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An analytical framework for incorporating land use change and forestry in a dynamic CGE model

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Abstract

Forestry poses a challenge to computable general equilibrium (CGE) modellers working with recursively dynamic models. This is because of the lag between its inputs and output, which do not correspond to the same time period as other sectors. Inputs are applied for a number of years before a forest is ready for harvest. As a result, attempts in the past to incorporate a well-specified forestry sector in a recursive CGE model have been only partly successful. The purpose of this paper is to fill this gap by presenting a consistent analytical framework which can be used to incorporate forestry into a recursively dynamic global CGE model. A key feature of the framework is that it splits the forestry activity into three parts—planting, holding and harvesting. Planting and harvesting are done by standard production sectors and holding is done by investors, whose behaviour is already modelled in these CGE models. In addition, global forests are classified into three groups—commercial plantation forests, environmental plantation forests and native forests. All harvested forest land is made available for competition for alternative agricultural uses and will be allocated to the activity it is best suited for, given productivity differences for different activities. This framework can be used in a CGE modelling framework to support implementation of the proposed reduced emissions from deforestation and forest degradation (REDD) schemes as well as being applied to study land allocations, nationally and globally, across activities under alternative scenario assumptions. For example, the model can be used to project the effects on food production and prices of an increase in bio-fuel subsidies.

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1 Introduction

In a carbon constrained world with emissions trading, it is important whether land use, land use change and forestry (LUCF) is a net source or sink of carbon dioxide emissions. At the very least, this affects carbon prices. In 2000, estimated net emissions from the land use change and forestry sector accounted for about 20 per cent of global greenhouse gas emissions. Permanent conversion of native forest into agricultural land (including forest degradation) is the main reason for these emissions, and tropical countries, particularly Indonesia and Brazil, are the biggest emitters of land use change based net emissions. The key reason, which is active only in the tropical region, is the potential for increasing agricultural land by clearing native forest. Locally, each year between 1999 and 2007 (except 2003 and 2004 when the share was a bit lower) about 10 per cent of total carbon dioxide emissions in Australia came from net emissions of the LUCF sector (DCC 2009).

Deforestation can be viewed as an economic decision, which is primarily driven by higher rates of return to land in agricultural activities, including biofuel production, or sufficiently high timber prices combined with relatively low cost of clearing forests. Any sustained change in relative prices is likely to induce a corresponding change in the land use patterns of any country, including Australia. This has clear implications on all fronts including the net emissions profiles of countries, the scale and composition of their agricultural production and trade, and food prices.

Therefore, a good model for climate change policy analysis needs to have the capability to explain changes in net emissions from the land use change and forestry (LUCF) sector endogenously. Only such models can project net emissions of greenhouse gases more reliably as they take into account the underlying behavioural responses of the LUCF sector to altered economic incentives. The recommended climate change response policies would then be closer to the optimum or, alternatively, the assessment of the response policy would be more reliable. Similarly, a good model of welfare and global trade also needs to have a good LUCF module to be able to sensibly project the activity levels, output prices and trade of all land using sectors.

Modelling competition for land or other resources between a forestry sector and other agricultural sectors, such as crop production, is fraught with many problems especially in recursive models. This is because in recursive models it is assumed that all sectors can balance their books within a year; that is, their input costs and sales revenues are known within this period. This is not so with the forestry sector in which costs are incurred for a number of years and the sales revenue is realised at the end of the rotation length, which could be up to 50 years later (revenues from thinning are excluded). As a result, both the optimal rotation length and the demand price for land are not easy to determine for the forestry sector. This is why a properly specified land use, land use change and forestry module has thus far been absent from CGE models. Nevertheless, some sort of land competition based on relative rental rates can be found in many CGE models. However, the absence of a properly specified module renders these models less useful both in global climate change policy analyses and in projecting global emissions of greenhouse gases from deforestation of native forests for alternative land uses. Recent realisation of the importance of reduced emissions from deforestation and forest degradation (REDD) in reducing global costs of mitigation policies in the short run has raised the value of a model that can project baseline emissions from land use change endogenously. 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.[1]

1 See http://go.worldbank.org/57X9QKTON0 for details.

This paper outlines an analytical framework that consistently incorporates a well-specified module of land use, land use change and forestry into recursive dynamic CGE models. Specifically, it is designed to be incorporated into the global trade and environment model (GTEM), which is a recursively dynamic general equilibrium model of the global economy and environment developed at ABARE (Pant 2007).

The proposed framework divides global forests into three types—plantation forests, environmental forests and native forests. Plantation forests are harvested regularly, environmental forests are planted then left as carbon sinks and native forests are either left untouched, harvested as a renewable resource or cleared to make land available for alternative uses. The complexity of decision-making in these forestry activities, particularly in plantation forestry, is simplified by splitting a conventional forestry sector into three stages––planting stage, investment stage and harvesting stage. It is maintained that planting of trees and harvesting of forests will be done by separate sectors specialised for those activities. These sectors, like any other conventional production sector in a CGE model, have production functions which relate output in a year with inputs in the same year. As a result, books are balanced every year. In between the planting stage and harvesting stage, the plantation estates will be held by investors, who behave just like any other investors in a dynamic CGE model.

The partitioning of the forestry sectors into three parts is one of the key innovations proposed in this stage of model development. It allows investors to choose the length of rotation in plantation forestry to maximise their return subject to price expectations.

The possibility of selectively harvesting native forests as renewable resources by allowing them to regenerate naturally or harvesting to clear the land for alternative uses, including commercial plantation, is also modelled. In doing so, the approach of Golub, Hertel and Sohngen (2007) is followed to model the cost of accessing native forests but the cost function is specified somewhat differently in this study. This modification allows an additional calibration parameter to tune the rate of deforestation in response to economic incentives.

Productivity of a given type of land, such as forest land, is not the same across all uses. Therefore, a matrix of productivity coefficients, which are technologically given, is used to make sure that different types of land are concentrated more densely on different types of activities and the movement of land can be accounted for precisely in physical units.

In summary, this paper introduces a number of modelling innovations to put forward an analytical framework to incorporate a land use change and forestry module into GTEM, which is equally applicable to any other recursively dynamic global CGE model such as GTAP, or national models such as AusRegion. This framework can also be extended to be an integral part of a forward looking dynamic model. The key is to treat the future prices and other future variables as endogenous.

In this paper, the regional and specie dimensions of the variables are also suppressed for simplicity.

The remaining part of the paper is divided into nine sections. In section 2, a short review of the progress made so far in modelling LUCF activities in CGE models is provided, which shows there is a need for bringing insights from forestry economics in these modelling frameworks. In section 3 the basic principles of forestry economics are reviewed to determine the optimal rotation length of plantation forests.

Section 4 outlines the key features of the alternative modelling framework presented in the paper. In this framework, forests in each region are classified into three categories—commercial plantation forests, environmental forests and native forests. In section 5, the investor’s equilibrium is derived for plantation and environmental forestry sectors. In section 6, harvesting decisions for different forest types are modelled.

In section 7, profit conditions for the planting sector are specified and the market clearing condition is also given, establishing the equilibrium of the planting sector in the context of general equilibrium. In section 8, profit condition and market clearing condition for the logging sector are specified and the equations relevant to the land market are given in section 9. The paper is summarised in section 10.

2 Review of LUCF modelling in CGE models

Attempts have been made in the past to incorporate a LUCF module in GTEM (Ahammad and Mi 2005). This modelling work was inspired by the elaborate database on land use at a global scale (Lee, Hertel, Sohngen and Ramankutty 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 deriving a carbon accounting framework of the forest biomass that is informed by a 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 behaviourally and therefore could not identify deforestation of native vegetation as a major source of net greenhouse gas emissions. This limitation was later addressed by Golub et al. (2007) in which 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). With the possibility of native forest being cleared for agricultural use thus modelled, Golub and Hertel (2008) further analysed whether global integration (that is, more trade) would have implications in regional land use patterns and possibly deforestation.

These developments in GTEM and GTAP models were substantial. However, they still relied on exogenous determination of rotation length of forests as did other partial equilibrium models such as the one used in Lawson et al. (2008). Therefore, land rents offered by the forestry sector while competing 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 has two issues. First, it still needs to be integrated with a properly specified CGE model to take the full feedback into account and, second, it is also a single country model.

Because forestry involves a longer time horizon, from plantation to harvesting, output harvested in any one year depends on the inputs applied over a number of previous years. This is not the case with a standard production sector model in recursively dynamic CGE models. Outputs produced by these sectors depend on the inputs applied in the same year. Therefore, consistent modelling of input demand, particularly competition for land between these asynchronous sectors, becomes extremely problematic. It is difficult to determine how current input demands of the forestry sector can be related with the future output they will contribute to.

Many CGE models, including GTEM and GTAP, are recursive. This means that agents in these models cannot make informed decisions in choices that depend on future values of variables, such as the price a plantation forest will fetch at its harvest time down the track and its output level at that time. Nevertheless, these models use relativities of current rental rates to allocate land between forestry and other land using activities. Therefore, the demand price of land offered by the forestry sector in these models has remained ill specified. As a result, the responses of the forestry activity to policies such as carbon credits on sequestration services are not fully and properly captured.

Moreover, many of these models, except Golub et al. (2007), Golub and Hertel (2008) and Hertel et al. (2008), have so far failed to distinguish between native forests and plantation forests, which in itself is a significant limitation. This is the case because clearing of native forest is a major source of additional agricultural land and the major cause of land use change based carbon dioxide emissions. Agricultural activities have been able to get the supply of land increased mainly by clearing native vegetation, not by reducing plantation forests.

Further, it is not uncommon to find that the approach followed in these models implies that increased harvesting of forests leads to increased demand for land (or natural resources) 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 currently lack the ability to explain the extent of deforestation associated with increased timber harvests from native forests which is a worry from an environmental point of view. In addition to this, a clear accounting of land movements between the activities in physical units has not yet been instituted in these models.

In summary, significant progress has been made in modelling LUCF in CGE models but so far they have not been able to benefit from the insights forestry economics can offer as the modules suffer the limitations described above. In this stage of model development, some of these issues will be considered.

3 Insights from forestry economics

One of the principal issues for this modelling exercise is to explain the equilibrium of the investor in the forestry sector and determine the forest rotation length endogenously. The equilibrium of the planting and the logging sectors are more or less standard and do not need any special treatment. In the following section forestry economics literature that is concerned with the determination of the optimal rotation length is first reviewed. This insight is then used to establish equilibrium behaviour in the investors in both commercial and environmental forestry in the following sections.

Virtual rental rates for forest land with given rotation length

The virtual rental rate of forest land is the annuity equivalent to the net present value of its future harvests. A formal statement follows.

Let $Y(a)$ be the yield (cubic meter of timber) per hectare of forest harvested (sold to the loggers) at age a, P_f be the price of the logs received from the loggers (stumpage) at the time of harvest, $G(.)$ be the present value cost per hectare excluding land rentals of the forest land for keeping the forest stand (plantation and growing costs) and r be the discount rate that is based on the market interest rate. The net present value of the forest land is then given by:

(1) $$NPV_1(a) = Y(a)P_f e^{-ra} - G(.)$$

where a is the length of a single rotation of the forest.

Note that $G(.)$ represents all costs of planting in a hectare of forest land and may include present value of all maintenance costs net of incomes from thinning and other silviculture activities.

The annuity X of this NPV_1, which represents the maximum annual rent a forest investor can afford to pay for the land, is the virtual rental rate of the forest land. The virtual rental rate X satisfies the following condition:

(2) $$X = \frac{[P_f Y(a)e^{-ar} - G(.)](e^r - 1)}{(1 - e^{-ar})}$$

The rental rate offered rises with the price of logs and timber yield and falls with an increase in the cost of other inputs, given the discount rate.

Given prices and yield functions, land will move at the margin into forestry activity as long as the rental rates offered by the forestry sector are sufficiently higher (allowing for any imperfect mobility of land) than the rental rates offered by alternative uses including annual cropping activities.

The above derivation of the virtual rental rate on forest land, given by equation (2), assumes that the rotation length a is given. It may be possible to increase the land rental by varying the rotation length. Hence, the next problem is to find the optimal length of forest rotation a in the following sections.

The optimal length of forest rotation

The key problem faced by an investor on a tract of forest land is to decide on when to harvest the plantation forest so that the profits (land rents) are maximised.

Since land rents are paid out over a number of years, a single quantity has to be identified as the maximand, which depends on the length of forest rotation. As there is a possibility of expressing the maximand in many different forms, choice of its particular form has been a basis for alternative formulation of the problem and thus the alternative solutions. The following maximands are commonly suggested in choosing the rotation length: (a) maximise the sustainable yield (MSY) from the forest land, (b) maximise the net present value of all the rents attributable to the forest land over a single rotation, (c) maximise the annual average of the net present value of the land rent over a single rotation, and (d) maximise the net present value of the rent attributable to land over all future rotations (Samuelson 1976).

The MSY approach

The sustainable yield is defined as the maximum annual harvest that can be maintained forever from a given parcel of land. Given a yield function $Y(a)$ defined over the age a of the tree, the MSY is obtained by choosing the rotation length a of the forest which maximises $Y(a)/a$ (Pearse 1990; Samuelson 1976).

In other words, the problem can be stated as:

(3) $$\max_a \frac{Y(a)}{a}$$

This problem is solved at $a = a^*$ if we have:

(4) $$Y'(a^*) = Y(a^*) / a^*$$

where the primes denote the first derivative[2].

Equation (4) means that when the average annual cumulative yield equals the annual increment of the timber yield from the forest, the optimal rotation length of the forest is attained and it is profitable to harvest at this point. This is the point at which the sustainable yield, defined as above, is maximised. Beyond this age, annual increments will be less than the cumulative average yield and therefore the cumulative average yield will start to fall.

2 If log prices depend on age and the foresters maximise value rather than output, then the maximisation problem would be modified slightly and the optimal condition becomes $Y' = Y/a - Y(P'/P)$. This possibility will be ignored at this stage and log price will be treated independently of age.

As discussed in Samuelson (1976), this approach ignores the cost of resources used in managing forests, including the opportunity cost of land. It gives the optimal rotation length for forestry activities carried on land that have no opportunity cost and the planting and maintenance costs are zero. Therefore, the rotation length determined this way may not be optimal in managed forestry.

The Fisher's formula

The second approach, which maximises the net present value of the total land rent over a single rotation, is also known as the Fisher's formula (Fisher 1930). It takes account of the plantation and maintenance cost. The optimal rotation length under this rule is derived by solving the following problem:

(5) $$\max_a NPV_1(a) = \max_a (P_f Y(a) e^{-ar} - G(.))$$

The first order condition for the maximum is:

(6) $$\frac{Y'(a^*)}{Y(a^*)} = r$$

The condition (6) means that the forest is due for harvesting when the annual growth rate of timber in the forest is equal to the market rate of interest. This condition is known as Fisher's condition.

Holding the forest for one more year does not increase the revenue sufficiently to compensate for the interest income that can be obtained if the forest is harvested at age a^* and the proceeds are invested at the market rate. Prices are assumed to remain unchanged in this formulation.

Clearly, conditions (4) and (6) yield the same rotation length if:

(7) $$r = 1/a^*$$

Condition (7) may imply a rule of thumb that at a 5 per cent interest rate the forest would be cut down at 20 years of age. However, there is no guarantee that harvesting at the age equal to the inverse of the rate of interest would also satisfy the condition (6) because the yield function is independent of the interest rate and different species, such as soft wood and hard wood, have different growth functions. This means that the MSY approach and the Fisher's formula do not necessarily yield the same rotation length for any given forest.

Modified Fisher's formula

It is possible that an investor might choose the rotation length to maximise the annual average of the net present value of the land rent, rather than maximise the net present value of the total land rent. This approach is much closer to the MSY when the costs of planting and management are taken into account. Under this approach the modified problem can be specified as:

(8) $$\max_a NPV_1(a)/a = \max_a (P_f Y(a) e^{-ar} - G(.))/a$$

The first order condition for the maximum yields:

(9) $$\frac{Y'(a^*)}{Y(a^*)} = r + \frac{1}{P_f Y(a^*)} . \frac{(P_f Y(a^*) - G(.) e^{ra^*})}{a^*}$$

Noting that $(P_f Y(a^*) - G(.)e^{ra^*})$ gives the profit from forestry at current value which will be paid to land over a^* number of years, $(P_f Y(a^*) - G(.)e^{ra^*}) / a^*$ gives the imputed land rent should the forest be maintained without harvesting for one more year. Therefore, the second term on the right hand side of equation (9) gives the required adjustment on the Fisher's formula to allow for the opportunity cost of land in addition to the lost interest that needs to be recovered from the increased output should the harvesting decision be delayed by one year. In other words, equation (9) is a revision of the standard Fisher's formula that allows for the opportunity cost of land with the interest rate in determining the opportunity cost of keeping the forest for one more year.

The Faustmann formula

Alternatively, an investor may choose the rotation length to maximise the net present value of the land rent from all future rotations, not just from a single rotation, under the assumption that this land would always be planted with the same species of trees, with the land dedicated to forestry.

Let $NPV_1(a)$ denote the net present value of a hectare of forest land from a single rotation of length a years. The net present value from all future rotations of the same length is given by:

(10) $$NPV(a) = \frac{NPV_1(a)}{1-e^{-ra}} = \frac{P_f Y(a)e^{-ra} - G(.)}{1-e^{-ra}}$$

A key assumption used here is that in each rotation the net present value of income from the forest at the time of plantation is the same across all rotations. This assumption is consistent with recursive models.

A forest land owner will want to choose the rotation length to maximise the net present value of the income from the forest land from all future rotations, rather than just from one rotation. The solution to this problem is known as the Faustmann formula, which was established by M. Faustmann in 1849 (reprinted as Faustmann 1995). A land owner's problem can be specified as:

(11) $$\max_a NPV(a) = \max_a \frac{NPV_1(a)}{1-e^{-ra}} = \max_a \left\{ \frac{P_f Y(a)e^{-ra} - G(.)}{1-e^{-ra}} \right\}$$

Samuelson (1976) observed that Faustmann's optimal rotation length derived from maximising the net present value of land rents from infinite rotations, as done by Faustmann, is the same as the optimal rotation length obtained by maximising the annuity, or annualised rent payments to the forest land owner, in a single rotation. To see this we can specify the problem as:

(12) $$\max_a R(a)$$

$$\textit{subject to} \quad [P_f Y(a)e^{-ra} - G(.) - R\int_0^a e^{-rt}dt] = 0$$

After integrating, the problem can be restated as:

(13) $$\max_a R(a)/r = \max_a \left\{ \frac{P_f Y(a)e^{-ra} - G(.)}{1-e^{-ra}} \right\}$$

Clearly, for given r, the value of a, the length of rotation, that solves the problem specified in equation (13) also solves the problem specified in equation (10). Hence, Faustmann's rule can also be understood as the rule that chooses the rotation length to maximise the annuity payments (or the uniform current value annualised rental rate for the forest land) spanning over the horizon of a single rotation.

To find Faustmann's solution, both sides of equation (10) (or equation (13) by implication) are differentiated with respect to the rotation length a.

(14) $$P_f Y'(a^{**}) - rP_f Y(a^{**}) = r\frac{NPV_1(a^{**})}{1-e^{-ra^{**}}}$$

Equation (14) is Faustmann's famous equation. It has the following interpretation.

The right hand side of equation (14) is $r.NPV(a^{**})$, which is the annuity, or the virtual land rent, that can be expected from the expected wealth value of the forest land at interest rate r. The left hand side consists of two parts: the value of the marginal increase in log output if the forest is kept for one more year, and the loss in interest income (opportunity cost) for one year for not harvesting the forest in the year a^*. By rewriting equation (14) using (13), the following is derived:

(15) $$P_f Y'(a^{**}) = rP_f Y(a^{**}) + R^{**}$$

where R^{**} is the maximised annual rental payment for land.

The optimal rotation length a^{**} is thus obtained when the value of increased log output as a result of holding the forest for one more year is equal to the sum of the interest income foregone by not harvesting and the virtual rent of the land for one more year.

A comparison of Faustmann's formula and modified Fisher's formula

To compare the two formulae, equation (14) is rewritten as:

(16) $$\frac{Y'(a^{**})}{Y(a^{**})} = r + \frac{r}{P_f Y(a^{**})}.\frac{NPV_1(a^{**})}{1-e^{-ra^{**}}}$$

Using (1) equation (16) can be rewritten as:

(17) $$\frac{Y'(a^{**})}{Y(a^{**})} = r + \frac{r}{P_f Y(a^{**})}.\frac{[P_f Y(a^{**}) - G(.)e^{ra^{**}}]}{e^{ra^{**}}-1}.$$

Since $e^{ra^{**}} \approx 1 + ra^{**}$, taking only the first order in the Taylor expansion, equation (17) can be simplified to obtain:

(18) $$\frac{Y'(a^{**})}{Y(a^{**})} = r + \frac{1}{P_f Y(a^{**})}.\frac{[P_f Y(a^{**}) - G(.)e^{ra^{**}}]}{a^{**}}$$

A comparison of the right hand side of equation (18) with the right hand side of equation (9) shows the symmetry of the modified Fisher's condition with that of Faustmann. As equations (9) and (18) show, they are identical and hence will produce identical rotation length $a^{*}=a^{**}$.

In the above conclusion, it is maintained that $e^{ra^{**}} \approx 1 + ra^{**}$. However, since

(19) $$e^{ra} = \sum_{n=0}^{\infty}\frac{(ra)^n}{n!} = 1 + ra + \frac{(ra)^2}{2!} + \frac{(ra)^3}{3!} + ...$$

it can be observed that

(20) $$e^{ra^{**}} - 1 = ra^{**}(1+\nu)$$

where

$$\nu = \frac{(ra^{**})^{2-1}}{2!} + \frac{(ra^{**})^{3-1}}{3!} + \ldots$$

Using equation (20) in equation (17) gives:

$$\frac{Y'(a^{**})}{Y(a^{**})} = r + \frac{1}{P_f Y(a^{**})} \cdot \frac{[P_f Y(a^{**}) - G(.)e^{ra^{**}}]}{a^{**}(1+\nu)} \quad (21)$$

1 Rotation length and the value of the second and higher order terms
(interest rate of 4 per cent a year)

number of rotations	length of a rotation (years) 1	10	20	30	40	50	80	100
1	1	1	1	1	1	1	1	1
2	0.020	0.200	0.400	0.600	0.800	1.000	1.600	2.000
3	0.000	0.027	0.107	0.240	0.427	0.667	1.707	2.667
4	0.000	0.003	0.021	0.072	0.171	0.333	1.365	2.667
5	0.000	0.000	0.003	0.017	0.055	0.133	0.874	2.133
6	0.000	0.000	0.000	0.003	0.015	0.044	0.466	1.422
7	0.000	0.000	0.000	0.001	0.003	0.013	0.213	0.813
8	0.000	0.000	0.000	0.000	0.001	0.003	0.085	0.406
9	0.000	0.000	0.000	0.000	0.000	0.001	0.030	0.181
10	0.000	0.000	0.000	0.000	0.000	0.000	0.010	0.072
11	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.026
12	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.009
13	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003
14	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
15	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SUM	1.020	1.230	1.532	1.933	2.471	3.195	7.354	13.399

2 Rotation length and the value of the second and higher order terms
(interest rate of 5 per cent a year)

Number of rotations	length of a rotation (years) 1	10	20	30	40	50	80	100
1	1	1	1	1	1	1	1	1
2	0.025	0.250	0.500	0.750	1.000	1.250	2.000	2.500
3	0.000	0.042	0.167	0.375	0.667	1.042	2.667	4.167
4	0.000	0.005	0.042	0.141	0.333	0.651	2.667	5.208
5	0.000	0.001	0.008	0.042	0.133	0.326	2.133	5.208
6	0.000	0.000	0.001	0.011	0.044	0.136	1.422	4.340
7	0.000	0.000	0.000	0.002	0.013	0.048	0.813	3.100
8	0.000	0.000	0.000	0.000	0.003	0.015	0.406	1.938
9	0.000	0.000	0.000	0.000	0.001	0.004	0.181	1.076
10	0.000	0.000	0.000	0.000	0.000	0.001	0.072	0.538
11	0.000	0.000	0.000	0.000	0.000	0.000	0.026	0.245
12	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.102
13	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.039
14	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.014
15	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.005
SUM	1.025	1.297	1.718	2.321	3.195	4.473	13.399	29.481

Equation (21) shows that whether the optimal rotation lengths of a given forest are different between the modified Fisher's rule and Faustmann's rule depends on whether $\nu = 0$. The respective rotation lengths would be close to each other if ν, which is the sum of the second and higher order terms in the expansion of e^{ra}, is close to zero (that is, only the first order terms in the expansion matters), otherwise they will be different. Tables 1 and 2 provide numerical values of $(1+\nu)$ for interest rates 4 and 5 per cent, respectively.

Entries in table 1 show that the sum of the infinite series is stabilised well below 15 terms for many rotation lengths. The sum, representing $(1+\nu)$, increases with the rotation length. The sum is approximately equal to 1 if the rotation length is 1 and becomes 13.4 if the rotation length of the forest is 100. The same pattern can be observed in table 2. A comparison of the series sums provided in the two tables show that the value of $(1+\nu)$ rises with an increase in the interest rate and an increase in the length of rotation.

It is easy to see that equation (9) is a particular case of equation (21). Hence, the behaviour of both the modified Fisher's condition and Faustmann's condition can be represented by incorporating equation (21) in the calculations.

Given $\nu > 0$ for all reasonable values of the interest rate and length of forest rotation, and that the yield function is concave in the age of forest, it can be deduced that the Faustmann's rotation length a^{**} is longer than a^{*}, the optimal rotation length given by the modified Fisher's formula for a given yield function. This is a well known result in forestry economics literature (see Samuelson 1976).

Discussion

The key difference between the four different methods described above of determining the optimal length of forest rotation is in the maximand used by the forest landowner/investor. Although each one may be more relevant in a particular circumstance than the rest, they all share one common characteristic. None of them separate the land owner's problem from the problem of an investor in forestry activity. Land owners and investors are treated as the same when looking at who maximises the rental income on land. However, they face different market incentives—land owners can avoid risks and future uncertainties by simply renting out land on an annual basis, while forestry investors cannot.

4 An alternative framework for modelling LUCF (3 forests X 3 decisions)

In this section an alternative framework for modelling LUCF in a recursively dynamic CGE model is proposed. To assist in the modelling work, forests in all regions are grouped into three categories: plantation forest, environmental forest and native forest. Plantation forests, also referred to as managed forest or commercial forest, are planted with a view to maximise profits from harvests. Environmental forests are planted for environmental services, in particular for carbon sequestration services, and will never be harvested. These plantations are driven by carbon credits and hence have to be maintained forever. It is assumed that once planted these forests will grow and be maintained as untouched native forests, with regeneration balancing against dead trees. Fire and disease risks are ignored. Native forests exist naturally. A region can harvest it selectively as a renewable resource or clear fell to make the land available for alternative uses, which would represent land use change.

In principle, as shown in table 3, each type of forest will require three types of separate decisions: planting, investing and harvesting (logging).

3 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 loggers and the cost of planting and rent paid annually for the land occupied by the managed forest offers an opportunity for investors to make some money by holding the plantation until it matures. Similarly, the carbon credit revenue in excess of the cost of planting and land rent provides an opportunity to earn profit from environmental plantation. The value of logs harvested in excess of the access and harvesting cost provides incentive to selectively harvest native forests. The net present value of rents that can be expected from alternative use of land over the net cost of clearing the native forest provides incentive to clear the native forest.

An analytical framework is outlined in the following section that stylises the separate behaviour of plantation and logging sectors and the investors holding interests in different forest types.

The partition of the forestry sectors into three parts is one of the key innovations proposed in this modelling development. It allows the investors to choose the length of rotation in plantation forestry to maximise their return. The possibility of selectively harvesting native forest as a renewable resource by allowing it to regenerate naturally and harvest and clear the land for alternative uses, including commercial plantation is also modelled. Golub et al. (2007) is followed in modelling the cost of accessing native forest but specify the cost function somewhat differently in this study. This modification allows an additional calibration parameter to tune the rate of deforestation in response to economic incentives.

The planting sectors

The planting stage covers one year in which the planting sector bids for land, plants seedlings of a variety of species and sells the estate to the plantation investors. The production function is fairly standard, with constant returns to scale, and the sectors sells the product at market prices. It is maintained that all input and output markets are competitive. The planting sector bids for land with other sectors, including agriculture. The rent it can offer for the land therefore depends on the price at which it can sell its plantation estates to the investors. Clearly, the standard zero profit condition determines the scale of operation of the plantation sector as well.

Forestry investors

Investors on commercial plantation buy or lease the land planted with trees and hold onto it until the forest is harvested. The expected revenue from the sale of trees over the cost of investment provides investors with a rate of return on their investment. Investors on environmental forests buy the land planted with trees upfront and leave it under forest forever. They can claim income flow from the sale of carbon credits for the sequestration service provided by the forest. Other environmental services provided by the forest are ignored in the model 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 the rates against the opportunity cost of capital, which is taken as the rate of return on investment in physical capital. At this stage, the risk differences are also ignored. In the case of commercial forests, investors choose the optimal rotation length that maximises the expected rate of return on their investment.

Logging sectors

Logging sectors buy tracts of forests from investors and harvest the timber. These sectors also follow the standard behavioural rule as followed by other production sectors. In the final analysis, they earn zero profits, minimise cost of inputs and behave competitively in all markets. The price they offer to investors is the stumpage price, the difference between the price received from the millers less the cost of harvesting and transporting, which is the sum of all input costs excluding the cost of trees or forest capital. This provides the link between prices of forest products and the stumpage, which in turn determines rent that the planting sector can offer in the market to bid for the land.

Because the behaviours of the planting sector and the logging sectors are much the same as that of any standard production sector in GTEM, the key modelling issue is the description of the behaviour of the investors in plantation estates and environmental forests. These two are distinguished between and their behaviours outlined below.

5 Modelling investors problem in the forestry sector

As discussed above, the managed forestry (plantation forestry) sector can be viewed as consisting of three stages—plantation stage, capital formation stage and harvesting stage. The behaviour of the actors involved in the plantation and harvesting are the same as any sector in GTEM and therefore do not need any special discussion here. The behaviour of these sectors will be referred to only in those situations in which they need special treatment. The key problem is to model the behaviour of the investors with respect to the purchase of the plantation estate and the decision to harvest it.

An investor's problem in managed forestry

Suppose a forest investor can buy a one year old plantation estate at price G per hectare and that it has to pay the market clearing rental rate R per year for the land until it is harvested. Assume $Y(a)$, a quasi concave function, gives the timber yield in cubic meters per hectare by age a of the forest and that the stumpage is expected to be the current price P_f per cubic metre of merchantable timber.[3] The expected rate of return on a dollar invested in forest would then be given by:

$$\rho_f(a) = \frac{1}{a}\left[\ln(P_f Y(a)) - \ln[G(.) + \int_0^a \mathrm{Re}^{-rt}\, dt]\right] \qquad (22)$$

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

3 Static expectation is used in this module to be consistent with the recursive modelling approach of GTEM.

After integration, equation (22) can be written as:

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

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 maximization of the rate of return is given by:

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

which can be written, using equation (23), as:

(24b) $$\frac{Y'(a)}{Y(a)}=\rho_f(a)+\frac{e^{a(\rho_f-r)}R}{P_f Y(a)}$$

Alternatively, equation (24b) can be written as:

(24c) $$P_f Y'(a)=\rho_f(a)P_f Y(a)+e^{a(\rho_f-r)}R$$

The first term on the right hand side of equation (24) is the rate of return on forest investment. The denominator of the second term on the right hand side of equation (24) represents the present value of the investment cost and the numerator is the present value of the land rent payable for the final year. The left hand side of equation (24) represents the annual growth in timber stock for 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 (24b). Equation (24) becomes identical to equation (15) if $\rho_f=r$. In this case, the optimal rotation length will be the same as that under the Faustman–Samuelson framework. As equation (24c) 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 loss in income from forest capital for one year plus the additional rental cost.

If $\tilde{a}$ is the rotation length that maximises the rate of return for the investor, the optimised rate of return on forestry investment can be represented by

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

Investors in general would maximise their income by allocating investible funds to alternative forms of investment so that the (risk adjusted) rates of returns are equalised across all investment opportunities. This rule is represented here as:

(26) $$\rho_f(\tilde{a})=r$$

The level of investment in acquiring new forests $I_f(0)$ is determined by equation (26) as investment is the instrument available with the investor to have the condition satisfied. Higher level of investment would increase the demand for planted land, the output of the planting sector and, hence, the land rental. It would perhaps also increase the cost of planting per hectare and therefore lower the rate of return. In a forward-looking model, this is also expected to lower the stumpage at the time of harvest which will further reduce the rate of return on investment as shown by equation (25).[4]

4 The effect on the rate of return operating via the stumpage indicates that a recursive model overstates the investment in forestry relative to a model with forward-looking agents.

Proposition 1: *The optimal rotation length given by the Faustmann–Samuelson condition and that given by the condition that maximises the rate of return on forestry investment are equal.*

Proof: This result follows from equations (25), (26) and (13). QED

The beauty of this result is that we are able to validate the separation of the forestry activity into three stages—planting, investing (capital formation) and harvesting—while remaining in line with the time-honoured Faustmann–Samuelson condition.

The demand for currently planted land, forest of age 0, by investors is thus given by:

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

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

Note that $R(1 - e^{-\tilde{a}r})/r$ gives the present value of the lease cost of the land per hectare for the length of the forest rotation. In writing equation (27) it is maintained that the investor pays land rental each year at the market rate, a future liability is thus created. The investor takes this future liability into account and the lease costs are set aside from the investment budget before the plantations are purchased. Hence, the actual investment on plantation forest, excluding the land rentals, is given by:

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

Equation (26) derives the level of financial investment committed in newly planted forests and equation (27) determines the area of new plantation demanded by investors over the year.

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

(29) $$I_f^s(a) = F^M(a) * (R + M) \text{ for all ages } a \geq 1$$

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. 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 or sunk. At this stage of model development, the existence of silviculture activities is ignored and $M=0$ is set.

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

So far the per hectare yield function has been used in a generic form. To come to a usable model of land use change and forestry, the function needs to be specified and parameterised. As the database compiled by Sohngen et al. (2009) will be used for the numerical specification of the model, it is natural to use the function they have suggested.

Sohngen et al. (2009) make a distinction between a carbon yield function and merchantable timber yield function of a forest. Trees do not deliver a merchantable timber yield until they are of a certain age, depending on the species and the location, but they sequester and store carbon while they grow from an early stage. Sohngen et al. (2009) specify carbon yield function as:

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

while the merchantable timber yield function is given by:

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

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

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

(32) $$\overline{Y}^M = \overline{Y}^C = \mathrm{e}^{\alpha}$$

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

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

For $a > \gamma$, logarithmic differentiation of equation (31) is taken with respect to a to get

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

Using equation (33) in equation (24b), while taking note of equation (26), yields:

(34) $$\frac{\beta}{(a-\gamma)^2} = r + \frac{R}{P_f Y^M(a)}$$

Now we can solve equation (34) for the optimal harvesting age $\tilde{a}$ for the plantation forest being considered. Equation (34) is nonlinear, given equation (31). However, the denominator of the second term on the right hand side of equation (34) represents the stumpage value of a hectare of the forest being harvested in a years time. This is expected to cover the land rental for the same period, plantation cost and other maintenance cost over time. The numerator of the same term is the expected land rental per hectare for one year. This ratio could be small for forests that have a long rotation length. Ignoring the cost of land rent for now, and solving equation (34) for the rotation length gives:

(35) $$a = \gamma + \sqrt{\frac{\beta}{r}}$$

Differentiating equation (35) with respect to r then gives:

(36) $$\frac{da}{dr} = -\frac{(a-\gamma)}{2r} < 0 \quad \textit{for} \quad a > \gamma .$$

The rotation length shortens for a rise in the market rate of return (or the discount rate). This result is the same as that derived from Fisher's formula.

If the effect of land rentals is taken to be significant in size relative to the size of the discount rate, equation (34) implies that the rotation length also depends on the equilibrium land rental rate and the stumpage.

To see how the optimal harvesting age responds to changes in these variables equation (34) is differentiated to get:

(37) $$da^* = \frac{1}{\theta} dr + \frac{1}{\theta P_f Y^M} dR - \frac{R}{\theta P_f^2 Y^M} dP_f$$

where

(38) $$\theta = \left(\frac{R}{P_f Y^M} \frac{dY^M}{da^*} \frac{1}{Y^M} - \frac{2\beta}{(a^* - \gamma)^3} \right)$$

As can be seen from equation (38), the sign of θ cannot be assigned a priori without specifying the values of various parameters and variables involved. A reasonable assumption can still be made on their ranges and a meaningful sign assignment can be established.[5]

First equation (29b) is used in equation (38) to get:

(39) $$\theta = \left(\frac{R}{P_f Y^M} \left(r + \frac{R}{P_f Y^M} \right) - \frac{2\beta}{(a^* - \gamma)^3} \right)$$

On simplification using equation (34), equation (39) can be rewritten as:

(40) $$\theta = \left(\frac{\beta}{(a-\gamma)^2} - \frac{1}{(a-\gamma)} \right)^2 - \frac{1}{(a-\gamma)^2} (1 + r\beta)$$

$\theta < 0$ if [6]

(41) $$(1 + r\beta) > \left(\frac{\beta}{(a-\gamma)} - 1 \right)^2$$

In other words, it follows that $\theta < 0$ if $r(a-\gamma)^2 + 2(a-\gamma) - \beta > 0$. On further simplification, the condition reduces to:

(42) $\theta < 0$ if $a > \hat{a}$ where $\hat{a} = \frac{-2 + \sqrt{4 + 2r\beta}}{2r} + \gamma$

The sufficient condition for $\theta < 0$ as derived in equation (42) expresses the optimal rotation length in terms of the parameters of the yield function and the discount rate.[7] Given the ranges for the parameter values of the yield function, (as used by Shongen et al. (2009), for example) and a possible range for the discount rate, it can be deduced that the condition will always be satisfied and, hence, it is safe to take $\theta < 0$.

It now follows from equation (37) that the optimal rotation length falls with an increase in the discount rate and the rental rate of the forest land, but rises with an increase in the stumpage, other things remaining the same. These results are intuitively clear. As the opportunity cost of capital or the discount rate rises it becomes more expensive to hold a mature forest for one more year because the marginal value product falls short of the additional cost of capital plus the cost of land. Hence, harvesting early becomes a profit maximising choice. Similarly, other things being the same, a rise in the price of stumpage will increase the value of the annual increment of timber at the margin, which exceeds the cost of holding the forest for one more year. Hence, profits can be increased by holding the forest for one more year when the price of logs increases.

5 While deriving equation (37) it is maintained that the market price of the stump (stumpage) is unaffected by these variables, interest rate, land rental and the change in the rotation length of a particular forest, but the yield rate would be affected by the change in the time of harvest. Hence, these contributions should be regarded as partial.

6 Using hindsight from equation (36) and equation (37) it is expected that $\theta < 0$.

7 Note that $r(a-\gamma)^2 + 2(a-\gamma) - \beta = 0$ is a quadratic equation in $(a-\gamma)$ with a positive root $\frac{-2 + \sqrt{4 + 4r\beta}}{2r}$ as $\sqrt{4 + 4r\beta} > 2$. If the sufficient condition for $a > \hat{a}$ is met for the positive root, then it will also be met for the negative root.

For a given age profile of trees, it follows that a rise in the price of timber, and hence stumpage, will reduce the area harvested and will therefore also reduce the supply of logs and timber. Other things being the same, the supply curve of logs is thus downward sloping. Hence, there is the following proposition:

Proposition 2: *Other things remaining the same, the short run supply curve of logs, in a partial equilibrium setting, and hence of timber, is downward sloping.*

The downward sloping supply curve may raise stability issues in the timber market. This will not be a problem as long as the supply curve is steeper than the demand curve for logs. However, an equilibrium price increase will not necessarily increase the supply of timber from the existing forest land. In fact, it may reduce the supply, but this price increase is expected to induce an increase in tree planting and thus increase the future supply of timber. What happens to future prices remains a question that cannot be answered by a recursive model. It is maintained that any current change in price will be sustained and thus future prices will remain the same as current price levels despite increases in supply (static expectations).

This 'perverse' outcome is likely to disappear in a general equilibrium setting in which land rentals may respond positively to changes in the price of logs (see section 6 for further discussions).

Equations (31) and (34) are solved for the optimal rotation length and the yield rate. Alternatively, equation (34) can be used to calibrate the initial optimal rotation length of a given forest type and then equation (37) can be used for its annual changes.

An investor's problem in environmental forestry

In a carbon constrained world, carbon credits for the carbon dioxide sequestration from trees may induce some environmental plantation. These forests need to be maintained forever as logging will release the carbon stored and make the harvesting activity liable for the carbon credited so far.[8] For simplicity, it is also assumed that the carbon price rises at the discount rate.

An investor can expect carbon credits on the incremental carbon stored in the trees each year but has to invest resources upfront to establish the forest. Whether environmental forestry could be a profitable business that attracts investors depends on the rate of return they can expect on such investments.

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

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

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 metre of biomass (yield) into tonnes of carbon, and $T(t) = C_0 e^{rt}$ gives the carbon price path.[9] The first term in the right hand side of equation (43) gives the total carbon credit that can be expected from a hectare of environmental plantation and the second term expresses the investment required as a sum of the plantation cost and the net present value of rental payments for the land. Both terms in natural logarithms and their difference divided by the number of years taken by the growth process gives the implied rate of return on the investment. As a result, equation (43) calculates the expected rate of return from environmental forestry.

8 Because of this liability, it is maintained in this paper that plantation forests will not claim carbon credits irrespective of the carbon prices. There may be small discrepancies between this assertion and the reality, but these will be ignored at this stage.

9 It may be possible to provide an exogenously specified carbon price path instead of the Hotelling's rule employed here. This rule simplifies this task and is also commonly employed in studies of environmental response policies with stabilisation targets in mind (for example, see Australian Government (2008)).

Note that $\int_0^{\infty} R_{enf} e^{-rt} dt = \frac{R_{enf}}{r}$, where R_{enf} is the market rental for the land type used for the environmental plantation. The total investment cost for the environmental plantation is the sum of the price of land and the cost of planting seedlings (regeneration cost).

After simplification, equation (43) can be rewritten as:

(43b) $$\rho_{enf} = \frac{1}{\tau}[\ln(T(\tau)\mu Y^C(\tau)) - \ln(G(.) + R_{enf} / r)]$$

Equation (43b) shows that claiming carbon credits each year for the quantity of carbon sequestered in that year and claiming once when the tree growth stops at the going carbon price are equivalent, provided the carbon price grows at the discount rate. In this study, it is maintained that carbon price follows the Hotelling rule and grows at the discount rate[10].

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

(44) $$\rho_{enf} = r$$

Given equation (43b), equation (44) postulates that investment in environmental forestry responds positively to carbon price and negatively to land rent and plantation costs. To have the equilibrium re-established with each disturbance, it is necessary that the cost sides—the rental rate and per hectare plantation costs—have a positive derivative with respect to the level of investment allocated to environmental forestry. Otherwise, increasing investment will not close the gap if it occurs. Scarcity of land and its opportunity cost would guarantee that this condition is met.

Equation (43b) also implies that it does not trigger any additional investment now if the carbon price is going to be imposed at a future date, as the investors are myopic. 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

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

In the case of environmental plantation it is maintained in this paper that investors buy the planted land upfront as they would be responsible to keep 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 just planted land). Therefore, equation (45) states that the area of land demanded 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, where the price of land is determined by the going market rental rate for such lands. It is also assumed that there is no further investment required to maintain the environmental forest.

In terms of income accounting, once planted, the land under environmental forests would be considered lost from the system and would not bring any returns to the land owner. However, it will bring incomes to the regional household (society) from carbon credits each year until the forest reaches the maturity age of 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 forest land completely stop.

10 This assumption can be relaxed and an exogenously given price of carbon may be imposed. However, the analytics are simplified by the assumption that the carbon price path follows the Hotelling rule.

6 Harvesting forests: the supply side of the logs market

In this section the harvesting decision of the owners of the managed and native forests will be outlined separately.

Demand for forest capital by the logging sector is a derived demand to meet the demand for logs to produce timber and pulp products. The demand price for logs is determined by the market prices of timber and pulp products. Similarly, the supply side of logs is ultimately governed by the return maximising behaviour of the forest investors. When the log market clears, it determines a market clearing price, $P_{\log s}$. All agents take this price as given.

In a competitive environment, P_f , so-called stumpage, is given by the difference of the price of logs $P_{\log s}$ and the unit cost of harvesting Ω, including the cost of transportation. In plantation forests all relevant infrastructures are assumed to exist.

In other words, this pricing condition could also be viewed as the zero profit condition for the logging sector, which determines its profit maximising scale of operation. So,

(46) $$P_{\log s} = P_f + \Omega$$

Demand for stumps, a derived demand, would be proportional to the demand for logs, or as specified by the production function. Given this stumpage, the optimal harvesting decision, which describes the supply side of logs, of the agents under different environments are described in the following subsections.

Optimal harvesting of managed forests

Optimal rotation length determined at the time of investment/plantation gives the ex-ante or planned harvesting horizon of the commercial forest. However, with time, market prices for logs may have changed and the optimal time for harvest needs to be determined in response to the current price signals. In other words, it will be assessed whether the plantation of age a should be harvested in that year. This is a requirement of recursive models.

Recall equation (14), which is the Faustmann-Samuelson condition for determining the optimal rotation length and applying for the forest stock of each length. The right hand side of equation (14) is the virtual land rental, and the second term on the left hand side is the interest cost of the capital value of the forest stand. Adopting equation (14) in this framework means that the virtual rent or the annuity is replaced by the market rental for the land and the interest rate is replaced by the expected rate of return on investment in forestry P_f. Hence, the condition is restated as:

(47) $$P_f Y'(a) \le \rho_f P_f Y(a) + R$$

This condition means that if the expected growth in market value of the forest stand is less than or equal to expected return from the capital value of the forest and the rent for the land the forest stands, then it is economic to harvest the forest. This means that all trees of age a would be harvested if the above condition holds. If this condition holds for any tree of age $a*$ then it also holds for the tree of all ages $a \ge a*$ because the marginal yield declines with age.

Under the maintained assumption that the markets for the logs are cleared by flexible prices, in equilibrium, the inequality in condition (47) turns into an equality and hence the equilibrium condition is written as:

(48) $$P_f Y'(a) = \rho_f P_f Y(a) + R$$

Once the yield function is specified, equation (48) can be solved for the harvesting age using equilibrium condition (26) as well.

It can be seen from equation (25) that the forestry rate of return is positively related with the stumpage price. Therefore, an increase in the stumpage would induce more investment in forestry. This is likely to induce an increase in plantation activities which, in turn, will raise the rental rate of land. With this possibility in mind, the terms in equation (48) are examined to see that a rise in price of logs would increase both the sum of the terms on the right hand side and the value on the left hand side. If the right hand side increases by more than the left hand side, then the length of forest rotation shortens with a rise in price of logs. This means that the supply of logs in the market increases. The supply curve for the logs, in general equilibrium, therefore may remain upward sloping.

Whether the supply increases in response to a given increase in the price of logs, and by how much, depends on the responsiveness of the rate of return and the rental rate on the log price. If these two variables are not sufficiently responsive to the price of logs, then it is possible that the general equilibrium supply curve of logs would be sloping downward instead. For example, suppose R does not respond to an increase in P_f. Also suppose that P_f increases from P_f^0 to P_f^1 then at (P_f^0, a^0) if equation (48) is satisfied, then we will have $P_f^1 Y'(a^0) > \rho_f P_f^1 Y(a^0) + R$. To see this result, both sides are divided by P_f^1 and it is noted that $R / P_f^1 < R / P_f^0$. Hence, the optimal harvesting age would rise from a^0 to re-establish the equality and, therefore, the current supply of logs will fall. This outcome is a possibility in a recursive model, which may lead to unstable model solutions.[11] It is therefore important to make sure that the variable R is well-behaved with respect to P_f. R rises sufficiently to nullify this apparently 'perverse' effect.

It is assumed that the optimal rotation length is obtained at $a = a*$. Hence, the area of plantation forest available for harvesting is given by:

(49) $$L_{DEFP} = \sum_{a \geq a*} F(a)$$

where $F(a)$ is the area of forest of age a and L_{DEFP} is the total area available for harvesting of plantation forest.

Supply of merchantable timber from plantation forest is given by:

(50) $$S_{LogsP} = \sum_{a \geq a*} F(a) * Y^M(a)$$

There will be a market clearing condition for the logs, which will determine the equilibrium price for logs (stumpage).

Optimal harvesting of native forests

For a country with substantial native forests estates three ways of using it are considered: conservation for biodiversity, harvest as a renewable resource or harvest and use as a source of additional agricultural land. The first use is treated here as an exogenous process. The remaining two are modelled. Native forests could be harvested selectively in a sustainable way and the land could be left to regrow naturally or clear felled to be employed in other uses including commercial forestry. The difference between the two uses is in the way the harvested land is treated and whether it is available for use in alternative activities.

11 Instability becomes an issue if the slope of the supply curve is less than that of the demand curve in absolute value. As long as the supply curve is steeper than the demand curve, there is a stable solution.

Native forest land can be considered to have zero opportunity cost and the plantation costs in such forests are also zero. The only cost incurred is the harvesting cost and the country can benefit from the revenues of timber sales if it exceeds the harvesting cost. What proportion of such forest would be harvested annually is a pertinent question. Similarly, it is also possible that some of the native forest is cleared to meet the increased demand for agricultural land, as observed at agricultural frontiers of heavily populated, less-developed countries.

To model the possibility of land use change, the stocks of native forest land are distinguished between for those: selectively harvested but left to regenerate naturally; harvested by clear felling and converted into other agricultural and commercial forestry uses; and never harvested as they are inaccessible or made non-convertible by law.

The non-convertible forests are assumed to be in a steady state. The process of regeneration and the process of dying and decaying balance each other.

Of the native forest land that can potentially be converted into other uses, it is assumed that there are costs associated with the type of conversions being implemented. There will be access costs, such as costs of building roads and fencing, if the land is being converted into commercial forestry and there will be additional land development costs if the land will be used for agriculture. The behavioural relations in each of these land use changes are set out below.

Selective harvesting of the native forest

Native forests are usually slow growing and their optimal rotation length could be determined by equation (4).

The key condition for equilibrium rotation is:

(51) $$Y'(a)/Y(a) = 1/a$$

As discussed previously, satisfaction of this condition is consistent with the MSY approach.

Access cost will be considered in addition to the cost of harvesting. Assume that the government or the owner of the native forest needs to spend $C^N(h)$ per hectare of forest harvested in accessing the forest. Following Golub et al. (2007), it is assumed that the marginal access cost increases with the cumulative area accessed. While doing so, a different approach is taken in specifying the mechanism by which the cost escalation is realised. It is assumed that more factors per unit of forest are needed to be accessed as more of the previously inaccessible forest land is accessed.

In other words, it is assumed that the input productivity in accessing the native forest could be represented by the following functional form:

(52) $$A^N(H^c) = e^{-\alpha\left(\frac{H^c}{\bar{H}}\right)}$$

where $\bar{H}$ is the total available area of potentially accessible native forest land in the region, H^c is the cumulatively accessed area and α is a positive parameter (normally greater than unity). It is assumed that any infrastructure built will be used just once, as the rotation length is rather long.

Linearization of equation (52) gives:

(53) $$a^N = \ln(A^N)h^c < 0$$

where a^N and h^C represent percentage changes in A^N and H^C, respectively.

Further, it is also assumed that native forests are mature forests ('old growth' type) and the yield per hectare has already stabilised. Hence, the government or the owner solves the following problem:

(54) Min $C(W, H^N) = \sum_i W_i F_i^{RN}$ subject to:

$$H^N = H(A^N(H^c)F_L^{RN}, A^N(H^c)F_K^{RN}) = A^N(H^c)H(F_L^{RN}, F_K^{RN}) \text{ and } H^C = H_{-1}^C + H^N$$

where $H(.)$ is a CRS function possibly of a Leontief type, which gives the area of land cleared per year as a function of the quantity of factors employed in land clearing expressed in efficiency units.

It is maintained that the efficiency impacts of harvesting native forests are determined by past actions and thus the factor productivity levels are taken as given but decline as the cumulative access of the native forest increases. The factors may become absolutely unproductive in clearing the forests, by the appropriate choice of the value of α, as the cumulative access level approaches the level $\overline{H}$.

The solution to this problem yields the cost minimising demand for factor inputs in land clearing. As more land is cleared, the unit cost of land clearing rises and optimal land clearing is attained when zero profit in land clearing holds. In other words, in equilibrium:

(55) $$P_f \overline{Y}^M = C(W,1) + \mu T \overline{Y}^C$$

where the left hand side gives the income from a hectare of land harvested, $C(W,1)$ is the unit cost of land clearance, T is the carbon penalty imposed on a tonne of carbon content to the biomass lost, $\overline{Y}^C$ is the estimated volume of the biomass per hectare and μ is the carbon conversion factor, in tonnes of carbon per cubic meter of biomass. It is noteworthy that the left hand side of equation (55) contains merchantable volume of timber, while the right hand side includes all biomass, including the root system. This is because carbon accounting needs to be done on the basis of biomass volume, not on the volume of merchantable timber. However, given the timber growth functions used in this study, $\overline{Y}^C = \overline{Y}^M$ as shown in equation (32).

Annual supply of native timber from regular harvesting of native forest is given by:

(56) $$S_{LOGSRN} = H^N \overline{Y}^M$$

In this case, the land goes back to native forest through natural regeneration.

As stumpage depends on the clearing of the logs market, it depends on how many logs are harvested from the native forest and also what is happening in other sectors such as plantation forests. This indicates that the extent of the harvesting of the native forest is linked with other sectors through factor and output markets.

Clear felling of native forest for alternative use (land use change)

Change in land use, such as deforestation of native forests and conversion into agricultural land and vice versa, is one of the key modelling problems that is being addressed in this paper. Any part of native forest harvested this way increases the supply of land for commercial uses: agriculture, livestock and managed forestry activities. If the area of native forest is increased through reforestation/afforestation activities, then the supply of land to other commercial uses declines.

Under the current modelling framework, it would not be feasible to value the environmental benefits of maintaining a native forest or the possible benefits to future generation of such forests. Plantation of environmental forests induced by carbon prices have already been covered above. Hence, one way movement of land use change, which is movement from inaccessible native forest to accessible land for commercial uses such as agriculture and plantation forestry, will be evaluated. The movement of agricultural land into native vegetation for biodiversity, ecotourism and other benefits will be left to future developments.

The decision to change the use of land from native forest to other uses, particularly agriculture, needs to be based on a comparison of two values: the current costs of land conversion and the flow of benefits in the form of land rents over a number of years. In this sense, the land use change decision is akin to an investment decision. This is already recognised by Golub et al. (2007) who argued that as long as the expected price of land in other uses exceeds the cost of land conversion, deforestation continues.

The same principle as in Golub et al. (2007) is followed here, but the rate of return from deforestation activities is compared with the rates of return in all other activities before the investment is made. By doing this it is explicitly recognised that the land use change activity involves investment decisions, it responds to changes in the rate of return elsewhere in the economy and that this activity, just like any other investment activity, is also funded from the overall savings available for investment.

If $\overline{R}$ denotes the average rental rate expected on a hectare of land in commercial uses, $\overline{C}$ represents the net input cost of converting (net of log revenue) a hectare of native forest land into commercial use and $\mu T\overline{Y}^{c}$ measures the carbon penalty in harvesting a hectare of native forest land, then the unit factor cost $\overline{C}$ is given by a function similar to the one described by equation (54) above with superscript ND (for deforestation of native forest). The only difference is perhaps the technology of production, which is captured by the differences in underlying parameters. The function has the key property that the more money that is invested in land clearing, the more land that will be cleared. However, the marginal cost of land clearing will rise as factors become gradually less and less productive. In other words, this means that $\overline{C}$ will rise with investment in deforestation and therefore ρ^{LUC}, the internal rate of return on deforestation, will fall. This remains true even if it is ignored that as more land becomes available for agriculture, the land rental will also fall. This effect will further lower the rate of return on the investment. In short, it is expected that the rate of return on deforestation activities falls with a rise in the level of investment on deforestation.

An investor would solve the following problem:

(57) $$\rho^{LUC}: \quad \overline{C} + \mu T\overline{Y}^{C} = \int_{0}^{\infty} \overline{R} e^{-\rho^{LUC} t} dt = \frac{\overline{R}}{\rho^{LUC}}$$

The variable ρ^{LUC} is the internal rate of return in deforestation activities and equation (57) means that $\rho_{LUC} = \overline{R}/(\overline{C} + T\mu\overline{Y}^{C})$. An investor will continue investing in clearing the native forest to make it available for other uses as long as $\rho^{LUC} > r$.

In other words, if the internal rate of return in deforestation activity exceeds the market rate, there is an incentive to invest more in deforestation. Higher carbon penalty will lower this incentive, other things remaining the same.

The equilibrium would be established when:

(58) $$\rho^{LUC} = r$$

The area of native forest that will be cleared should there be an incentive to do so will depend on the deforestation investment demand function and the investment opportunities available elsewhere.

There is also the issue of property rights. In countries where the property rights over native rights are ill specified, privately owned or local community owned the above rules may apply. It is likely that the 'tragedy of the commons' may result if it is a communal property. Alternatively, if it is owned by the government and strict rules and regulations to access the resource are in force, then the level of deforestation is restricted by the concessions or quota issued by the government. Illegal deforestation may result if the concession is not sufficiently large and law enforcement is relatively weak.

Observing that illegal deforestation is many times larger than the government sanctioned deforestation of the Brazilian Amazon, attempts have been made to assess the overall effects of issuing concessions (Banerjee and Alavalapati 2009). In this modelling, this issue will be addressed by enforcing government quotas in countries with strong institutions and letting free market work in countries with weaker institutions. In the former case, equation (58) will be made redundant and level of deforestation will be exogenously set as a policy variable. For the key tropical countries, where the deforestation problem is quite severe, illegal logging will take the level of deforestation to the market equilibrium consistent with equation (58). When carbon prices are imposed, policies will be adjusted to bring the illegal logging into the legal fold by allowing the forest concessions to expand.[12]

The area of the native forest cleared each year is determined by the amount of money invested and the unit cost of land clearing and development net of stumpage revenue for the logs harvested. Here, those countries that would enforce the level of deforestation exogenously are ignored. Therefore,

(59) $$L_{DEFN} = \frac{I_{DEF}}{(\bar{C} + T\mu\bar{Y}^{C})}$$

Supply of logs from the deforestation of native forest is given by:

(60) $$S_{\log sDN} = L_{DEFN}\bar{Y}^{M}$$

where $\bar{Y}^{M}$ is the maximum yield (steady state level) of merchantable timber from a hectare of native forest land.

National investment in value terms is given by:

(61) $$I_f + \sum_{a \in AGE} I_f^s(a) + I_{enf} + I_{DEF} + I_k = I.$$

where I_k and I are money invested in physical capital formation and total investments, respectively, and the other terms refer to investments associated with forestry activities: I_f is investment in new plantation, $I_f^s(a)$ is the total investment required to upkeep the forest of age a that includes the land rent, I_{enf} is the annual investment in environmental forestry and I_{DEF} is the investment in clearing native forests and developing it for alternative use. The allocation of national investment to various forestry related activities is determined by their relative rates of return and each region has to compete with the rest of the world for the funds by offering higher rates of return.

Total aggregate supply of logs is given by the sum of logs supplied from harvesting of plantation forest, regular harvesting of native forest and deforestation of native forest. As an equation, this gives:

(62) $$S_{LOGS} = S_{LOGSP} + S_{LOGSRN} + S_{LOGSND}$$

where S gives the aggregate supply of logs from all forest sources and the percentage change in S will be linked with the aggregate output of the logging sector. This aggregate output will be distributed to various users by the standard price mechanism.

There will be three stylised logging sectors, with three zero profit conditions. They will produce identical output, will be sold in the same market and will face a single market clearing condition giving the same equilibrium price. There will be three price equations to translate one price into three prices—in names.

12 This is a brave assumption. Imposition of carbon penalty may encourage illegal logging further if the governance system is weak in the country. When risks of being prosecuted are low, illegal logging avoids the royalty payable, the need for the licence and also avoids a carbon penalty on the forest cleared.

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

(63) $$H = L_{DEFN} + L_{DEFP}$$

Here the regular harvesting of native forest is excluded because the land will be returned back to nature for regeneration, by assumption.

In each year, plantation of forests removes the land from the supply of annual crops. This area is obtained by summing the area planted for the plantation forests and the environmental forests. In other words, aggregate area planted in any year is given by:

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

7 Equilibrium conditions for the planting sector

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

The zero profit condition can be specified as follows:

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

The left hand side of equation (65) gives the sales revenue and the right hand 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 (65) describes the equilibrium in plantation activity.

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

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

Given the land area planted in each year, we can use the standard approach to move the age profile of the forest stands year after year. The only way forest capital stock would be reduced is by way of harvesting. The harvesting decisions are modelled as follows.

8 Equilibrium conditions for the logging sector

In this modelling work, it is maintained that aggregate log demand is met by logs of different species coming from harvesting of both plantation and native forests. They are considered perfect substitutes of each other in each use. However, the demand for pulp wood is to be separated from the demand for timber and an Armington type structure on the demand side of timbers is to be followed to generate demand for logs of different species with a further nest to derive the demand for species from different sources, which can then span the module into a global timber trade module. However, in this stage of model development, such an ambitious attempt will not be made. The demand for pulpwood will not even be identified separately from the demand for timber for simplicity, despite that they may imply a different behaviour on the part of the investors. Demand for composites of all species (by management types at the most) will be generated. The extension to the timber trade module is expected to be straightforward, although it may need some database work.

In this document, the regional and specie dimensions of the variables are also suppressed for simplicity but that does not mean these variations would not be implemented.

Zero profit in logging plantation forests:

(67) $$P_f * S_{LOGSP} + \sum_{i \in Fac} W_i X_i^{\log P} + \sum_{i \in TRAD\_COMM} P_i X_i^{\log P} = PS^{\log gs} * Q_{LOGSP}$$

Zero profit in selectively logging native forest as renewable resource:

(68) $$P_f * S_{LOGSRN} + \sum_{i \in Fac} W_i F_i^{\log RN} + \sum_{i \in TRAD\_COMM} P_i X_i^{\log RN} = PS^{\log gs} * Q_{LOGSRN}$$

Zero profit in logging native forest (clear fell) – for land use change:

(69) $$P_f * S_{LOGSDN} + \sum_{i \in Fac} W_i F_i^{\log DN} + \sum_{i \in TRAD\_COMM} P_i X_i^{\log DN} = PS^{\log gs} * Q_{LOGSDN}$$

Market clearing condition in the logs market (all logs are homogenous):

(70) $$\mathrm{Q_{LOGSP}} + Q_{LOGSNR} + Q_{LOGSDN} = \sum_{j \in PROD\_COMM} X_{\log s, j} + X_{\log s}^{\exp ort} + X_{\log s}^{HH}$$

Equation (70) states that log supplies by all logging activities will be sold in a single market to meed the demand for logs from all users/destinations. There is some scope for the separation of the logs markets, especially into pulp wood and sawn wood markets. This level of detail has been postponed until the model is successfully implemented.

9 Modelling the land market

The forestry sector is connected to the rest of the sectors in GTEM mainly via the land market. The other key market is that of the logs. In modelling the land market it is maintained that there are k types of land used by j activities, including plantation, logging and other non-forestry sectors.

Productivity of a given type of land, such as forest land, is not the same across all uses. By using the matrix of productivity coefficients, which are technologically given, different types of land can be concentrated more densely on different types of activities and the movement of land can be accounted precisely in physical units.

The cost minimising demand for composite land by a sector j is given by:

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

where p_j^* is the percentage change in the price of composite land, irrespective of its type, $\overline{p}_f$ is the percentage change in the average price of all primary factors, f_j is the percentage change in the demand for factor composite and σ_j is the elasticity of factor (factor substitution).

Demand for land type k in efficiency units by activity j is given by:

(72) $$l_{jk}^e = l_j^* - \sigma_{lj} (p_{jk}^e - p_j^*)$$

where the variables and coefficients have similar meanings.

The efficiency units are linked to the physical units by:

(73) $$L_{jk}^e = \lambda_{jk} L_{jk}$$

where L_{jk} is in hectares and L_{jk}^e are expressed in sector specific efficiency units. λ_{jk} provides the productivity translations, which is calibrated to unity for the standard case such as paddy land used in paddy production. The value would be considerably smaller if grazing land were used for the production of vegetables, for example.

The market clearing condition can be written as:

(74) $$\sum_j L_{jk} = \overline{L}_k$$

where the supply of land type k is given by:

(75) $$\overline{L}_k = L_{k,-1} - F_{k,-1}(0) + H_{k,-1}$$

That is, 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. It is easy to see that equation (75) is a dynamic equation describing how the change in the supply of land of type k may occur year after year. If the area harvested is equal to the area planted, then the supply of land in the contestable market would not change.

It is useful to note here that the way sluggishness in the mobility of land across usages is modelled in standard GTAP, GTEM and in Ahammad and Mi (2005) has limited applicability when total land supply and its uses are expressed in physical units such as millions of hectare. A major problem with this approach is that once the initial allocation of land is calibrated using a CET function, or any other well-defined transformation function, any reallocation of land may not necessarily sum to the same total supply of land. There may be an unexplained gain or loss in the supply of total land. This situation can be defended using the argument that land allocations in that framework are defined in efficiency units, which has been the case so far, but cannot be continued if the land movements across alternative uses in physical units are to be fully accounted for. Full accounting of land in physical units may be necessary for the tractability of the model solution containing land use changes. The approach adopted in this paper addresses that problem.

10 Summary

Forestry poses some particular modelling challenges. Static and recursively dynamic CGE models have to date included a forestry sector, but these models cannot capture the full input–output relationships of the forestry sector in a consistent way. The key problem is that inputs are distributed over a number of years and output is produced at the end of the rotation length. As a result, it has been almost impossible to link the inputs applied in any period to the output it was contributing to. This difficulty has led to other inconsistencies not explored thoroughly in the literature.

In this paper, a framework has been outlined that tackles this modelling problem in a consistent way. The forestry sector is divided into three stages— planting, holding and logging. Planting and logging activities can be viewed as any other production activity modelled in a CGE model and holding a plantation estate until it is profitable to harvest is identified as investment. The behaviour of investors and production sectors with contemporaneous input–output relationship are a familiar concept and therefore the same approach can be applied to model the behaviour of these agents. This is a key innovation proposed in this paper.

The global forest is also partitioned into three classes––commercial plantation forest, environmental plantation forest and native forest. Commercial plantation forest requires planting, investing and harvesting decisions, while environmental plantation forest requires plantation and investment decisions. Environmental plantation is triggered by a carbon price and is maintained as a carbon store in perpetuity. The native forest requires only a harvesting decision, either as a renewable resource or for land use change (deforestation). Native forest by definition grows naturally. All of the required decisions are linked to rational calculations––optimisation.

Harvesting forest land increases the supply of logs and the supply of land in the contestable market. New plantation reduces the supply of land to these markets. Market clearing conditions have been identified for both land and logs. Investment required for maintaining plantations and accessing native forests are assumed to come from the national investment pool. The residual goes to physical (and human) capital formation.

The proposed framework can be extended to make the module even more useful in a practical sense. Some of these extensions are described below.

In this stage of the modelling work, aggregate log demand is met by logs of different species coming from harvesting of both plantation and native forests. They are considered perfect substitutes of each other in each use. However, the demand for pulp wood is to be separated from demand for timber and an Armington type structure on the demand side of timbers will be followed to generate demand for logs of different species with a further nest to derive the demand for species from different sources. The module can then span into a global timber trade module. In this stage of model development, such an ambitious attempt will not be made, as the data requirement would be substantial. The demand for pulpwood will not be identified separately from the demand for timber for simplicity, even though investors in each product may behave differently. Demand for composites of all species (by management types at the most) will be generated. The extension to the timber trade module is expected to be straightforward, although it may need some database work.

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