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Would Carbon Pricing Reduce Deforestation? Insights from illustrative simulations of GTEM augmented with a land use change and forestry module

Hom M Pant and Alasebu Yainshet
Australian Bureau of Agricultural and Resource Economics

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Abstract

This paper describes a numerical implementation of the global trade and environment model (GTEM) augmented with a new land use change and forestry module developed in Pant (2010), under some extreme assumptions. Also described are the simplifications made to the structure of the module and additional simplifying assumptions made in deriving a stylised database to calibrate the module in a way that is consistent with the overall structure of GTEM and its underlying database.

The results reported in this paper are based on a stylised database and parameter values, and extreme modelling assumptions. These are for illustrative purposes only and should not be used for policy design.

Preliminary simulation results indicate that a higher carbon price: (i) discourages land clearing, both legal and illegal, (ii) reduces net emissions from land use change, (iii) reallocates land mainly from livestock production to forestry activity, and (iv) encourages investment in commercial forestry more than in environmental forestry as logs from native forests become more expensive. The magnitude of these results could alter substantially under more plausible assumptions regarding the carbon policy scenarios, population and technologies involving a switch from wood to non-wood products.

The purpose of this technical paper is to seek expert advice and feedback on the analytical framework from the conference participants as well as identifying the need for critical data and, thereby, encouraging the development of a more realistic forestry related database and a consistent disaggregation of the GTAP database.

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1. Introduction

Over time, land use change and forestry (LUCF) can be a net source or sink for CO_2 emissions. In a carbon constrained world with emissions trading, net emissions from the LUCF sector may remain an important issue because of the effect on carbon prices. Estimated global emissions from the land use change and forestry sector accounted for about 17 per cent of global greenhouse gas emissions for the year 2004 (IPCC 2007). In Australia, about 10 per cent of total CO_2 emissions each year between1999 to 2007 (except 2003 and 2004 when the share was lower) came from emissions from the LUCF sector (DCC 2009).

Permanent conversion of native forest into agricultural land (including forest degradation) is the key reason that tropical countries, particularly Indonesia and Brazil, are the biggest emitters.

Deforestation can be considered an economic decision which is driven by higher rates of return on agricultural land and/or higher log prices. Any sustained change in relative prices is therefore likely to induce a corresponding change in the land use patterns of any country. This has many implications, including the net emissions profile of countries, the scale and composition of their agricultural production, trade and food prices.

A good model for climate change policy analysis needs to have the capability to explain changes in net emissions originating from the LUCF sector. Only these models can reliably project net emissions of greenhouse gases, as they take into account the underlying behavioural responses of the LUCF sector to altered economic incentives. Results from these models can help design climate change response policies that would be closer to optimum. Such models would also be capable of making more reliable assessments of alternative policy responses. Similarly, a good welfare and global trade model also needs to have a good LUCF module in order to sensibly project the activity levels, output prices and trade of all land using sectors.

Modelling competition for land or other resources between the forestry sector and other agricultural sectors, such as crop production, is fraught with problems, especially in recursive models. Recursive models assume that all sectors can balance their books within a year, meaning that input costs and sales revenues for the outputs are known within this period. This is not possible for the forestry sector where costs are incurred for a number of years and sales revenue is realised at the end of the rotation length. This could be 10, 20 or 50 years down the track (excluding revenues from thinning). As a result, both the optimal rotation length and the demand price for forestry sector land are not easy to determine.

This is why a properly specified land use, land use change and forestry module has been absent from computable general equilibrium (CGE) models. Although some types of land competition, based on relative rental rates, are found in many CGE models. The absence of a properly specified module renders GCE models less useful in terms of global climate change policy analyses and to project global greenhouse gas emissions from deforestation of native forests. The importance of reduced emissions from deforestation and forest degradation (REDD) in reducing global mitigation policy costs in the short term, has increased the value of a model that can project baseline emissions originating from land use change. A global CGE model with a properly specified LUCF module could underpin the Readiness Mechanism of the Forest Carbon Partnership Facility set up by the World Bank (www.Worldbank.org/57X9QKTON0).

Pant (2010) presented an analytical framework that incorporates a well specified module of land use, land use change and forestry into recursive dynamic CGE models. The framework divides global forests into three types, plantation forests, environmental forests and native forests. Plantation forests are harvested regularly; environmental forests are planted and left indefinitely as carbon sinks and native forests are either left untouched, harvested as renewable resources or cleared to make land available. The complexity of decision making in all these activities, particularly in plantation forestry, is simplified by splitting the sector into three stages, the planting, investment and harvesting stage.

Tree planting and harvesting is done by different sectors specialising in those activities. These sectors, like any other conventional production sector in a CGE model, have production functions which meaningfully relate output produced to inputs applied in the same year. As a result they can balance their accounts each year in an economic sense. Between the planting and harvesting stages, the plantation estates are held by investors, who behave similarly to other investors in a recursively dynamic CGE model.

Splitting the forestry sectors into three parts is a key innovation introduced by Pant (2010). This allows investors to choose the rotation length in plantation forestry, maximising their return subject to price expectations. Pant (2010) also allows the possibility of selectively harvesting native forests as a renewable resource, allowing them to regenerate naturally post-harvest or harvesting for alternative uses, including commercial plantation. This follows Golub, Hertel and Sohngen (2007) who modelled the cost of accessing native forests but specified the cost function differently.

This paper documents additional simplifications introduced while implementing the module within GTEM. The key assumptions used to derive a stylised database and key results from the illustrative simulations of the augmented model are also presented.

The remainder of this paper is divided into nine sections. Section two provides a short review of the progress made in modelling LUCF activities in CGE models. This shows that there is a need to bring insights from forestry economics into these modelling frameworks. Section three reviews the basic principles of forestry economics used to determine optimal rotation length of plantation forests.

Section four outlines the key features of an alternative modelling framework. Section five presents the conditions for equilibrium in the planting sector. Those required for the harvesting sector are provided in section six. The dynamics of land supply are described in section seven, and calibration of the LUCF module is discussed in section eight. Section nine contains results from illustrative simulations of the augmented model under an extreme set of modelling assumptions. The results are discussed in section ten, which would alter significantly under a more plausible set of assumptions.

2 Review of LUCF modelling in CGE models

To the best of authors’ knowledge, Dee (1991) is the first work to incorporate the forestry sector into a CGE model in a theoretically consistent way. This model represented the behaviour of a commercial forestry plantation in a steady state. It provided room to extend the modelling work to cover forests that are in non-steady state equilibrium, as claimed by many CGE models.

Past attempts have been made to incorporate a LUCF module in GTEM (Ahammad and Mi 2005). This was triggered by the availability of a large scale database on land use at the world regional level (Lee et al. 2005). Although Ahammad and Mi’s work did not include the LUCF module as an integral part of GTEM, it represented a step forward in constructing a carbon accounting framework of the forest biomass drawing information from the CGE model. Like many CGE models with a single forestry sector, the module developed by Ahammad and Mi (2005) did not distinguish between plantation and native forests and therefore could not identify deforestation of native vegetation as a major source of greenhouse gas emissions.

This limitation was later addressed by Golub et al. (2007, 2009). They allowed both heterogeneity of land as was done in Ahammad and Mi (2005) as well as the possibility of accessing new land using the access cost function developed in Gouel and Hertel (2006). Incorporating the possibility of clearing native forest for agricultural use in the model, Golub and Hertel (2008) further analysed whether global integration (more trade) would have implications for regional land use patterns and possibly for deforestation.

The developments in GTEM and GTAP models were substantial. However, they still relied on an external determination of forest rotation length, as did partial equilibrium models such as the one used in Lawson et al. (2008). Therefore land rents offered by the forestry sector, while competing in the model for land, are not based on the optimised harvesting time. This problem was tackled in Sands and Man-Keun (2008), but their model of land use change and forestry had two deficiencies. First, it needs to be integrated with a properly specified CGE model to take full feedback into account. Second, it is a single country model, of agriculture, land use change (AgLU) and forestry sectors in the United States.

Because forestry activity involves a much longer time horizon there is significant time between planting and harvesting. Consequently outputs harvested in any one year depend on the inputs applied over a number of previous years. This is not the case with standard production sectors modelled in recursively dynamic CGE models. Outputs produced by these sectors depend on the inputs applied in the same year. Consistent modelling of input demand, competition for land between these asynchronous sectors in particular, therefore, becomes problematic. Relating the input demands of the forestry sector with the future output is difficult.

Many CGE models, including GTEM and GTAP, are recursive. This means that agents in these models cannot make informed decisions on variables that depend on future values, such as the price of a plantation forest at harvest and its output at that time. Nevertheless, these models use relativities of current rental rates to allocate land between forestry and other land use activities. This makes the land's 'demand price' in the forestry sector poorly specified. As a result, the responses of forestry activity to policies, such as carbon credits on sequestration services, are not properly captured.

Moreover, many of these models, except Golub et al. (2007, 2009), Golub and Hertel (2008), and Hertel et al. (2008) have failed to distinguish between native forests and plantation forests, which in itself is a significant limitation. Native forest clearing for additional agricultural land is the major cause of CO_2 emissions from land use change. Extra agricultural land is gained by clearing native vegetation rather than reducing plantation forests.

It is not uncommon to find that the approach used in these models implies that increased forest harvesting leads to increased demand for land by the forestry sector. This is because demand for land from the forestry sector moves in proportion to timber output, if prices are constant. Therefore, these models lack the ability to explain the extent of deforestation and the CO_2 emissions associated with increased timber harvests from native forests. This is of concern from an environmental point of view. In addition, these models do not clearly account for land movements between these activities.

In summary, significant progress has been made in modelling LUCF in CGE models. As yet, they have not been able to benefit from the insights forestry/resource economics can offer due to the limitations described above. Some of these issues are addressed in this paper.

3 An alternative framework for modelling LUCF

In this section an alternative framework for modelling LUCF in a recursively dynamic CGE model is proposed. To assist in the modelling work, forests are grouped into three categories, plantation forests, environmental forests and native forests. Plantation forests, also known as managed or commercial forests are planted with a view to maximise profits from harvests. Environmental forests are planted for environmental services, particularly carbon sequestration services, and will never be harvested. These plantations are driven by carbon credits and have to be maintained forever. It is assumed that once planted these forests will remain as untouched native forests with regeneration balancing out degeneration. Fire and disease risks are ignored. A region can harvest native forests selectively, as a renewable resource, or clear fell to make the land available for competition.

In principle, as shown in Table 1, each type of forest will require up to three decisions: planting, investing and harvesting (logging).

Table 1: Decision stages and forest types covered in the model

	planting	investing	harvesting
Plantation forest	yes	yes	yes
Environmental forest	yes	yes	no
Native forest	no	no	yes

The difference between the stumpage paid by the loggers and the cost of planting, including rent paid annually for the land, offers an opportunity for investors to make a return from holding the plantation until it matures. Similarly, the carbon credit revenue, in excess of the cost of planting and land acquisition, provides an opportunity to earn profits from environmental plantations. The value of logs harvested in excess of the harvesting costs provides incentives to selectively harvest or clear fell native forests.

An attempt was made to treat additional agricultural land and logs (joint-products of land clearing) and to use the revenue from sold cleared land as a driver for land clearing. This turned out to be more problematic than initially thought. It was observed that two joint products having two separate markets and prices caused serious theoretical issues in modelling. There were situations in which excess supply in the market of one item (either land or logs, primarily logs) needed its equilibrium price to be negative to clear the market. It was decided to leave this issue to be addressed in future model developments. Alternative land use as a motivating force behind land clearing has been ignored. Revenue from the sale of logs has been included as this is the main driver for legally clearing native forests.

An analytical framework is outlined in the following section that stylises the separate behaviours of the planting and logging sectors and the investors that hold interests in different forest types.

Separation of the forestry sector into three parts allows investors to choose the length of rotation in plantation forestry to maximise their return.

The possibility of selectively harvesting native forest and then allowing it to naturally regenerate as a renewable resource was also modelled, as was land clearing for alternative uses, including commercial plantations. The approach of Golub et al. (2007) was used to model the cost of accessing native forest, but the cost function has been specified differently. This modification allows an additional calibration parameter to tune the rate of deforestation in response to economic incentives.

3.1 The planting sectors

The planting stage covers one year in which the planting sector bids for land, plants and seedlings and sells the estate to plantation investors. The production function is fairly standard, with constant returns to scale, and the sector sells the product at market prices. All input and output markets are assumed to be competitive. The planting sector bids for land with other sectors, including agriculture. The rent offered for the land depends on the price at which plantation estates are sold to investors. The standard zero profit condition (no economic rents in the activity) determines the operation scale of the planting sector.

3.2 Forestry investors

Investors in commercial plantations buy or lease tree-planted land and hold onto it until the forest is harvested. The expected revenue from the sale of the trees over the cost of investment provides them with a rate of return on their investment. Investors in environmental forests buy the land planted with trees and leave it under forest forever. They can claim income flow from the sale of carbon credits for the forests' sequestration services. Other environmental services are ignored at this stage because of measurement and pricing issues. Taking income flows into account, these investors can estimate their rate of return on their investment in forestry and compare it against the opportunity cost of capital (rate of return on investment in physical capital). Risk differences are ignored at this stage. In the case of commercial forests, investors choose the rotation length that maximises the expected rate of return on their investment.

3.3 Logging sectors

The logging sectors buy tracts of forest from investors or the government and harvest the trees. This sector follows the standard behavioural rule of all other production sectors. That is, in the final analysis, they earn zero economic rents, minimise the cost of inputs and behave competitively in all markets.

Since the behaviours of the planting and logging sectors are very much the same as any standard production sector in GTEM, the key modelling issue is the description of the behaviour of investors in plantation estates and environmental forests. The behaviour of such investors is discussed in the next section.

4 Modelling investor behaviour in the forestry sector

The key problem in modelling plantation forests is to explain the behaviour of investors with respect to the purchase of plantation estate and the decision to harvest it.

4.1 The investor decision in commercial plantation forestry

In this modelling exercise it is assumed that a forest investor can buy a one year old plantation estate at price G per hectare and has to pay the market clearing rental rate R per year for the land until it is harvested. It is further assumed that Y(a), a quasi concave function, gives the timber yield in cubic metres per hectare by age, a, of the forest and that the stumpage is expected to be the current price P_f per cubic metres of merchantable timber. All expectations in this module are assumed to be static, consistent with the recursive nature of GTEM. The expected rate of return, $\rho_f(a)$, on a dollar invested in the forest would then be given by:

(1) $$\rho_f(a) = \frac{1}{a}\left[\ln(P_f Y(a)) - \ln[G(.) + \int_0^a \mathrm{Re}^{-rt}\, dt]\right]$$

where *a* is the age at which the forest will be harvested.

After integration, equation (1) can be written as

(2) $$\rho_f(a) = \frac{1}{a}\left[\ln(P_f Y(a)) - \ln[G(.) + \frac{R}{r}(1-e^{-ar})]\right].$$

As the rate of return depends on the age at which the forest is harvested, a rational investor would choose the rotation length, *a*, to maximise the rate of return $\rho_f(a)$ on investment.

Assuming that $\rho_f(a)$ is a concave function in *a*, the first order condition for the maximisation of the rate of return is given by

(3) $$\frac{Y'(a)}{Y(a)} = \rho_f(a) + \frac{\mathrm{Re}^{-ar}}{G(.) + \frac{R}{r}(1-e^{-ar})}$$

which can be written, using (2), as

(3b) $$\frac{Y'(a)}{Y(a)} = \rho_f(a) + \frac{e^{a(\rho_f - r)}R}{P_f Y(a)}$$

Alternatively (3b) can be written as

(3c) $P_f Y'(a) = \rho_f(a) P_f Y(a) + e^{a(\rho_f - r)} R$

The first term on the right hand side of equation (3) is the rate of return on forest investment. The denominator of the second term on the right hand side of equation (3) represents the present value of the investment cost. The numerator is the present value of the land rent payable for the final year. The left hand side of (3) represents the annual growth in timber stock in the final year. The optimality condition for the rotation length requires that in the final year the annual growth rate of the timber stock equals the sum of the rate of return on capital invested plus the adjustment for the land rent payable for one more year. This condition becomes clear in the form expressed as equation (3b). As equation (3c) shows, the optimal rotation length is attained when the increased income that can be expected for holding the forest for one more year is equal to the foregone income from forest capital plus the additional rental cost in that year.

If $\tilde{a}$ is the rotation length, satisfying equation (3), then $\tilde{a}$ maximises the rate of return for the investor. The optimised rate of return on forestry investment can be represented by

(4) $$\rho_f(\tilde{a}) = \frac{1}{\tilde{a}}\left[\ln(P_f Y(\tilde{a})) - \ln[G(.) + \frac{R}{r}(1 - e^{-\tilde{a}r})]\right].$$

Investors in general would maximise their income by allocating funds to alternative forms of investment so that the (risk adjusted) rates of returns are equal across all investment opportunities. However, given that forest capital lacks mobility, forestry investment is modelled separately. It is assumed that the determination of optimal investment in forestry follows the same process as in physical capital. Thus the same form of investment demand function is applied for commercial forestry as that used in GTEM for physical capital:

(5) $$I_f(0) = P_{i,cf} * e^{\theta\left(\frac{D(r)}{Y(r)}\right)} * e^{\nu(\rho_f(\tilde{a}) - \rho^w)}$$

Where $I_f(0)$ is regional nominal investment in commercial forestry, $P_{i,cf}$ is the price of investment 'good', $\frac{D(r)}{Y(r)}$ is debt to GDP ratio of the region, ρ^w is the real interest rate in the global financial market, θ and ν are positive parameters. As a default, θ is assigned 0.5 and ν is set at 10.

The amount of investment needed to acquire new forests $I_f(0)$ is determined by equation (5). Higher level of investment increases the demand for planted land, the output of the planting sector and also land rental. Such investment may also increase the cost of planting per hectare, and therefore lower the rate of return. In a forward looking model, this would also be expected to lower the stumpage at the time of harvest, further reducing the rate of return on investment as shown by (4). A recursive model overstates the investment in forestry relative to a model with forward-looking market participants due to the impact on the rate of operational return through unchanged stumpage.

The demand for newly planted land, forest of age 0, by investors is given by

(6) $$F^M(0) = \frac{I_f(0)}{G(.) + \frac{R}{r}(1 - e^{-\bar{a}r})}$$

This equation can also be viewed as a part of the so-called zero profit condition in planting activity, where G(.) is the supply price of the planting sector output.

Note that $R(1 - e^{-\bar{a}r})/r$ gives the present value of the lease cost of the land per hectare, for the length of the forest rotation. It is maintained in equation (6) that the investor pays rental on the land each year creating a future liability. The investor takes this future liability into account and the lease costs are set aside from the investment budget before the plantations are purchased. The actual investment on plantation forest, excluding the land rentals is given by

(7) $$I_f^s(0) = I_f(0) - \frac{R}{r}(1 - e^{-\bar{a}r}) * F^M(0)$$

Equation (7) derives the financial investment in newly planted forests and equation (6) determines the area of new plantation demanded by investors over the year.

To keep the existing forest stands the investor also has to pay land rent and maintenance costs on a yearly basis until they are harvested. The annual investment required for each age of forest stand can be estimated as

(8) $I_f^s(a) = F^M(a) * (R + M)$ for all ages $a \geq 1$;

where M is the per hectare management cost net of revenues from silviculture activities, such as thinning, $F^M(a)$ is the area of managed plantation forest in hectares with trees aged a, and R is the annual rent payment per hectare of the forest land. Note that these costs have to be borne by the investor and will be funded out of total savings until the trees are harvested. These investments (costs) are unavoidable (sunk). At this stage of model development, the existence of silviculture activities is ignored and M is set to zero.

4.2 The investor decision in environmental forestry

In a carbon constrained world, carbon credits for the CO_2 sequestered by trees may encourage environmental plantations. These forests need to be maintained forever, as logging would release the carbon stored, creating liability for the carbon credited. Because of this liability, it is stated that plantation forests will not claim carbon credits irrespective of carbon prices. There may be small differences between this assertion and reality, but these are ignored in this paper. It is assumed, for simplicity, that the carbon price rises at a discount rate, assumed to be 4 per cent a year.

An investor can expect carbon credits on the incremental carbon stored in the trees each year, having invested resources upfront to establish the forest. The rate of return expected on such investments will determine whether environmental forestry could be an attractive, profitable business.

The rate of return, ρ_{enf}, on investments in environmental forestry can be derived as

(9a) $$\rho_{enf} = \frac{1}{\tau}[\ln(\int_0^{\tau}[T(t)\mu Y'(t)]e^{r(\tau-t)}dt) - \ln(G(.) + \int_0^{\infty} R_{enf}e^{-rt}dt)]$$

where $Y'(t)$ is the time derivative of the carbon yield function and gives the rate of increase in the biomass per unit of time, τ is the age at which the tree growth stops (carbon stocks are stabilised), μ converts cubic metres of biomass (yield) into tonnes of carbon, and

(9b) $$T(t) = C_0 e^{rt} \qquad t \in [0, \tau]$$

gives the carbon price path.

It may be possible to provide an exogenously specified carbon price path instead of the Hotelling's rule (9b) employed here. But this rule simplifies the task. It is commonly employed in studies of environmental response policies with stabilisation targets in mind to attain intertemporally efficient carbon price paths (Australian Government, 2008).

The first term on the right hand side of equation (9a) gives the total carbon credit expected from a hectare of environmental plantation in present value terms and the second term expresses the investment required as a sum of the planting cost and the price (asset value) of land. As a result equation (9a) calculates the expected rate of return from environmental forestry.

To simplify, equation (9a) can be rewritten as

(10) $$\rho_{enf} = \frac{1}{\tau}[\ln(T(\tau)\mu Y^C(\tau)) - \ln(G(.) + R_{enf}/r)].$$

Equation (10) illustrates that claiming carbon credits each year for the quantity of carbon sequestered in that year and claiming once when the tree growth 'stops' are equivalent, provided the carbon price grows at the discount rate.

Given the expected rate of return on environmental plantation, an investor's optimal investment on environmental forestry, I_{enf} , is attained when

(11) $$I_{enf} = P_{i,enf} * e^{\theta\left(\frac{D(r)}{Y(r)}\right)} * e^{\nu_{enf} * (\rho_{enf} - \rho w)}$$

where, the terms in equation (11) have symmetric interpretation as defined for the corresponding terms in equation (5). The parameter ν_{enf} , however, has initially been given a higher value which gradually declines to 10 as the proportion of environmental forest relative to plantation forest area reaches 5 per cent. This adjustment is made to reflect the large percentage changes that can be observed in the early stage of activities. It is assumed that in year one, the base year of the database, all regions have 15 000 hectares of environmental plantation. This is an arbitrary assumption which could be replaced.

Given equation (10), equation (11) states that investment in environmental forestry responds positively to carbon price and negatively to land rent and planting costs. To have equilibrium re-established after each disturbance, it is necessary that the costs (rental rate and per hectare planting costs) have a positive derivative with respect to the amount of investment allocated to environmental forestry. Otherwise, increasing investment will not close the gap. Land scarcity and opportunity cost would guarantee that this condition is met.

Equation (10) also implies that additional investment is not triggered if the carbon price is going to be imposed at a future date because investors are myopic in the model. This limitation cannot be overcome within the recursive dynamic specification of GTEM.

Demand for land for environmental plantation, $F^{enf}(0)$, can now be expressed as

(12) $$F^{enf}(0) = \frac{I_{enf}}{G(.) + R_{enf} / r}\ .$$

In the case of environmental plantations, investors are assumed to buy the planted land upfront as they would be responsible for keeping the land under forest forever. The cost of land purchase is given by R_{enf} / r and the term G(.) is the per hectare cost of planting services (on newly planted land). Equation (12) therefore states that the area of land for environmental forestry is equal to the area that can be bought from the total investment fund allocated to environmental forestry less the planting cost. It is also assumed that there is no further investment required to maintain the environmental forest.

4.3 Specification of the yield function and implementation of the optimal rotation length of plantation forest

So far the per hectare yield function has been expressed in a generic form. In order to come to a usable model of land use change and forestry, however, the function needs to be specified and parameterised. As the database compiled by Sohngen et al. (2009) is utilised in the numerical specification of the module, the yield function they have suggested is also employed.

Quite logically, Sohngen et al. (2009) make a distinction between a carbon yield function and the merchantable timber yield function of a forest. Although trees do not deliver a merchantable timber yield until they are of a certain age, depending on the species and the location, they sequester and store carbon as they grow. Sohngen et al. (2009) specified carbon yield function as

(13) $Y^C(a) = \mathrm{e}^{\alpha - \beta / a}$,

while the merchantable timber yield function is given by

(14) $Y^M(a) = \begin{cases} \mathrm{e}^{\alpha - \beta/(a-\gamma)} & \textit{for} \quad a > \gamma \\ 0 & \textit{otherwise} \end{cases}$

where α, β and γ are positive parameters and $Y^C(a)$ and $Y^M(a)$ are biomass in cubic metres and merchantable timber in cubic metres per hectare of forest of age a respectively.

Clearly, $Y^C \to \mathrm{e}^{\alpha}$ and $Y^M \to \mathrm{e}^{\alpha}$ as $a \to \infty$.

Let

(15) $\bar{Y}^M = \bar{Y}^C = \mathrm{e}^{\alpha}$.

This means that both $\bar{Y}^C$ and $\bar{Y}^M$ give the upper bound on the yield per hectare of the forest. This may be applicable to measure the biomass and merchantable timber harvests from a hectare of native forest.

An alternative is to use a merchantable yield function. This estimates the carbon content of the merchantable timber and grosses up to allow for carbon content of the additional biomass and the root system (carbon stored in the soil) (see for example, Wood and Ajani 2008).

For $a > \gamma$, logarithmic differentiation of (15) with respect to *a* yields

(16) $\frac{dY^M / da}{Y^M} = \frac{\beta}{(a-\gamma)^2}$

Using (16) in (3b) gives

(17) $$\frac{\beta}{(a-\gamma)^2} = \rho_f(a) + \frac{e^{a(\rho_f - r)}R}{P_f Y(a)}$$

Equations (14) and (17) can be solved for the optimal rotation length and the yield rate. Alternatively, equation (17) can be used to calibrate the initial optimal rotation length of a given forest type. Its linear form can be used to calculate the marginal changes in the optimal rotation length.

4.4 Parameterisation of the yield function

To calibrate, G(.) is taken as the market price of the output of the planting sector, R_{enf} as the average rental for contestable land and the discount rate r as the global market clearing real interest rate endogenously determined in GTEM. It is worth noting that two discount rates are used in this paper. One, 4 per cent per year, is used to grow carbon tax rates. The other is used to discount financial flows, which is the externally determined global interest rate. This distinction was made to separate 'social' discounting normally used with carbon tax rate and a long term market rate used for private commercial decisions. In the base year, the area of planted land is taken from external sources and the appropriate values from the GTEM database are used to infer prices as required.

In this exercise, an attempt was made to solve the initial value of the optimal rotation length using equation (17) and exogenously set yield function parameters. Given the diverse information on the yield function parameters with other biophysical information and the value information derived from the GTEM database, it was difficult to find a solution.

The arbitrarily chosen fixed rotation length and the yield function parameters were therefore used to generate smooth yield curves with upper bounds. This means that the area harvested roughly yields CO_2 emissions as reported in the literature (FAO, 2006). The yield function parameters, rotation length and maturity age when the growth of the biomass nearly stops are given in Table 2. In the next stage of model development and application, these parameters need to be empirically established.

In terms of income accounting in GTEM, once planted the land under environmental forests would be considered lost from the system. It would not bring any rental income to the land owner. It will, however, bring carbon credit capital incomes to the regional household (society) each year until the forest reaches maturity age, τ. This income can be considered as the rental income from 'forest capital' which depreciates fully at the end of the growth phase, when incomes from the environmental forests stop. This account is currently ignored and treated as change in the structure of wealth.

Table 2: Parameterisation of the yield function, rotation length of commercial forests and maturity age of environmental and native forests [a]

Regions/countries	α	β	γ	Rotation length	Maturity age
1 USA	4.9	7.5	15	38	55
2 EU25	4.85	7.35	14.7	39	55
3 China	5.03	7.545	15.09	44	75
4 FSU	5.01	7.515	15.03	73	75
5 Japan	5.1	7.65	15.3	47	75
6 India	5.02	7.53	15.06	25	75
7 Canada	5.04	7.56	15.12	42	75
8 Australia	4.6	6.9	13.8	29	55
9 Indonesia	5.33	7.995	15.99	26	75
10 South Africa	4.7	7.05	14.1	48	75
11 Other ASEAN	4.95	7.425	14.85	38	75
12 OPEC	4.4	6.6	13.2	40	55
13 Rest of World	4.93	7.395	14.79	45	75
14 New Zealand	5.05	7.575	15.15	43	75
15 Brazil	5.22	8.1	16.2	42	75
16 Rest of Sub-Saharan Africa	4.967	7.575	15.15	41	75

[a] Numbers selected by authors for illustrative purposes.

5 Equilibrium conditions for the planting sector

The planting sector meets the demand for planted land by both commercial forest and environmental plantation investors. Its production function is a standard CRS and satisfies market clearing and zero profit conditions.

The condition for no economic rent can be specified as follows:

(18) $$(F^M(0) + F^{enf}(0)) * G(.) = \sum_{i \in TRAD\_COMM} P_i X_{if} + \sum_{k \in FAC} W_k X_{kf}$$

The left hand side of (18) gives the sales revenue. The right side gives the sum of material input cost and factor input cost, which also includes land rent for one year, of the planting sector. Therefore equation (18) describes the equilibrium in planting activity. The distinction between the supply prices, the market prices and the purchaser's prices are ignored. These differences are tracked in model code as far as the database reflects the differences.

The market clearing condition for the planting sector as a whole can be written as

(19) $$[F^M(0) + F^{enf}(0)] = \frac{I_f(0)}{G(.) + (R/r)(1 - e^{-\tilde{a}r})} + \frac{I_{enf}}{G(.) + R_{enf}/r}.$$

Given the land area planted each year, the age profile of forest stands can be tracked yearly by moving the forest age up one year annually until the maturity age is reached. The existing database requires an allowance made for output demand from the planting sector by other users on the right hand side of equation (19). They are covered in the model code. The harvesting decisions are modelled as follows.

6 Equilibrium conditions for the harvesting sector

In this section the harvesting decision of commercial forest owners, as well as legal and illegal harvesting and clearing of native forests are outlined. This covers the supply side of the logs market. The demand side is already covered in GTEM.

Demand for forest 'capital' (trees) by the logging sector is a derived demand. Demand for logs is determined by the conditions of timber and pulp product markets. The output of the logging sector represents supply. The standard market clearing condition determines the market price for logs. The supplies of logs come from the equilibrium behaviour of harvesters, including logs gained through illegal land clearing activity.

Similarly, the logging sector demands trees, in the same way as any input demanded by a production sector. However, the supply of trees in the model needs structure, as there is a lack of understanding on how the area of native forests harvested is determined. As discussed below, supply of trees from commercial forests is determined by the return maximising behaviour of the investors. The supply of trees from native forest has been assumed to be infinitely elastic at a given price. This means that the area harvested from native forests is demand determined, while the price of trees (royalty rate) is exogenously determined. The assumption regarding the supply of trees from native forest can be easily altered by changing the model closure.

Demand for trees (derived demand) is assumed to be proportional to the production of logs (or as specified by the production function). Log supply side is determined by stumpage for native forests and optimal harvesting decisions made by the agents in the case of commercial forests. These are described in the following sections.

6.1 Optimal harvesting of commercial forests

The optimal rotation length of commercial forest is given at $a = a^*$ and it is assumed to remain fixed over time, differing by region. Therefore the area of commercial plantation forest available for harvesting is given by

(20) $$L_{DEF\_CF} = \sum_{a \geq a^*} F(a) .$$

Where $F(a)$ is the area of forest of age a, L_{DEF_CF} is the total area available for harvesting of plantation forest (the regional index is suppressed for simplicity).

Supply of merchantable timber from plantation forest is thus given by

(21) $$S_{Logs\_CF} = \sum_{a \geq a^*} F(a) * Y^M(a)$$

Given that the rotation length is fixed, the supply curve for commercial plantation trees in any one year becomes vertical. This position may shift annually. As a result, the price of trees is demand determined.

One key consequence of this assumption is that the area of commercial forest harvested under a reference case and the area harvested under any policy case will remain the same for the first a^* years. The area harvested will not necessarily be the same beyond the first a^* years as the new plantation trajectory may be different between the scenarios. It is assumed in constructing the stylised database that the commercial forest is uniformly distributed over all ages up to the rotation length. The consequence of this assumption is that the supply of logs from commercial forests will also remain constant for the first a^* years, irrespective of the policy environment. Native forests will supply logs to meet the excess of demand over supply from commercial forests and illegal sources (discussed below).

6.2 *Optimal harvesting of native forests*

Native forest land can be considered to have zero opportunity cost as far as log supply is concerned and the planting costs in such forests are also zero. The only cost is the harvesting cost. What proportion of such forest would be harvested annually and how are pertinent questions. It is also possible that some native forest will be cleared, possibly illegally, to meet the increased demand for agricultural land.

Four ways of using substantial native forest estates are considered, conservation for biodiversity, selective (renewable resource) harvesting, legal and illegal land clearing.

The first use, conservation is regarded as an exogenous process. An attempt is made to model the remaining three.

To model the possibility of land use change a distinction is made between the stocks of native forest land (i) selectively harvested but left to regenerate naturally; (ii) harvested by clear felling and the land made available for competitive uses, including forest plantation and (iii) illegally cleared native forest, usually done to meet the demand for agricultural land by marginal farmers.

Of the native forest land that can potentially be converted into other uses all costs of development, if any, are ignored at this stage.

In a carbon constrained environment, there is a carbon impost on all legal harvesting of native forests, whether it implies a land use change or not. That is, both sustainable use and land clearing are subject to a carbon impost given by

(22) $CT\_k = T * \omega * \bar{Y}^{C} * L_{DEF\_k}$

where CT represents the carbon tax liability to the harvester, T is the carbon penalty per tonne of CO_2, L_{DEF} is the area harvested in hectares, $\bar{Y}^{C}$ is yield of biomass in cubic metres per hectare, and ω is the conversion factor from cubic metres of biomass to tonnes of CO_2. The default value for ω is set at 3.3. As will be clear below, k is the type of harvesting. Clearly, the carbon impost is zero in an unconstrained environment. In a constrained environment, however, commercial plantations are not taxed as they could claim carbon credits for CO_2 sequestered while the forest is growing. Under reasonable assumptions it can be seen that the credits and tax will balance when discounted appropriately.

6.2.1 Selective harvesting of the native forest

Normally native forests are slow growing and their optimal rotation length 'a' could be determined by the following condition: $Y'(a)/Y(a) = 1/a$.

As discussed elsewhere (for example, Pant 2010), satisfaction of this condition is consistent with the maximised sustainable yield (MSY) approach. This approach, however, ignores the cost of harvesting and the price of logs.

Access cost is considered in addition to the cost of harvesting native forests. Instead of adopting a cost function that rises as the cumulative area harvested approaches its capacity limit, as done in Golub et al. (2007), in this exercise the resource exhaustion cost function built in GTEM (Pant 2007) is used. This means that factor productivity in harvesting native forests is reduced as the cumulatively harvested area rises relative to the last period. As a result the unit cost of legally harvesting native forest increases with the area harvested.

Given input prices, the price of logs (determined in the market) and the royalty rate given, the condition for zero economic rent determines the area of native forest that would be harvested in a sustainable way. The conditions for equilibrium harvesting are described in the following sections.

6.2.2 Clear felling of native forest for land use change

Changes in land use, deforestation of native forests and conversion into agricultural land and vice versa, are one of the key modelling problems addressed. Any native forest harvested this way, increases the supply of land for commercial uses, such as agriculture and managed forestry activities. If the area of native forest is increased through reforestation or afforestation then, similarly, the supply of land for other commercial uses declines.

Under the current modelling framework, it is not possible to value the environmental benefits of maintaining a native forest, nor is it possible to value the benefits of these forests to future generations. Environmental forests planted as a response to carbon prices have been covered above. Here, one way movement of land use change (from inaccessible native forest to accessible land for commercial uses) will be evaluated. The movement of agricultural land back into native vegetation for biodiversity, ecotourism and for other non market benefits is excluded.

There is also the issue of property rights. Who owns native forests? In countries where property rights are ill specified, privately or locally owned, it is likely that the 'tragedy of the commons' may result. Alternatively, if native forests are owned by the government, strict rules and regulations regarding access may be in force. This means that the amount of deforestation is restricted by the concessions or quotas issued by the government. Illegal deforestation can result where the concessions are not large enough and law enforcement is weak.

It is assumed that the government sets the royalty rate per cubic metre of trees harvested from native forests. The logging sectors decide whether they use clear felling or selective harvesting and how much native forest they harvest.

6.3 Illegal land clearing

Illegal deforestation is greater than government approved clearing in the Brazilian Amazon. Attempts have been made elsewhere to assess the impacts of issuing concessions (Banerjee and Alavalapati 2009). In this modelling exercise an attempt is made to capture this process. This is done by specifying a function to allow illegal land clearing to respond positively to increases in land prices. The exact form of the specification used in the following should be taken as an illustration and should not be mixed with reality.

Land price is determined by the average land rental and the real global interest rate (used as a measure of the long term interest rate).

(23) $$L_{DEF\_NILL}(r) = \varsigma(r) * A(r) * \bar{P}_L(r)^{\varsigma(r)}$$

where L_{DEF_NILL} is the area (in million hectares) of native forest illegally cleared, $\bar{P}_L$ is the capitalised price (in thousand dollars) of land that is based on average rental of land, and A(r) and $\varsigma(r)$ are non-negative parameters with arbitrary default values as given in Table 3.

Table 3: Default Values [a] of A(r) ar $\varsigma(r)$

Regions (r)	$\varsigma(r)$	A(r)
1 United States	0	1
2 EU25	0	1
3 China	0.1	1
4 FSU	0.9	1
5 Japan	0	1
6 India	0.5	1
7 Canada	0	1
8 Australia	0	1
9 Indonesia	0.8	1
10 South Africa	0.5	1
11 Other ASEANcountries	0.3	1
12 OPEC	0	1
13 Rest of World	0.5	1
14 New Zealand	0	1
15 Brazil	0.9	1
16 Rest of Sub-Saharan Africa	0.8	1

[a] Values selected by authors for illustrative purposes.

Equation (23) represents native forest encroachment by marginal farmers as the land prices rise. Since such farmers may burn the forest to clear it for agriculture, they do not have a well specified land clearing cost/production function. It is done without cost, if it is done in a way the government cannot monitor, regulate and/or prosecute. Some logs from illegal land clearing may be salvaged which could be sold to the market. In this model it is assumed that 25 per cent of the potential maximum log output from illegally cleared areas will be recovered and sold.

As the parameter values indicate, the functional relationship in equation (23) is meaningful for only a subset of countries including the tropics, the former Soviet Union, China, South Africa and the ‘rest of the world’. This specification should not indicate that these countries have illegal land clearing going on. They are there as counterfactual experiments.

The illegal land clearing mechanism instituted in the module also helps to examine whether or not imposition of carbon prices encourages more illegal land clearing. There may be an important mechanism at work that cannot be easily dismissed. Imposing a carbon penalty makes logs from native forests expensive. Returns from commercial forests go up as log prices rise. This increases the plantation sectors’ demand for land, to meet the demand from commercial plantation investors. If other land using sectors are not as carbon intense then land rental may go up, this encourages illegal land clearing.

Introducing carbon penalties may thus indirectly encourage or discourage illegal logging through changes in the price of land. This process is captured by equation (23).

When prosecution risks are low, illegal logging not only avoids paying royalties and the need for a licence but also effectively avoids carbon penalties on the forest cleared. Therefore carbon taxes create additional gaps between incentives offered to legal and illegal logging. The higher the carbon price the higher the rent from illegal logging. Thus the illegal logging becomes more attractive with increasing carbon price, but this incentive operating via the logs market and its consequences are not captured in the current framework.

Demand for trees determines the area of the native forest cleared each year by the harvester. The possibility of a country enforcing deforestation exogenously is ignored and it is assumed that native forest harvesting is allowed at a given (policy determined) royalty rate.

6.4 Markets for trees and the market for logs

The modelling assumes that there is a unified single market for logs (that is logs are homogenous) but that trees are different. In other words, trees from commercial forests are purchased by loggers specialising in commercial plantation forest harvesting and trees from native forests are only sold to their respective harvesters (through licensing arrangements). However, sufficient individual loggers are assumed to ensure that each market segment remains competitive.

These assumptions mean that the price for trees could be different, but the price of logs for all loggers is the same. Sawmills and pulp mills will not be able to distinguish where the logs came from.

This structure comes close to the electricity production technologies modelled in GTEM. Reflecting this, the technology bundle approach of GTEM is extended to model the three harvesting “technologies” with the requirement that the log output also remains additive (Pant 2007 details the technology bundle with additive constraints).

It is assumed that each harvester has a Leontief production function. This means, demand for trees (in cubic metres) is proportional to profit maximising output level of logs, Q_{LOGS_k} . If X_{natres_k} is the demand for trees by harvester type k then,

(24) $$X_{natres\_k} = \beta_k Q_{LOGS\_k} \qquad k \in \{CF, RN, DN\}$$

β_k in (24) is the input/output coefficient and the set element CF refers to harvesting of commercial forests. RN refers to harvesting of native forest as a renewable resource and DN refers to harvesting of native forest by clearing. The supply of trees (in cubic metres) from the harvest of native forests is, by assumption, demand determined (constant royalty rate), and can be written as

(25) $$X_{NATRES\_k} = L_{DEF\_k} * \bar{Y}^M , \qquad \text{for } k \in \{RN, DN\};$$

For commercial forests supply of logs is given by equation (21). Note, however, that $\overline{Y}^{M}$ in equation (25) is the maximum yield (steady state level) of merchantable timber per hectare of native forest land.

The market for trees from commercial forests is cleared by flexible prices (stumpage). Therefore:

(26) $S_{\log s\_k} = X_{natres\_k}$ for k = cf.

The zero economic rent in logging commercial plantation forests, which can be understood as:

(27) $$P_f * X_{NATRES\_CF} + \sum_{i \in (Fac-NATRES)} W_i X_i^{\log\_CF} + \sum_{i \in TRAD\_COMM} P_i X_i^{\log\_CF} = PM^{\log gs} * Q_{LOGS\_CF}$$

will determine the scale of operation, Q_{LOGS_CF}. In equation (27), X represents the quantity of the respective inputs used. W and P refer to their respective prices and PM refers to the market price of the output. Tax wedges are ignored for simplicity of presentation.

Equations (24) to (26) determine L_{DEF_CF}, the area harvested from commercial forest.

In the case of native forests, the royalty rate (per cubic metre of trees) is exogenously determined. That means the respective zero economic rent conditions, (28a) for renewable harvesting and (28b) for clear fell harvesting,

(28a) $$P_{royalty} * X_{NATRES\_RN} + \sum_{i \in (Fac-NATRES)} W_i F_i^{\log\_RN} + \sum_{i \in TRAD\_COMM} P_i X_i^{\log\_RN} + CT\_RN = PM^{\log s} * Q_{LOGS\_RN}$$

(28b) $$P_{royalty} * X_{NATRES\_DN} + \sum_{i \in (Fac-NATRES)} W_i F_i^{\log\_DN} + \sum_{i \in TRAD\_COMM} P_i X_i^{\log\_DN} + CT\_DN = PM^{\log gs} * Q_{LOGS\_DN}$$

determine the scale of operations. Using equation (25) the area harvested or cleared can be derived.

Clearly the market price of logs is determined by the market clearing condition for logs. This states that logs produced and supplied by all harvesters should be equal to the aggregate demand for logs from all users.

(29) $$\mathrm{Q}_{\mathrm{LOGSP}} + Q_{LOGSNR} + Q_{LOGSDN} + Q_{LOGS\_ILL} = \sum_{j \in PROD\_COMM} X_{\log s, j} + X_{\log s}^{export} + X_{\log s}^{HH}$$

Equation (29) states that logs supplied by all logging activities will be sold in a single market to meet the demand from all users/destinations. There is some scope for separating the logs markets, especially into pulp wood and sawn wood markets. This level of detail has been postponed until the model is successfully implemented and the basic database work is completed.

Total land freed by the forest sector for potential competition by other activities is thus given by

(30) $H = L_{DEF\_CF} + L_{DEF\_DN} + L_{DEF\_NILL}$.

The regular harvesting of native forest is excluded because the land is assumed to be returned for regeneration.

Each year tree plantation removes an area of land available in the contestable market shared by other land using activities, such as cropping. This area is equal to the sum of the areas purchased respectively by the commercial plantation investor and the environmental plantation investor. In other words, aggregate areas planted in any year should satisfy the condition

(31) $F(0) = F^{M}(0) + F^{enf}(0)$.

In implementing the model, allowance is made for the production sector or any other user to use planting sector output as intermediate input or otherwise. This simplifies the data adjustment that would have been necessary should equation (31) be enforced strictly.

7 Supply of land and market equilibrium for contestable land

The forestry sector is connected to other GTEM sector mainly via the log and land markets. To simplify land market modelling, the assumption that there is only one type of land used by j activities (including plantation, cropping and livestock sectors) is made. However, these differ in land use efficiency. This difference is represented by a constant elasticity of transformation (CET) frontier.

In standard GTEM formulation, the cost minimising demand for land by a sector j, in a linearised form, is given by

(32) $l_j^* = f_j - \sigma_j (p_j^* - \bar{p}_f)$

where p_j^* is the percentage change in the rental price of land faced by sector j, and $\bar{p}_f$ is the percentage change in the average price of all primary factors f_j is the percentage change in the demand for factor composite which normally moves in proportion with the sectoral output and σ_j is the elasticity of factor–factor substitution.

Land is not assumed to be perfectly mobile, however it is assumed to respond to higher rental returns. Given the total supply of land, allocation of land to different income maximising activities is represented via a CET function as

(33) $l_j^s = \bar{l} + \sigma_l (p_j^* - \bar{p})$

where $\bar{p}$ is the percentage change in the average rental of land across all land using activities, and σ_l is the CET parameter.

Equilibrium in the land market requires that the market clears, which means:

(34) $L_j^s = L_j^*$ for all land using sector j.

Equation (34) determines sector specific land rentals. Whether the sector specific rental rates will be different depends on the initial rental rate and the size of the CET parameter σ_l. In this exercise, the parameter has been given a large value, 10.

Finally, the supply of land is derived by

(35) $\bar{L} = L_{-1} - F_{-1}(0) + H_{-1}$.

Equation (35) shows that the current supply of land in the contestable market is equal to the supply of land in the previous period, less the land planted with trees, plus the area cleared of forest in the previous period. Equation (35) is dynamic, describing how the change in land supply may occur annually due to planting, harvesting and clearing of forests. If the area harvested is equal to the area planted, then the supply of land in the contestable market does not change.

8 Calibration of LUCF module: building database for the land use change and forestry module of a dynamic CGE model

Building a forestry database that meets the requirements of the land use change and forestry module of a global dynamic CGE model had been attempted. The aim was to compile a range of data, including land use, land rentals, land prices, timber yield function parameters, rotation length and forest carbon stocks for 16 global regions/countries, and to restructure the social accounting matrix of the GTEM database.

First, the forestry sector in GTEM was split into two sectors, planting (frs_plnt) and harvesting (frs_hvst) using SplitCom (Horridge 2005). The arbitrary shares allocated were 30 per cent for planting and 70 per cent for harvesting. In the factor payments matrix of the harvesting sector, 99 per cent of the land rentals were reallocated to natural resources, as the payments to trees (to investors) were made using this transaction.

Secondly, investment was split into three columns, investment in physical capital (phy_cap), investment in environmental forestry (enf_inv) and investment in commercial forestry (cf_inv). All sales from the planting sector to the conventional investment sector were reallocated to environmental forestry (1%) and to commercial forestry (99%). It is assumed that these two forestry investors do not purchase any other intermediate inputs.

In the third step, existing stands of commercial forest of all ages were derived from the forestry data and their estimated land rents were allocated as payments to natural resources by commercial forestry investors. To estimate the land rents, implied rental rates were estimated from the rent paid by the planting sector for the area planted, which is available from the forest database. This rental rate was applied to the total area covered by commercial forests of all ages, to estimate their rental expenses.

Estimates of all other prices were made in the same fashion, by comparing the quantity information available from the forestry database with the value data of the GTEM database. In isolated cases small cell adjustments were made and the underlying tax rates were used, if necessary, to keep the accounts balanced. These instances were rare and any adjustments were small. Finally, as regional investments were altered as a result of the process described above, regional savings were then adjusted by the same amount to keep the base year macro-accounts in balance. Regional GDP was altered by a small amount as a result.

Land use is divided between five categories, commercial forest, environmental forest, native forest, crop land and grazing land. Land area under commercial and environmental forest is distinguished by age. This facilitates the dynamics of timber production and carbon accumulation in the model. The age profiles of commercial forests span up to the rotation length, which is different for different region. Note that the rotation lengths were not determined by satisfying the optimality condition (3b) for the base year. It was difficult to find a solution as the information gathered from various sources was not necessarily consistent with the corresponding values of the GTEM database. Therefore the numbers presented in this paper should be taken as arbitrary, first approximations.

For environmental forests, an equal amount of area is assigned to age zero in all regions in the base year. It is assumed that this exogenous planting process will be continued over the entire time horizon of the reference case. In the simulation years, however, the environmental forest moves from its base year values as additional environmental plantings are induced by the policy change.

The forest land use data was adapted from the Forest Resource Assessment 2005 (FAO, 2006). The 219 countries in the Food and Agriculture Organisation (FAO) data are grouped into 16 regions. As the FAO data is for all ages of forests, there is a need to split it between different ages for commercial forest. An alternative source provides forest stocks by 10 year age cohorts and regions (Sohngen et al, 2009). It was initially attempted to create one-year cohorts of forest by splitting the ten-year age groups into single ages of equal distribution within each group. However, large fluctuations in forest area between consecutive ten-year age groups made it difficult. Large fluctuations resulted in large swings of timber supply and prices. Instead, the total land under commercial forest was divided equally across all ages.

The land use for the five forest sectors were constructed from the different characteristics of forests in the FAO data. These are, primary forest, productive plantation, protective plantation, modified natural forest and semi-natural forest. In the absence of information to objectively classify the FAO data into the forest land use required in the model, the following method is applied:

- Commercial forest, all productive plantations, up to 50 per cent of semi-natural forest and up to 15 per cent of modified natural forest.
- Native forest for selective harvesting, around half of modified natural forest and semi-natural forest and up to 60 per cent of primary forest.
- Native forest for conservation, all protective plantation, up to 100 per cent of primary forest, up to 25 per cent of semi-natural and up to 15 per cent of modified forest;
- Environmental forest, an equal set area of 15 000 hectares for all regions.
- Native forest for clear felling, the total area under forest, less commercial forest and native forest for selective harvesting, native forest for conservation and environmental forest.

Native forest for conservation is not included in the current database.

Timber yield function parameters were initially obtained from Sohngen et al., (2009). Data in Sohngen et al. (2009) is provided by timber type which makes the timber yield function parameters specific to timber types. Average parameters were estimated by weighting the timber specific parameters by land area. It is assumed that these parameters are applicable to all forest sectors modelled. The yield function parameters along with other variables were used to estimate rotation lengths.

Rotation lengths for commercial forest were estimated by applying Sohngen's timber model (Sohngen et al., 2009). As these became incompatible with other data in the model, they were replaced with tentative numbers. The parameters used in the timber model may not be consistent with the implicit parameters (yield function parameters) and prices in GTEM. This indicates the need for serious database work.

In building this forestry land use database a number of assumptions, approximations and estimations have been applied, to implement the module numerically. In order to apply the modelling framework profitable, a database that closely reflects the actual situation required by the model is needed.

9 Results from illustrative simulations

The land use change and forestry (LUCF) augmented GTEM did not require any special model closure rules, except that the price of trees harvested from native forests was taken as exogenous. All other naturally exogenous variables (representing taste, technology and policy) of the standard GTEM were retained. The LUCF augmented model was simulated under four different scenarios. The first being a reference case in which the global economy moves under its own momentum, that is, endogenous accumulation of debt and capital stock built into the base year database are the key drivers. In addition, the model's population module was turned off to save computing time while the model was developed. A labour saving productivity shock of 3 per cent a year was uniformly applied across all regions, over the whole time horizon. No other exogenous shocks were applied to the model in the reference case scenario.

In the other three counterfactual policy cases, a tax of $10, $20 and $30 per tonne of CO_2e (greenhouse gas emissions) was imposed in the first year. This rose by 4 per cent each year. In this paper these are subsequently referred to as carbon price trajectories. These tax shocks are additional to those applied to generate the reference case. Therefore, the difference between the variables in a policy scenario and the reference case provides the impact of the policy shock, that is carbon tax.

The model was simulated for 25 years. The impacts of imposing alternative carbon tax trajectories on forestry related variables are presented in the following figures as deviations from the reference case.

First are three figures that project the forestry variables under the reference case.

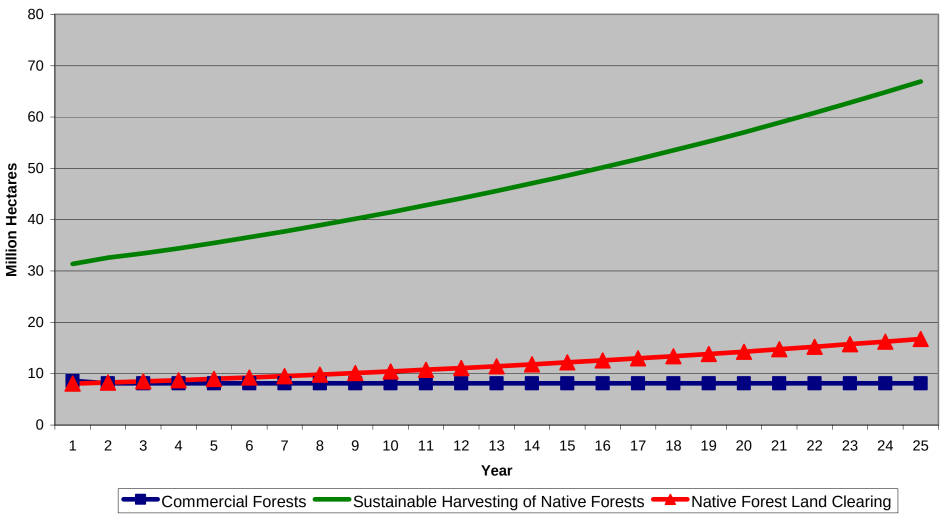

Figure 1: Global annual harvests of all forest types under the reference case

Figure 1 illustrates that in the reference case, the area of commercial plantation forest harvested remains constant over time. This is an artefact of the database assumption that the age distribution of the forest is uniform and the modelling assumption that the optimal rotation length is exogenous and constant. Because of these assumptions, the area of commercial plantation forest harvested for the next 30 or more years (up to the rotation length for each region) is already set out on the age profile of the forest in the base year.

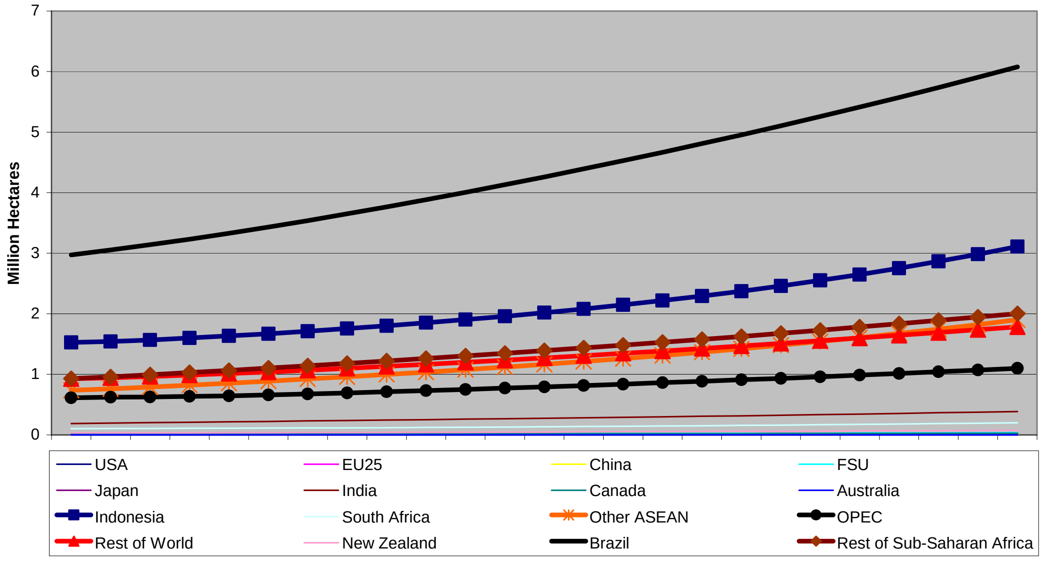

Figure 2: Land clearing (deforestation of native forest) by region under the reference case

Figure 2 shows model estimates of the regional distribution of native forest land clearings. The figure illustrates that over the projection period, to year 25, Brazil, Indonesia, Sub-Saharan Africa and other ASEAN regions lead the world in clearing native forests. Deforestation in Brazil starts at around 3 million hectares per year in the base year, year one and rises to about 6 million hectares per year by year 25. Globally, the legal deforestation rate of native forests rises from 8 million hectares per year in the first year to 16 million hectares a year in year 25.

In this modelling exercise it is assumed that commercial plantation forestry and sustainable harvesting of native forests are both carbon neutral. That is, carbon emissions from these harvests are equal to the carbon sequestered while growing. Neither of these forests is credited for the carbon they sequester, nor are they liable for emissions.

Note that under many proposals for domestic carbon markets, commercial forests are able to earn sequestration credits. This includes the argument that a proportion of the carbon sequestered remains stored in timber products for many years after harvesting. Therefore commercial forests should be credited for part of the carbon they sequester. Given this argument, commercial forests will be more competitive than assumed in this paper, under an emission trading scheme. Lawson et al. (2008) discusses this issue in detail.

Net carbon emissions from forestry arise when native forest is cleared (potential land use change). Estimated net emissions from the forestry sector under the reference case are shown in Figure 3. The figure shows that as with land clearing, the lead emitter is Brazil followed by Indonesia. Other ASEAN countries and Sub-Saharan Africa are major sources of land use change emissions. Globally, net CO_2 emissions from deforestation are projected to rise from about 5 billion tonnes in year one to about 11 billion tonnes in year 25.

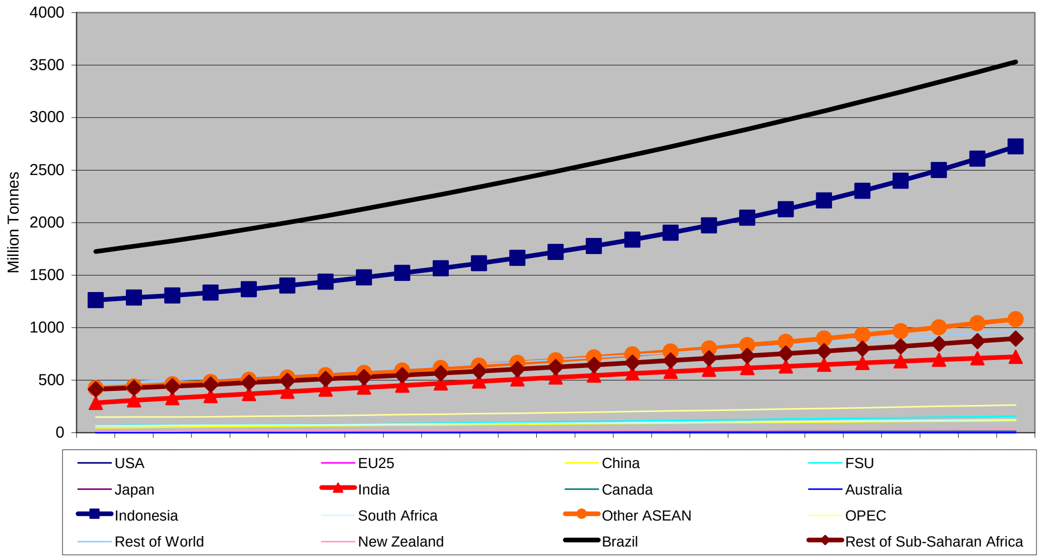

Figure 3: Net emissions of CO_2 from land use change by regions under the reference case.

The consequences of imposing alternative uniform carbon price paths in all countries (ignoring the exchange rate differences) are examined below.

Carbon Pricing - Commercial versus Environmental Forestry

Figure 4a shows projections of the changes in the global area of new plantation purchased for commercial forestry under the three carbon price trajectories. Figure 4b shows the total global cover of commercial forests of all ages. The figures demonstrate that as carbon prices rise from $10 to $30, the area of newly planted land acquired for commercial forestry increases (despite not earning carbon sequestration returns) and as a result the total area of commercial forestry also increases. It also shows that as tax is increased along the trajectory, the area of new plantations purchased and the total area of commercial forestry increases.

The initial jump in the area of new plantations is an artefact of the recursively dynamic general equilibrium model. If these models are given a large initial shock, such as a $20 per tonne tax on CO_2 emissions, the economy has to fully adjust to this shock within a year. In subsequent years, however, the tax rises by 4 per cent (an arbitrary number) per year only and therefore big jumps are not required to regain the equilibrium. In the $20 per tonne initial tax trajectory, the annual increment in the carbon tax starts at 80 cents in year two and rises each subsequent year.

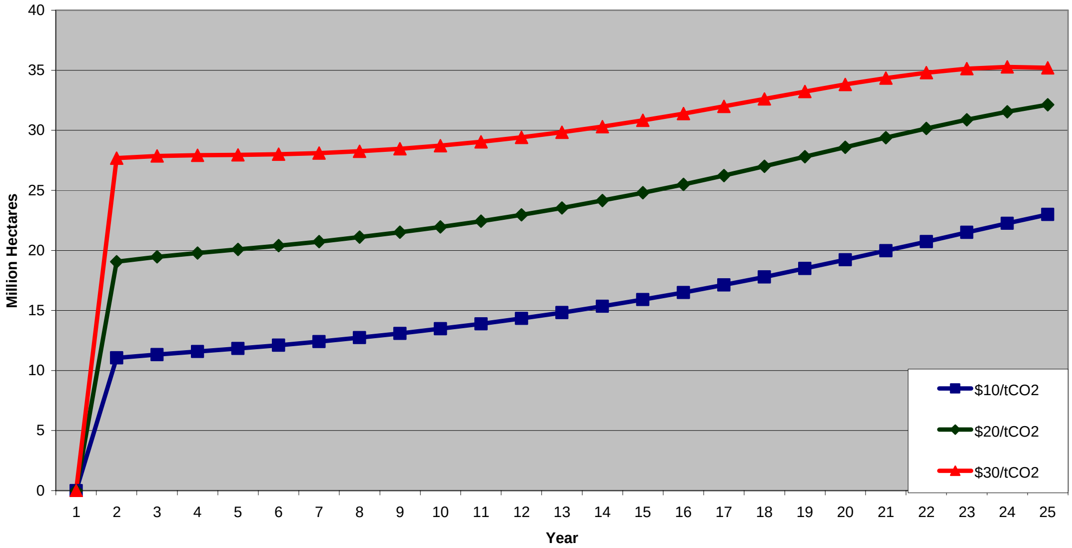

Figure 4a: Annual increase in global area of commercial forests purchased (new investment) under different carbon price trajectories relative to the reference case.

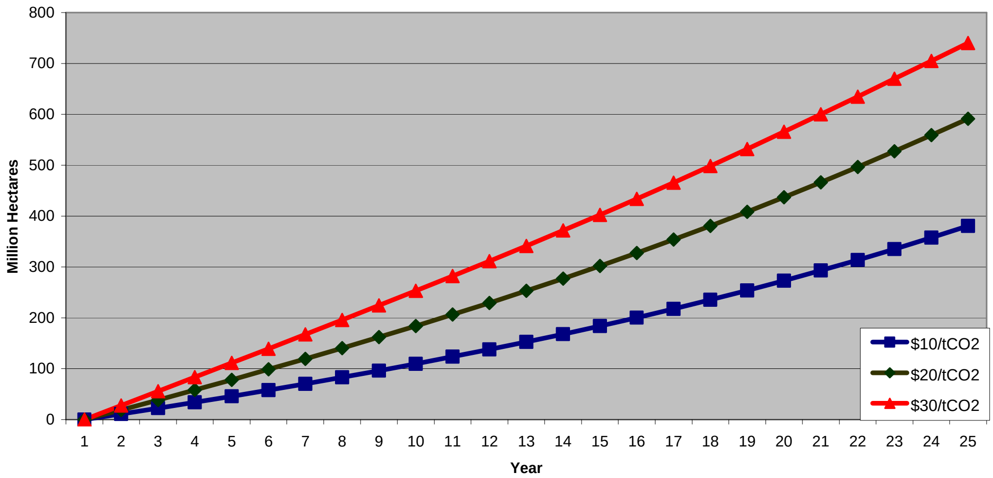

Figure 4b: Total increment in global area of commercial forests under different carbon price trajectories relative to the reference case

Figures 5a shows the projections of the annual purchases of new plantations by environmental investor over time. Figure 5b shows the total area of environmental forest induced by the three carbon price trajectories. These areas are changes relative to their respective values in the reference case. The figures show that a higher carbon price induces increased investment in environmental forestry, with more planted land being acquired each year. The forest cover also increases with time.

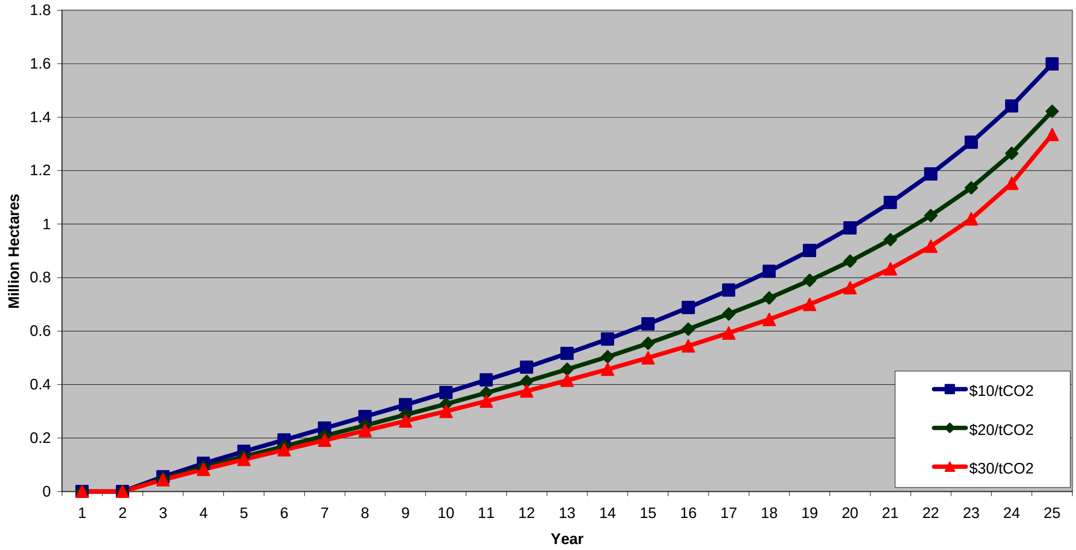

Figure 5a: Change in global area of environmental forests purchased (new investment) under different carbon price trajectories relative to the reference case.

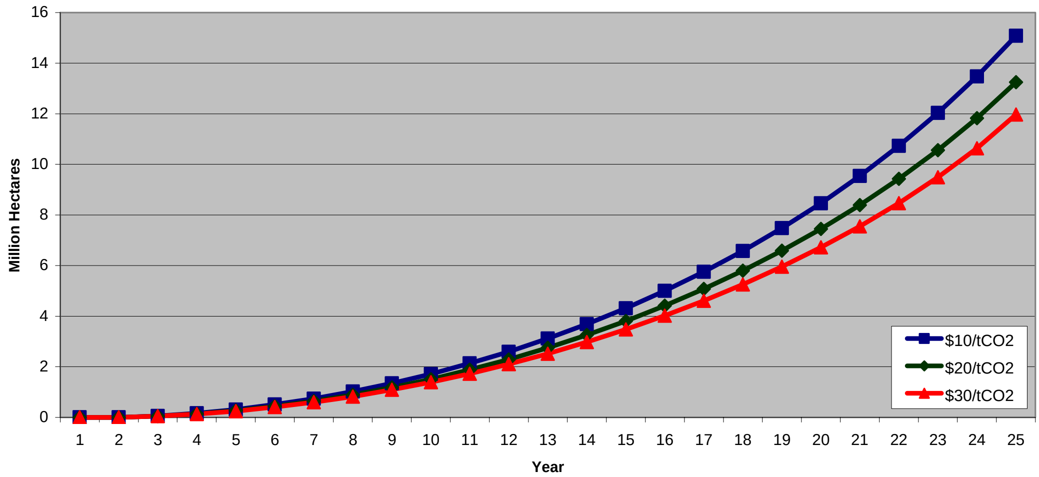

Figure 5b: Change in the global area of environmental forests under different carbon price trajectories relative to the reference case

It can be seen from figures 5a and 5b, that the purchase of new plantations for environmental forest and the total environmental forest areas are lower for higher carbon price trajectories. The modelling outcome that shows investment in environmental plantations being less attractive when compared with commercial plantation, under higher carbon price trajectories, requires more explanation.

Investors compare rates of return to decide whether to put their money into environmental or commercial forestry. Note that the rate of return on environmental forestry is governed by the growth rate of carbon taxes and the biomass. For commercial forestry, the rate of return is governed by the growth in stumpage (price) and the merchantable timber volume.

There are two things to note, first that commercial forests tend to be harvested when the average annual growth of the biomass is greater than the average annual growth of the biomass of environmental forests, which grow rather slowly as they mature. Secondly that higher carbon taxes make logs from native forest more expensive. This shifts the timber demand to commercial forests (which don't incur an emission charge). Preliminary analysis indicates that this substitution effect raised the stumpage in commercial forests, which grew faster than the carbon tax rate, set at 4 per cent in this exercise. This effect increased the rate of return on commercial plantation forestry faster than on the environmental forestry thus making commercial plantations more attractive to investors than environmental plantations under higher carbon price trajectories.

The results shown in figures 4a, 4b, 5a and 5b suggest the following proposition, which should be tested against real world data:

Proposition 1: Increasingly higher carbon price trajectories make environmental plantation forestry a less attractive proposition compared with commercial plantation forestry

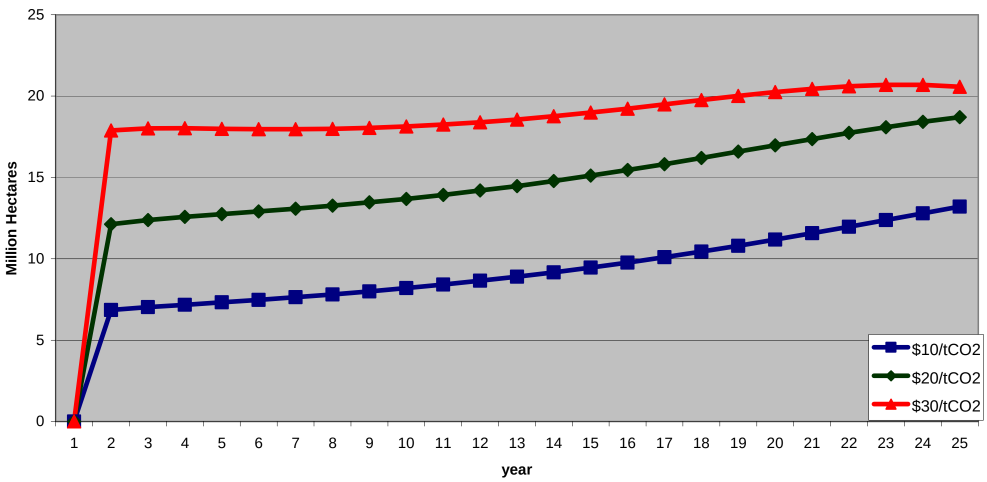

Figure 5c: Change in global total area planted under different carbon price trajectories relative to the reference case

Despite investment in environmental forestry being crowded out by increases in commercial forestry investment as carbon prices move on a higher trajectory, the total area planted each year rises with the rise in the carbon price. This result is shown in Figure 5c.

Land Clearing and Carbon Pricing

The main question asked in this paper 'does carbon pricing reduce land clearing?' can now be addressed. Simulation results that shed light on this question are shown in Figure 6. It is important to note that these results may be sensitive to modelling assumptions. In particular, the assumptions regarding the imposition of carbon price on sustainable harvesting of native forests.

Three trajectories of changes in native land clearing at the global level, under the three carbon price scenarios, relative to the reference case are displayed in Figure 6. Legal land clearing declines with a rise in the carbon price. A $30 carbon price trajectory reduces legal deforestation by about 6 million hectares per year in year one and this figure increases to about 13 million hectares per year by year 25. Land clearing is discouraged more by higher carbon price trajectories. Figure 6 also shows that the difference between the three trajectories is not that pronounced.

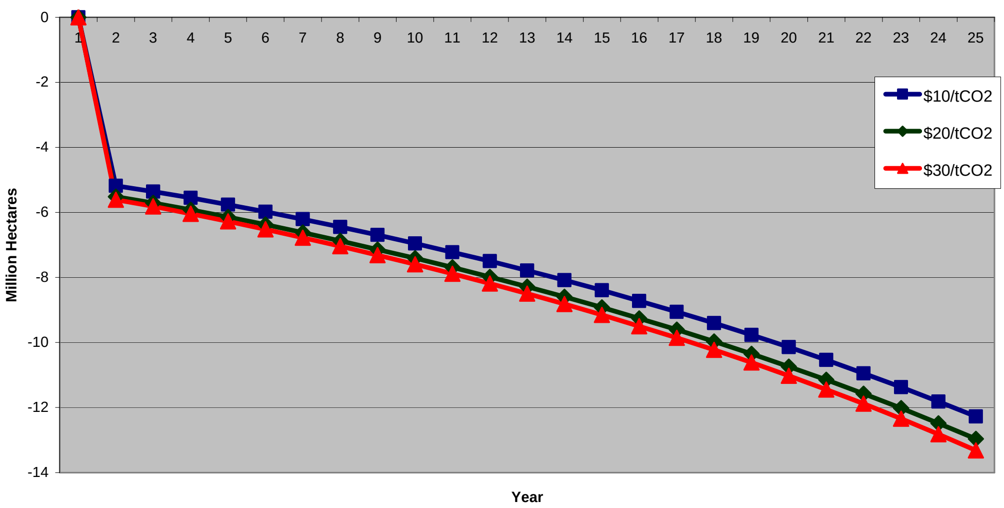

Figure 6: Changes in global land clearing under different carbon price scenarios relative to the reference case

Reduced deforestation also implies reduced carbon emissions. The estimated impacts of the three carbon price trajectories on net CO_2 emissions from land use change are shown in Figure 7.

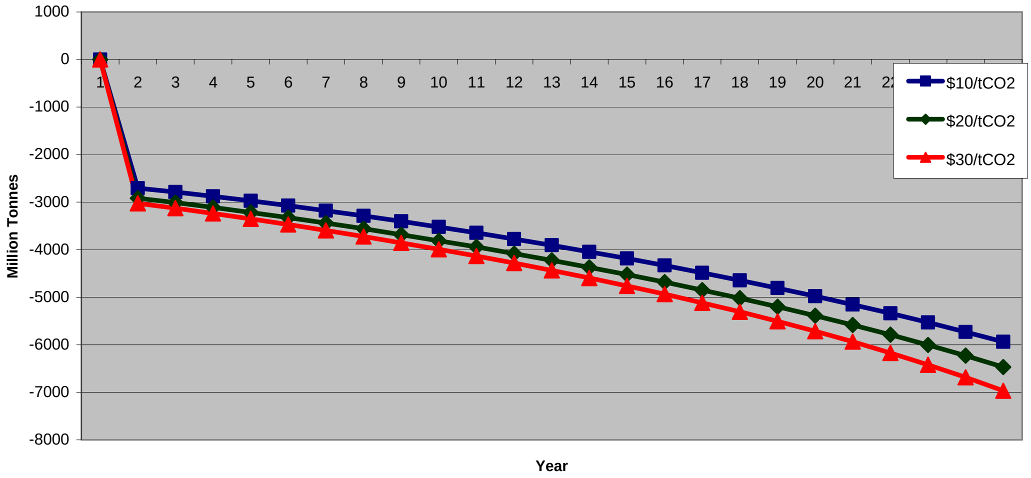

Figure 7: Deviation of CO_2 emissions from land use change activities under different carbon pricing scenarios relative to the reference case

Under the $30 carbon price trajectory the net emissions from the forestry sector are reduced by about 3 billion tonnes in year one and about 7 billion tonnes per year by year 25. A higher carbon price trajectory reduces land use change emissions by more than a lower carbon price trajectory does. The $10 trajectory lowers net emission by 2.7 billion tonnes in year one. This number increases to about 6 billion tonnes in year 25. Thus, moving the trajectory to from $10 to $30 will increase the forest sink by about one billion tonnes of CO_2 by year 25.

These simulation results show that imposing a carbon price will reduce deforestation. Although the numbers are based on a rough calibration, they still serve to illustrate the LUFC augmented model's capability.

Carbon Pricing and Illegal Land Clearing

In addition to the results presented above, the issue of whether reducing legal land clearing would result in a commensurate increase in illegal clearing of native forests were also examined. In this situation, the effectiveness of the carbon price in reducing net emissions from land use change would be reduced or even nullified.

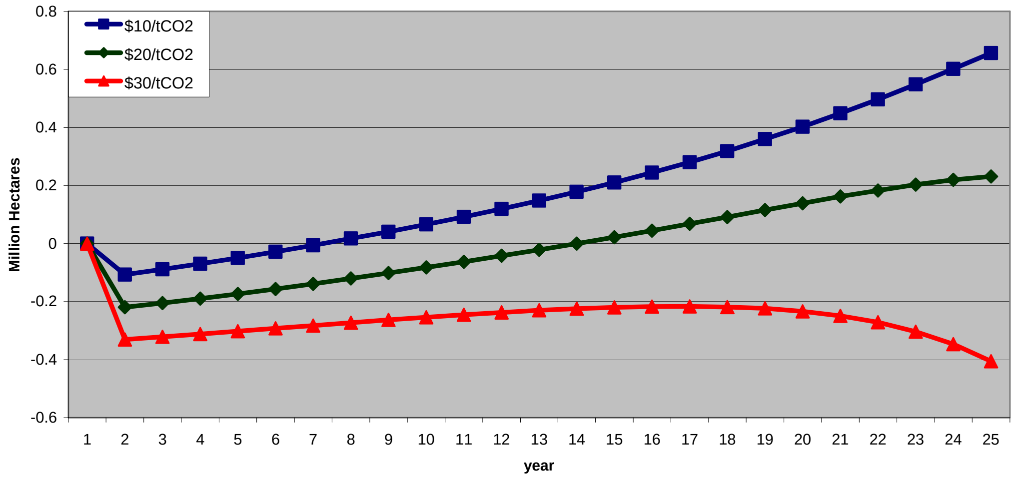

Figure 8: Change in the global area of native forests illegally harvested under different carbon price trajectories relative to the reference case

A reduced form equation was included in the model to capture illegal land clearing, carried out in response to higher land prices. The price elasticity of land clearing was exogenously set and the default values are reported in Table 3. It was assumed that 25 per cent of the potential log output from illegally cleared forest is sold to the market.

As might be expected, illegal land clearing initially declines, relative to the reference case in all three carbon price scenarios. But it increases over time after the initial adjustment of the first year and eventually crosses the X-axis under $10 and $20 carbon price trajectories. However, illegal land clearing remains less than in the reference case and actually declines further in the longer term under the $30 carbon price trajectory. Under lower carbon prices, there is an increase in the demand for land, which increases the price of land and encourages illegal land clearing. Higher carbon price trajectories make agriculture and livestock sectors less competitive due to their higher emissions intensities. This releases land from these sectors which causes prices to plummet. As shown in Figures 9 and 10 higher carbon price trajectories release increasing quantities of land from the cropping and livestock sectors.

These results are based on extreme scenarios and have been simulated using a stylised database. While these model results are internally consistent, they could change substantially under more plausible assumptions and a more realistic database.

A decline in the average land rentals and price will reverse the incentive to illegally clear land. Then illegal land clearing reduces relative to the areas harvested legally. This is a consequence of the arbitration applied to calibrate the module and the illegal logging function.

Proposition 2: In spite of illegal logging, higher carbon prices reduce native forest clearing and help avoid net emissions of CO_2 from land use change and forestry.

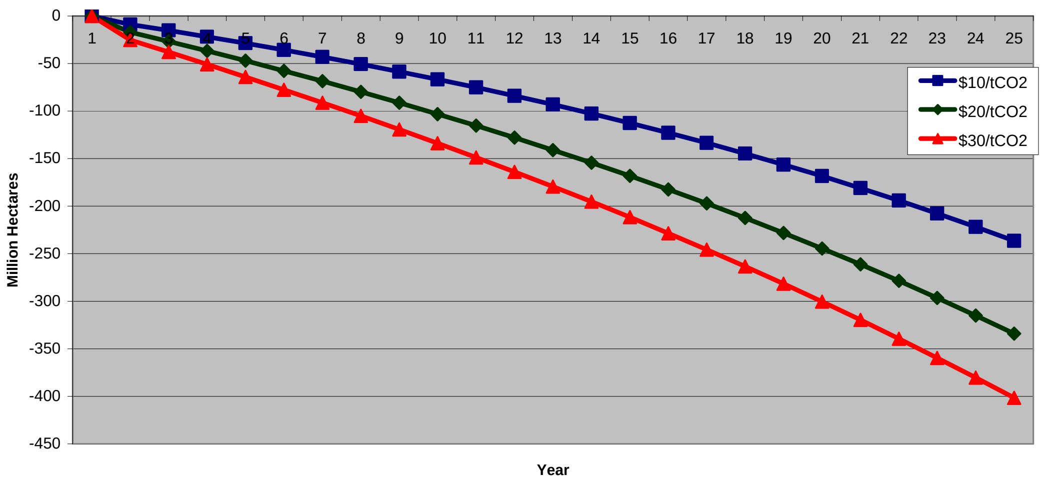

Figure 9: Change in land used for cropping under the three carbon price trajectories relative to the reference case

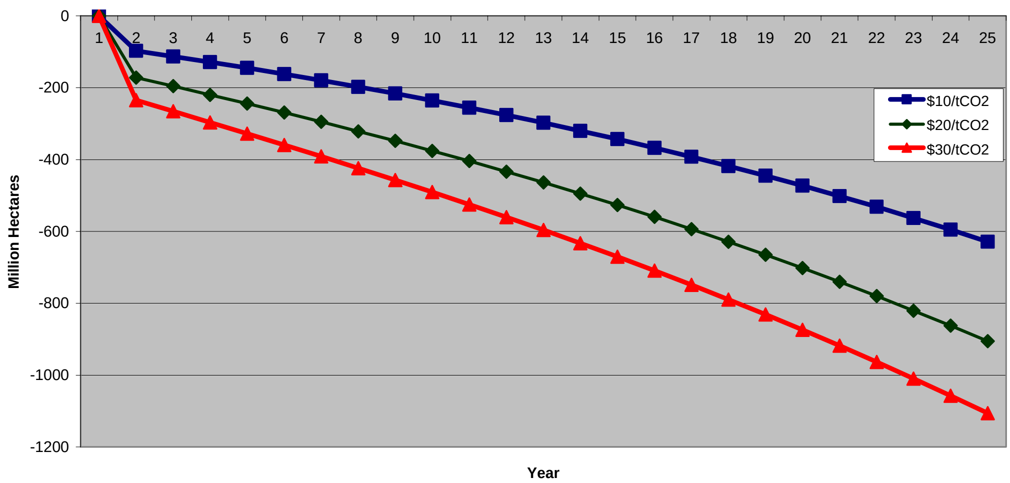

Figure 10: Change in land used by livestock under the three carbon price trajectories relative to the reference case

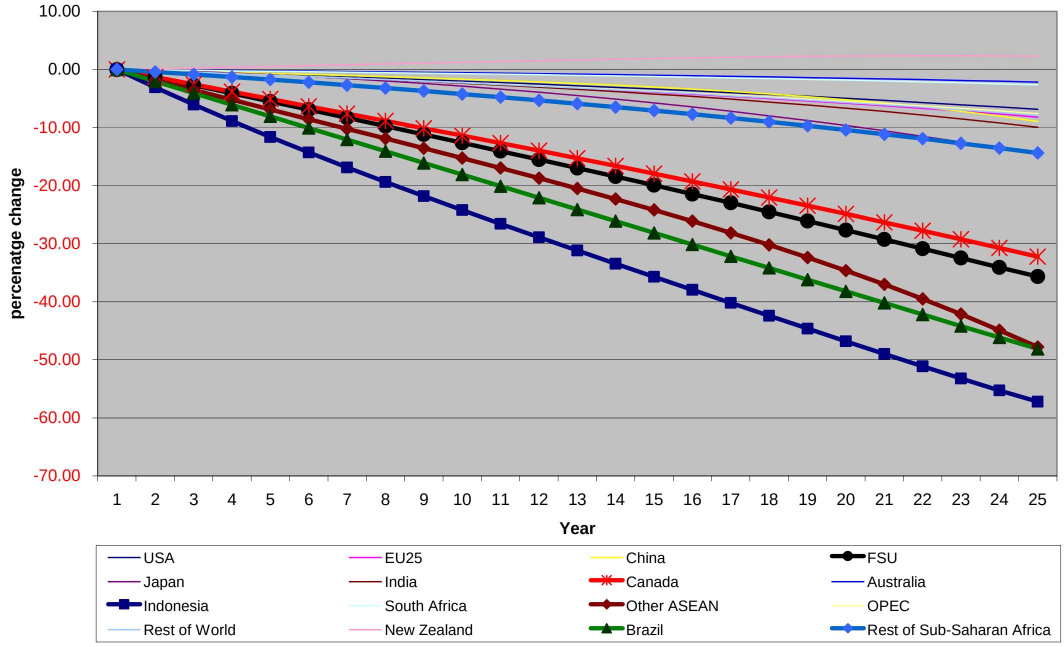

Figure 11: Percentage change in the contestable land supply under the $20+ 4 per cent per tonne tax on CO_2 emissions scenario relative to the reference case

As can be seen from Figure 11, land supply to the contestable market declines with higher carbon prices. There are two main reasons for this. First, land clearing declines in all carbon price scenarios relative to the reference case. This in turn reduces the land available for the contestable market. Second, tree planting for commercial and environmental forestry increases with rises in carbon price, which reduces annual land supplies for future years. The decline is more pronounced in countries, such as Indonesia, Brazil, and other ASEAN, than it is in others such as Australia. This could reflect the way the model parameters have been set. This means that the model needs to be parameterised correctly before it can be used for policy analysis.

10 Conclusions

Static and recursively dynamic CGE models have included a forestry sector, but they cannot capture the full input/output relationships of the forestry sector consistently. The key issue has been that input costs are distributed over a number of years and the output is produced at the end of a rotation length. As a result it was difficult to link the inputs applied in any period to the output it was contributing to. This difficulty has led to other inconsistencies not explored in the literature.

In order to address this problem, Pant (2010) outlined a theoretical framework. This framework divided the forestry sector into three parts, planting, holding and logging. Planting and logging activities were identified as any other production activity modelled in a CGE model while holding a plantation estate until it is profitable to harvest, was identified as an investment. The behaviour of investors and production sectors with a contemporaneous input/output relationship are a familiar concept, so the same approach can be applied to model these agents. However, numerical implementation of the framework remains a challenge as the database needed did not exist.

In this paper, the framework is implemented in a simplified way, with a stylised database and under some extreme policy scenarios. Some interesting forestry related insights are reported. Preliminary simulation results indicate that the imposition of a higher carbon price, discourages land clearing (legal and illegal), reduces net emissions from land use change, reallocates land from livestock production to forestry activity and encourages investment in commercial forestry rather than in environmental forestry as logs from commercial forests become more expensive because of the substitution effect.

The results reported in this paper are based on a stylised database and parameter values and an extreme set of assumptions. As such, they should not be used directly for policy design.

If these results and the analytical approach used encourage the development of a full forestry related database and a consistent disaggregation of the GTAP database then they will have made a useful contribution to methodological development in this field.

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