CO_2 out of the atmosphere for 1 year can also be estimated. We refer to this value as the *Equivalence Factor (Ef)*, or *tonne carbon.year factor*, which is equal to 1/- T_e or 0.0182 t CO_2 emissions avoided. Other authors have proposed different equivalence factors, assuming non-linearity between CO_2’s atmospheric residence and radiative forcing (e.g., Fearnside et al. 2000).

6. Applications of the Equivalence Parameters

These equivalence parameters could have useful applications for the assessment of GHG benefits of sequestration-based forestry projects under the terms of the Kyoto Protocol. In particular, the equivalence factor, E_f, could be used as means for determining the offset value of forestry activities over different project timeframes.

6.1. *EX ANTE* FULL CREDITING WITH T_e STORAGE COMMITMENT

One way of incorporating the concept of equivalence into the evaluation of sequestration-based forestry projects is to credit only those units of sequestered carbon which are stored for the full equivalence time, T_e. In an *ex ante* accounting system, these credits can be awarded in advance of the project activities if guarantees or other forms of commitment are given by the project for a full T_e storage period (Figure 3). In effect, this represents a forward sale of the project’s carbon benefits, underwritten by a storage guarantee. Such *ex ante* crediting has the advantage of providing additional ‘carbon’ incentives at the project implementation phase. However, this would require long-term commitments which may be hard to implement (and to enforce), and it would not provide any benefit for activities that are terminated before the equivalence time, T_e.

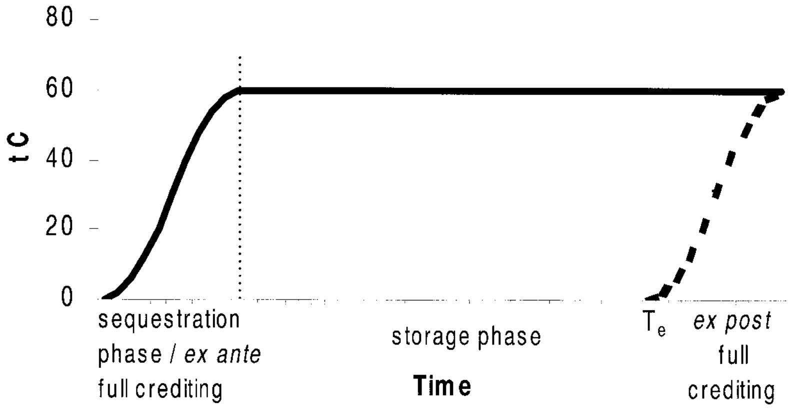

Figure 3. Projection of carbon stored in an afforestation project (with baseline assumed to be zero), illustrating the concept of *full crediting.* With *ex post* full crediting, the project only receives credits after planted trees have been kept for a period of time, T_e (55 years). With *ex ante* full crediting, the project receives credits during the initial sequestration phase if the project commits to storing the sequestered carbon for the full duration of the equivalence time, T_e.

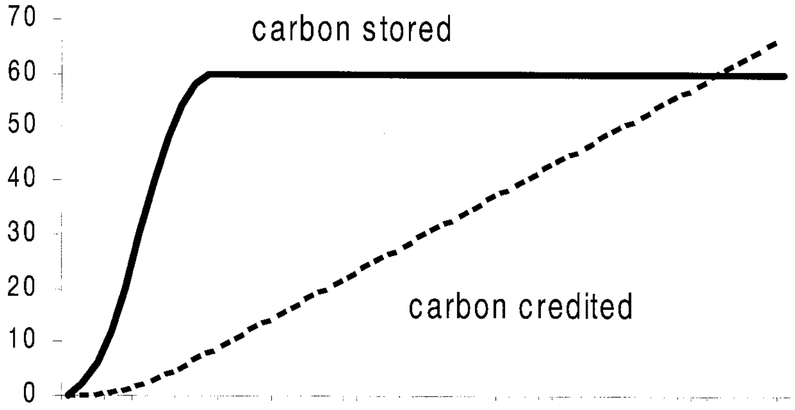

Figure 4. Projection of carbon stored in an afforestation project, illustrating the concept of *equivalence-factor yearly crediting (tonne-years).* The project receives yearly credits calculated as the total amount of carbon stored in any given year, multiplied by an equivalence factor, E_f, in this case 0.0182. The dotted line represents the cumulative amount of credits awarded.

6.2. *EX POST* FULL CREDITING

Alternatively, full crediting of a unit of sequestered carbon could be awarded only after the carbon has been stored for the time period T_e (Figure 3). Although the lowest risk accounting system, *ex post* crediting may reduce the attractiveness of sink creation projects because the carbon benefits yielded will only be realizable retrospectively, and, once discounted, are unlikely to provide additional 'carbon' incentives for forestry projects with sequestration-based carbon benefits.

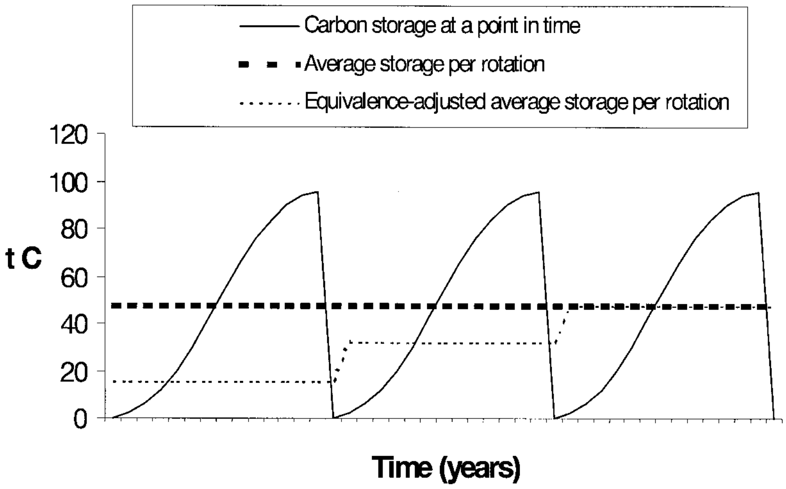

Figure 5. Projection of carbon stored in an afforestation project over 3 growth cycles. For simplicity, it is assumed that the baseline is zero and that harvesting leads to an immediate release of all carbon stored. The thick dashed line illustrates the average over the full 3-rotation time period. The thin dashed line illustrates the average storage for each growth cycle, if T_e is used as the reference time period for the analysis (i.e. equivalence-adjusted average storage).

6.3. EQUIVALENCE-FACTOR YEARLY CREDITING (TONNE.YEARS)

Another possibility is to recognize only a fraction of the full credit on a yearly basis, based on the tonne-year equivalence factor, E_f. For each tonne of carbon stored for a year, the project receives credits for 0.0182 tC.yr^{-1} (Figure 4). If the project is run for the whole time frame T_e, the cumulative amount of yearly credits eventually equates to the amount fixed in vegetation in time T_e. A variation of this approach is to calculate the fraction of the full credit to be awarded (*ex ante* or *ex post* – see above) based on the ratio of the project time frame to the equivalence time, T_e. For reasons explained above, if the project timeframe is longer than T_e, a maximum of one credit per tonne of carbon stored can be awarded.

6.4. EQUIVALENCE-ADJUSTED AVERAGE STORAGE CAPACITY

To account for dynamic systems, in which planting, harvesting and replanting operations take place, an alternative carbon accounting approach has been used (e.g., Dixon *et al.* 1994), called the *average storage method* (Schroeder 1992). This method consists of averaging the amount of carbon stored in a site over the long-term according to the following equation:

$$Average\ net\ carbon\ storage(tC) = \frac{\sum_{t=0}^{t=n}(carbon\ stored\ in\ project - carbon\ stored\ in\ baseline)}{n\ (years)} \tag{3}$$

where t is time, n is project time frame (years), and measurements are expressed in tC ha^{-1}. Although this method accounts for the dynamics of carbon storage over the whole project duration, it would provide identical results for projects that run for one, two, or many growth cycles, as long as the denominator n was always the last year of the project time frame (thick dotted line, Figure 5). This problem, however, could be avoided if the same equation used the equivalence time, T_e, as the denominator, so that the average net storage at the end of each rotation would provide different values (thin dotted line, Figure 5).

7. Conclusions

The adoption of equivalence parameters would provide useful solutions to various problems associated with land-use sequestration projects. Firstly, it removes the uncertainty related to the long-term permanence of forests, because crediting for forestry activities can be calculated in proportion to the project timeframe on a ‘pay-as-you-go’ basis. This in turn removes the need for long-term guarantees and provisions to compensate for risks of forest degradation or removal, for if the carbon-storing forest is damaged, the project either stops receiving credits (in the case of the yearly crediting approach) or the amount of credits lost can be easily calculated. Secondly, equivalence parameters allow for full comparability between projects. Thirdly, the need to introduce the subjectivity of time preference is avoided (Fearnside *et al.* 1999; Price and Willis 1993).

The main disadvantage of the equivalence method is that, whilst the approach is sound, there is still much uncertainty regarding the residence time and decay profile of CO_2 in the atmosphere, and consequently the values of the equivalence parameters T_e and E_f. Further research is required to test the validity of these methods utilizing more robust climate models and functions. In this context, both equivalence parameters should also ideally be dynamic, subjected to review as new research findings become available (much the same as the GWPs).

Acknowledgements

This paper benefited from discussions between the authors and P. Fearnside, D. Lashof and R. Tipper.

Notes

1. Carbon offsets is used as a generic term in this paper to encompass the various more specific terms applied in different contexts: in particular, ‘Emission Reduction Units’ or ERUs for offsets

generated under Article 6 of the Protocol on Joint Implementation, and 'Certified Emission Reductions' or CERs for offsets generated under Article 12 on the Clean Development Mechanism. Note that carbon credits is often used as another generic term, referring more specifically to offsets' potential use in carbon trading regimes.

2. For CO_2, the absorption efficiency of infrared radiation (of which a_x is a measure) varies non-linearly with concentration. In effect therefore, a_x, and thus cumulative radiative forcing, are a function of time when future changes in atmospheric concentrations of CO_2 are considered. The sensitivity of CO_2's decay profile to background CO_2 levels in the atmosphere further reinforces this time-dependence, and potentially stresses the importance of selecting appropriate CO_2 emission/concentration scenarios to estimate future radiative forcing trends. However, analyses show that the cumulative radiative forcing of CO_2 (and thus its AGWP) is not highly sensitive to atmospheric CO_2 concentrations being taken into account. For example, model runs show that increased CO_2 concentrations of the IPCC's S650 scenario (in which CO_2 concentrations increase from 1993 levels to about 650 ppmv near the end of the 22nd century) would yield AGWPs that are less than 15% lower than those for constant current concentrations of around 356 ppmv (Houghton *et al.* 1994). In part, this low level of possible error can be attributed to changes in absorption efficiency due to increasing atmospheric CO_2 concentrations canceling out changes in the decay profile (for the same reason). As both these changes are assumed constant for the purposes of this analysis, the possible error is implicitly discounted. An additional point worth noting is that, as the radiative properties of CO_2 are particularly sensitive to changes in concentration (due to decreasing absorption efficiencies), 'the forcing for a particular incremental change of CO_2 will become smaller in the future, when the atmosphere is expected to contain a larger concentration of the gas' (Houghton *et al.* 1994, p. 218). This implies that estimates of the radiative forcing of CO_2 based on current concentrations will be over-estimates, such that derivations of the equivalence time period for the sequestration of CO_2 will err on the conservative side.
3. This 100 year timeframe is a policy-determination not a technical one. The IPCC developed GWPs as a means of measuring the radiative forcing effects of different greenhouse gases relative to the Absolute Global Warming Potential (AGWP) of a reference gas, CO_2. The timeframe over which the cumulative radiative forcing of CO_2 is measured is a key determinant of this AGWP: for much of its analyses, the IPCC uses 20, 100 and 500 year time horizons. However, as well as accepting the use of the IPCC's GWPs (Article 5.3), the Kyoto Protocol also sets the time horizon against which they are to be determined at 100 years (addendum to the Protocol, Decision 2/CP.3, para. 3, cited in Chomitz (1998)). To be consistent, it can be implied therefore that the Protocol also requires the benefits of sequestration in counteracting the radiative forcing effects of CO_2 emissions to be evaluated over a 100 year time horizon. A further implication worth noting is that any uncertainties derived from both this choice of time horizon, as well as future scenarios of atmospheric CO_2 concentrations, are not technically-driven but rather are a natural consequence of 'arbitrary' policy selections. If 500 years had been chosen as the GWP timeframe, for example, the AGWP of CO_2 would be markedly higher, in turn making the offset value of carbon sequestration and subsequent storage over the short-term significantly lower, without any change in the underlying land use activity.

References

Chomitz, K.: 1998, 'The permanence and duration issue in carbon offsets based on sequestration', Draft paper, Development Research Group, World Bank.

Dixon, R.K., Winjun, J.K., Adrasko, K.J. and Schroeder, P.E.: 1994, ‘Integrated land-use systems: assessment of promising agroforestry and alternative land-use practices to enhance carbon conservation and sequestration’, *Climate Change* **30**, 1–23.

Dobes, L., Enting, I. and Mitchell, C.: 1998, ‘Accounting for carbon sinks: the problem of time’, in L. Dobes (ed.), *Trading Greenhouse emissions: some Australian perspectives*, Occasional papers No. 115, Bureau of Transport Economics, Australia.

Fearnside, P., Lashof, D. and Moura-Costa, P.: 2000, ‘Accounting for time in mitigating global warming’, *Mitigation and Adaptation Strategies for Global Change*. Submitted.

Fearnside, P.: 1997, ‘Monitoring needs to transform Amazonian forest maintenance into a global warming-mitigation option’, *Mitigation and Adaptation Strategies for Global Change* **2**, 285–302.

Greenhouse Challenge Office: 1997, *Greenhouse Challenge Carbon Sinks Workbook: A Discussion Paper*, Greenhouse Challenge Office, Canberra, Australia.

Houghton, J.T., Jenkins, G.J. and Ephramus, J.J. (eds.).: 1990, *Climate Change: The IPCC Scientific Assessment*, Cambridge University Press, Cambridge, UK, 365 pp.

Houghton, J.T., Callander, B.A. and Varney, S.K. (eds.).: 1992, *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, Cambridge University Press, Cambridge, UK, 198 pp.

Houghton, J.T., Meira Filho, L.G., Bruce, J., Hoesung Lee, Callander, B.A., Haites, E., Harris, N. and Maskell, K. (eds.): 1994, *Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the 1992 IPCC IS92 Emissions Scenario*, Cambridge University Press, Cambridge, UK, 339 pp.

Kyoto Protocol: 1997, www.unfccc.de.

Moura Costa, P.: 1996, ‘Tropical forestry practices for carbon sequestration’, in A. Schulte and D. Schone (eds.), *Dipterocarp Forest Ecosystems – Towards sustainable management*, World Scientific, Singapore, pp. 308–334.

Price, C. and Willis, R.: 1993, ‘Time, discounting and the valuation of forestry’s carbon fluxes’, *Commonwealth Forestry Review* **72**, 265–271.

Schroeder, P.: 1992, ‘Carbon storage potential of short rotation tropical tree plantations’, *Forest Ecology and Management* **50**, 31–41.

Tipper, R. and de Jong, B.H.: 1998, ‘Quantification and regulation of carbon offsets from forestry: comparison of alternative methodologies, with special reference to Chiapas, Mexico’, *Commonwealth Forestry Review* **77**, 219–228.

Wigley, T.M.L.: 1994, ‘How important are carbon cycle model uncertainties?’, in T. Hanisch (ed.), *Climate Change and the Agenda for Research*, Westview Press, Boulder, CO, pp. 169–191.