

Land Use Change Modeling in GTEM

Accounting for forest sinks

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The objective in this paper is to document the approach adopted for modeling alternative land uses in ABARE's global trade and environment model (GTEM). A methodology is also developed in the paper to explicitly model carbon sequestration in forests in GTEM. These modeling innovations have been motivated by the land use database developed by the Global Trade Analysis Project and the US Environmental Protection Agency.

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Introduction

The aim in this paper is to document the new approach to modeling land use change and related emissions in ABARE's global trade and environment model (GTEM). GTEM is a multisector, multiregion, dynamic computable general equilibrium model of the world economy.

In the standard version of GTEM, only one broad class of land is specified, which is used across various agricultural activities.¹ Land is not distinguished by key attributes such as moisture content, soil nutrient levels and temperature. Because most agricultural (as well as forestry) activities are viable only on lands with specific attributes and temperature, the land suitability issue ought to be taken into account while modeling land mobility across various land use sectors. Also in standard GTEM, forestry is modeled to use no land but a sector specific factor called natural resources. Therefore, mobility of land (or natural resources) between agriculture and forestry is not allowed.

Furthermore, carbon sequestration into forestry is not endogenously determined within the standard GTEM framework. Greenhouse gas emissions from land based agriculture activities and carbon sequestration into forestry are important components of carbon accounting at the national and global levels. To model the net emissions from agriculture and forestry one has to model land use change in these activities appropriately. Recently, the Global Trade Analysis Project (GTAP) with the sponsorship of the US Environmental Protection Agency (EPA) has developed a new land class database (Lee et al. 2005), which opens up possibilities for detailed modeling of land use change within a computable general equilibrium modeling framework. This paper documents the refinements of the land use change and associated emissions modeling in GTEM in the light of the new GTAP-EPA database.

Explicit modeling of land class and land use change in a global computable general equilibrium modeling framework has been attempted in the past. Darwin et al. (1995) modeled six land classes, distinguished by the length of the growing season, in the Future Agricultural Resources Model (FARM) — a computable general equilibrium model of the global economy. Total land of a particular type is allocated to eleven commodity producing sectors (including crops, livestock and forestry sectors) on the basis of a constant elasticity of transformation (CET) function. The FARM framework, however, does not capture forest growth dynamics, and does not explicitly model greenhouse gas emissions and sinks in forestry (Wong et al. 2003).

More recently, Burniaux and Lee (2003) incorporated intersectoral land transitions in the GTAP model, a computable general equilibrium model of the global economy

¹ For some trade policy analyses (see, for example, Freeman et al. 2000), three land types are distinguished in one version of GTEM — land suitable for broadacre crops (such as rice, wheat, coarse grains and oilseeds) production; land suitable for livestock (such as cattle and sheep) pasture; and speciality land suitable for the production of sugar, vegetables and fruit, etc. Each type of land is assumed to be mobile across agricultural activities within a broad group (that is, crops, livestock or other) but not between broad groups. For example, land allocations can be altered between wheat and coarse grains production but not between wheat and cattle production.

(Hertel 1997). Applying a specific set of net emission coefficients to the land transition matrix (which shows changes of land use status over a period of time), they have estimated net emissions associated with land use changes. The land use transitions and the relevant net emissions coefficients used in their model (called GTAPE-L) all have been derived from IMAGE 2.2, an integrated model for assessing the global environment (Alcamo 1994), corresponding to a particular socioeconomic scenario. Like Darwin et al. (1995) and Wong et al. (2003), the forestry growth dynamics are not captured by Burniaux and Lee (2003).

The two broad but related aspects of the GTEM enhancements presented in this paper are: land class and land use change modeling, and the modeling of forestry inventory and the associated carbon sequestration. The land class and land use change modeling in GTEM is not significantly different from what have been previously attempted in other global computable general equilibrium models. However, the contribution of this paper lies in the incorporation of forestry vintages in a computable general equilibrium framework to explicitly model carbon sequestration in forestry. Together with the standard GTEM methodologies for modeling greenhouse gas emissions in nonforestry sectors (Matysek et al. 2005: pp. 67–9), the enhanced GTEM capacity would allow forest carbon sequestration to be determined simultaneously (as opposed to recursively or extraneously) with combustion and noncombustion greenhouse gas emissions from other sources in a regional (and hence the global) economy.

The GTEM approach to land use change and emissions modeling

Land use change and emissions modeling in GTEM comprises four building blocks:

- demand for land
- land allocations across alternative uses
- greenhouse gas emissions from agriculture and
- carbon sequestration in forestry.

These are discussed below in some detail. For completeness, however, an overview of the theoretical structure of GTEM is presented in the appendix.

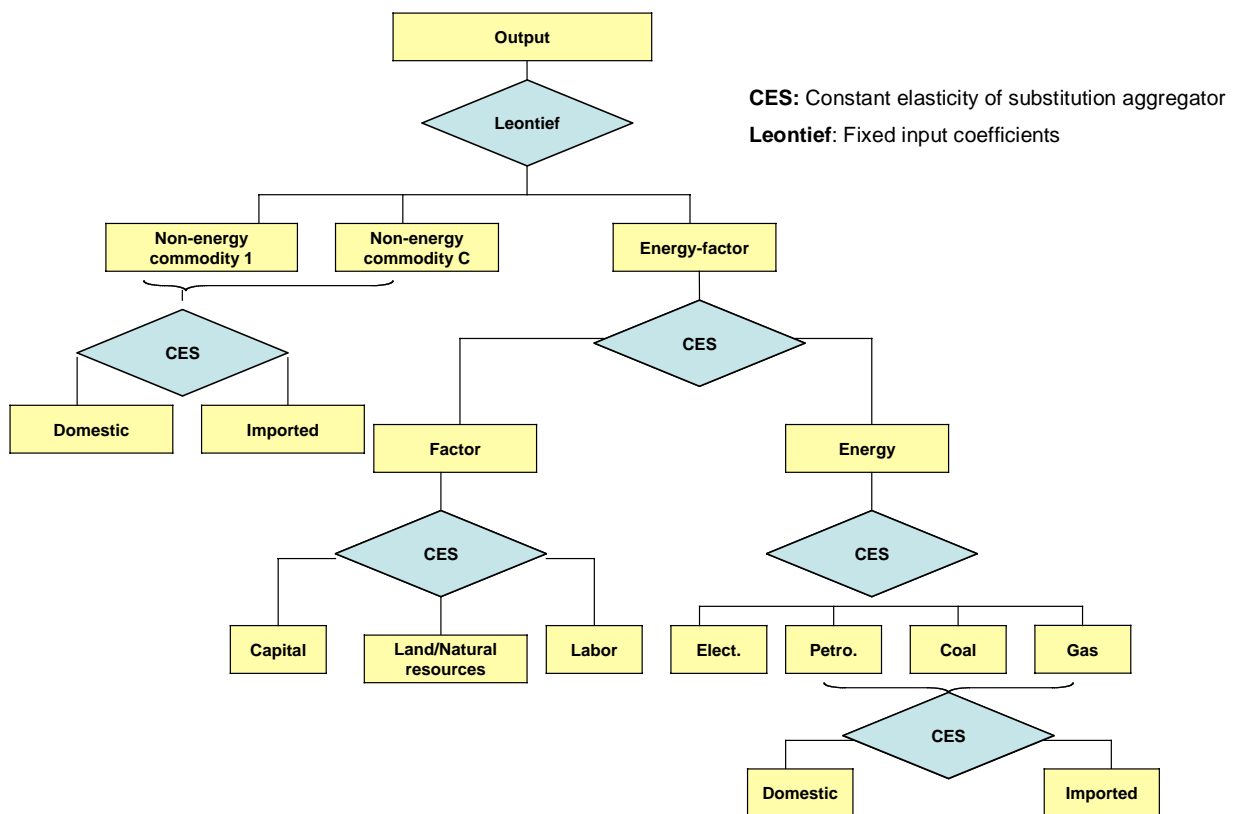
Demand for land in GTEM

In the standard GTEM framework, demand for land (natural resources) in agriculture (forestry) is modeled as part of a multilevel production decision process as depicted in figure 1.² The multilevel process follows from the assumption of separability in production. More specifically, at a particular level (or ‘nest’), farms’ choice for the optimal mix of the components in an ‘effective’ input branch (for example, primary factor) is independent of the prices of those of the other input branch(es) of the nest (for

² Agriculture in GTEM comprises twelve crops and livestock sectors, either identified separately or aggregated at some levels in various applications.

example, energy or materials). As can be seen from the figure, the demand for the primary factor composite is a constant elasticity of substitution (CES) aggregate of labor, capital, land and natural resources.³ The composite primary factor is combined with an energy composite using a CES aggregator at the next higher level to constitute an energy-factor composite. The energy-factor composite is then combined in fixed proportion (that is, using a Leontief aggregator) with material inputs (including fertiliser), at the top level.⁴

Figure 1: Standard production technologies in GTEM agriculture and forestry

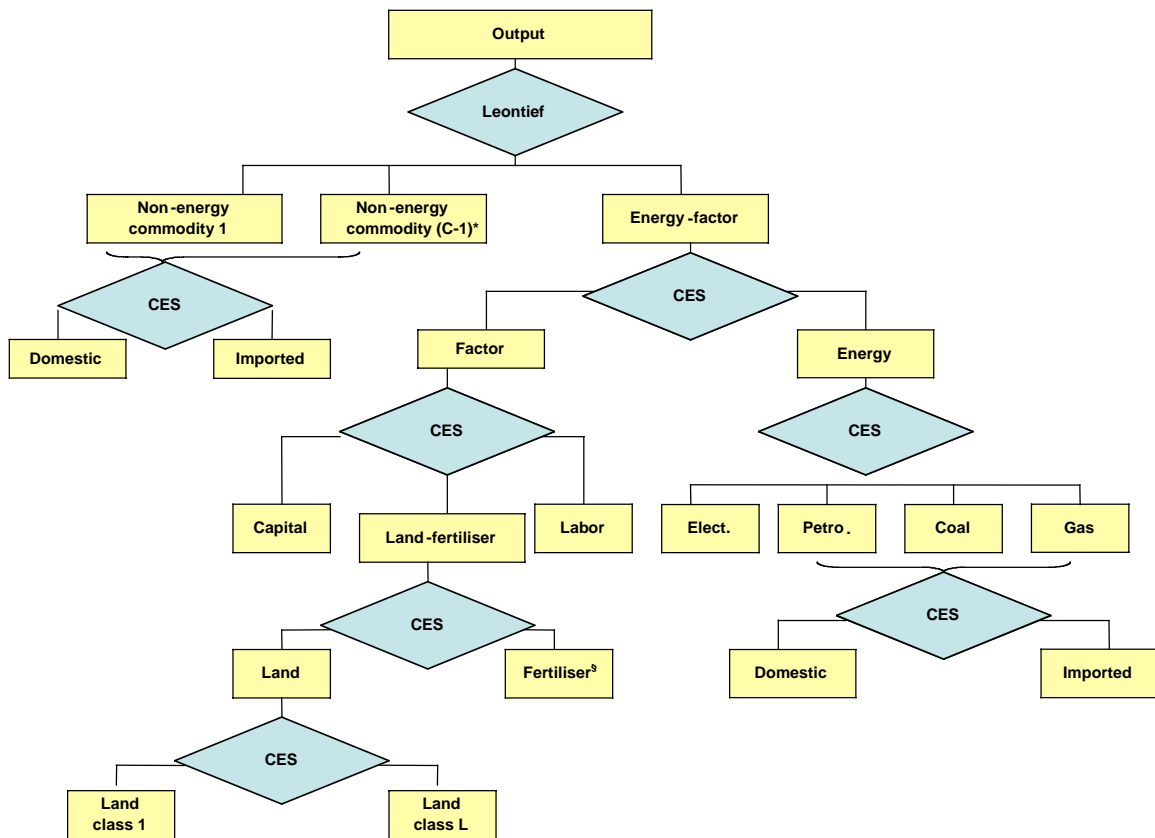


³ Although all four primary factors are included in the theoretical construct, in GTEM applications the effective primary factor is taken as a composite of land, labor and capital in case of agriculture and of labor, capital and natural resources in case of forestry.

⁴ The technology tree in figure 1 represents the production technologies in other GTEM sectors except for electricity generation and iron and steel production. For electricity and iron and steel sectors, GTEM uses technology bundle approach — see ABARE (1996) for details.

The modified land demand modeling in GTEM is presented in figure 2, which represents the new multilevel production technologies for the agriculture and forestry sectors. In the new approach, various types of land are incorporated, distinguished by key attributes such as the length of growing season. Substitution possibilities are allowed between the composite land and fertiliser in response to changes in the relative price of fertiliser to land.⁵ This is to capture the empirical evidence that the rate of fertiliser application tends to change considerably in response to changes in the relative price of fertiliser to land (Huang et al. 2004). Furthermore, the forestry sector is assumed to use land (instead of natural resources) as an input.

Figure 2: Modified production technologies in GTEM agriculture and forestry



* Non-energy commodity set excludes fertiliser
 § Fertiliser can be purchased from domestic and imported sources
CES constant elasticity of substitution

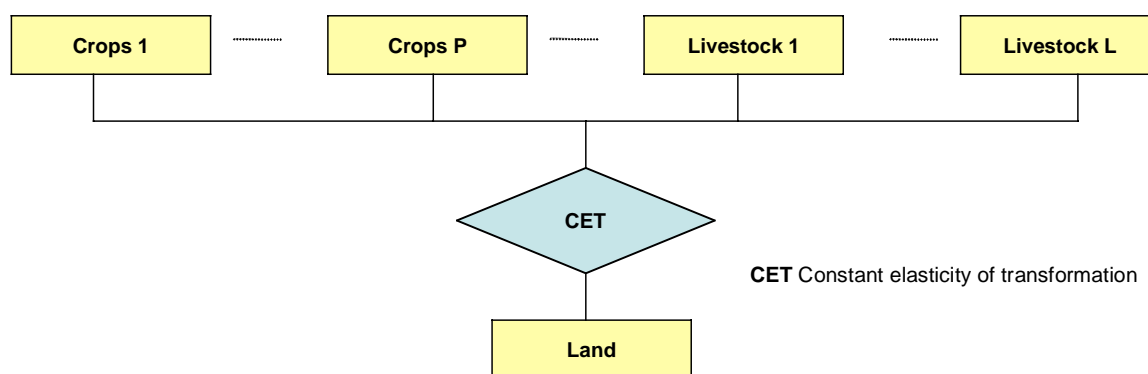
⁵ Fertiliser is part of the broad commodity/sector called chemical, rubber and plastic products (crp) in GTEM. In the case of agriculture and forestry, it mainly represents fertiliser and pesticides.

As can be seen in figure 2, the demand for composite land, a CES aggregate of demands for individual land types, is combined with fertiliser⁶ to constitute a land–fertiliser composite. The land–fertiliser composite is then aggregated with other primary factors (labor and capital) to form a primary factor composite that is combined with the energy composite. The rest of the technology structure is identical to that in standard GTEM.

Land allocations

Figure 3 shows the allocation in standard GTEM of the single homogeneous type of land that is imperfectly mobile across various agricultural activities in standard GTEM. In other words, land in the standard model can be allocated to various agricultural activities in pursuit of higher rentals but not to the extent to enforce a uniform rental rate across the economy. Also in the standard model, land is assumed *not* to move from agricultural activities to forestry and vice versa.

Figure 3: **Standard GTEM land allocation scheme, one homogenous land type**



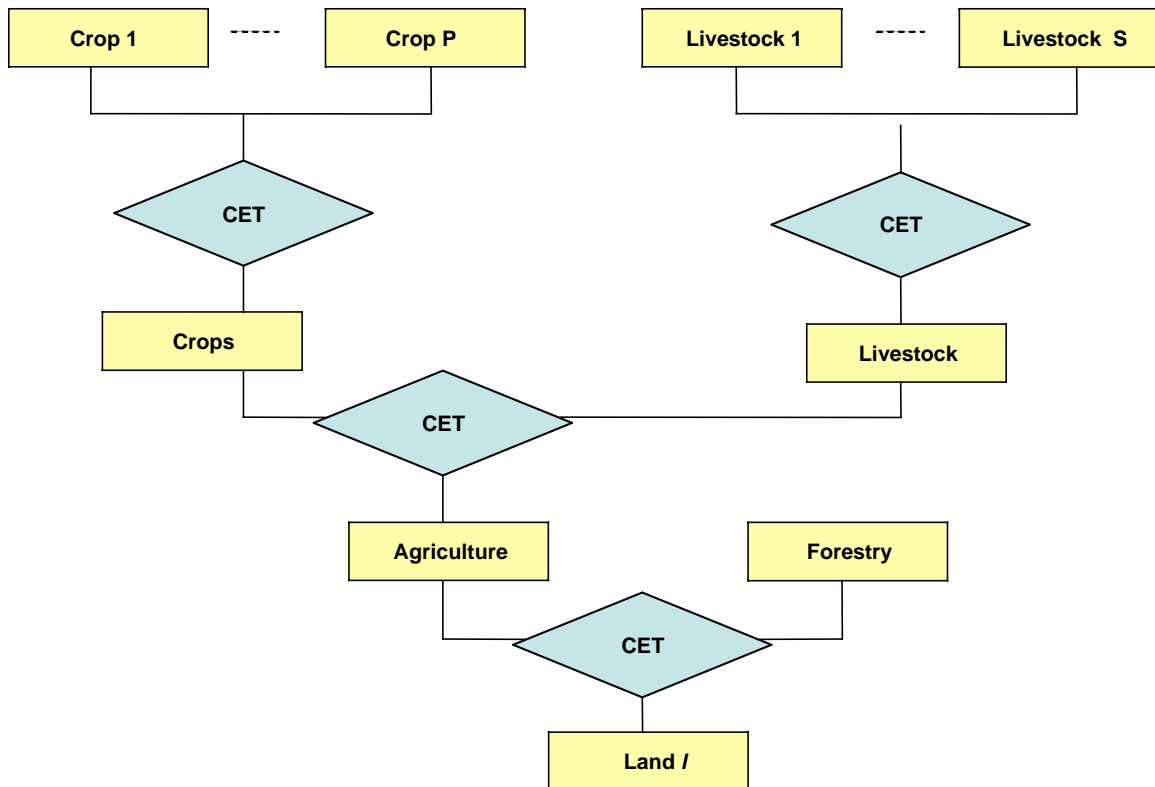
This land allocation has been modified in the enhanced GTEM framework that assumes that each type of land (distinguished by land attributes) be mobile between various agricultural and forestry activities. However, land is not mobile across land types. While the old assumption of imperfect mobility of land across agriculture activities is retained, the degree to which land can be moved within and between various cropping and grazing activities is modeled to vary. All these are captured by a multilevel land allocation scheme based on the separability assumption, as depicted in figure 4.

According to the new land allocation modeling in figure 4, owners of a particular type of land in GTEM allocate land between the broad class of agriculture and forestry activities first, governed by a constant elasticity of transformation (CET) function, so as to maximise the total rents from land. Once the amount of land available to agriculture is determined, the land allocation to livestock grazing and crop production within agriculture is decided, again, using a CET aggregation function. At the final stage, the

⁶ Although not shown in the diagram, fertiliser can be purchased from domestic and/or foreign sources.

total cropland is allocated to various types of GTEM crops and the total grazing land is allocated across different livestock types. Such a multilevel allocation structure assumes that, for example, the decision to allocate land between crops is independent of the relative rental rates in the livestock activities. It also allows flexibility in setting different values for the CET parameters at different levels of the nest.

Figure 4: New land allocation in GTEM, by land type



CET: constant elasticity of transformation

$l = 1, 2, \dots, L$

It is important to note that the chosen land allocation structure may not be unambiguously the best option. For example, one could use an alternative specification for land allocations similar to the one represented in figure 3 but using a CRETH (constant ratios of elasticities of transformation, homothetic) function instead of a CET function. This may ensure the desired flexibility in allocating land across different pairs of uses. However, the use of the multilevel land allocation scheme depicted in figure 4 seems to offer more flexibility in specifying different elasticity values and hence carrying out sensitivity tests by changing the relative ease with which land allocations are varied within and between various groups.

Emissions from agriculture

In GTEM, agricultural activities are modeled to emit three types of greenhouse gases: carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O).

Carbon dioxide emissions arise from the combustion of fossil fuel used in running agricultural and irrigation equipment. Fossil fuels when converted into energy emit carbon dioxide.

Methane emissions arise from paddy cultivation and livestock husbandry. Methane emissions from paddy cultivation occur when organic matter decomposes in flooded or irrigated paddy fields. The intensity of methane emissions from paddy cultivation depends on the extent to which paddy fields are submerged throughout the year as well as on rice variety, number and duration of harvests, soil type, irrigation practices and fertiliser use (IPCC 1996, p. 4.1). Although it is desirable to incorporate all these aspects in as much detail as possible, due to data limitations, methane emissions from paddy cultivation are linked only to land area harvested for paddy production in each region.

Methane emissions from livestock occur mainly through two processes: enteric fermentation and manure management (IPCC 1996). Enteric fermentation refers to the digestion of feed by animals and is a source of methane. Manure management refers to emissions of methane (and nitrous oxide, described later) attributable to the decomposition of animal manure. In general, larger ruminant animals tend to emit more methane than smaller or nonruminant animals, and animals living in warm climates tend to emit more methane than animals living in temperate or cold climates. In GTEM, methane emissions arise from the dairy cattle (raw milk) sector, the wool sector, the cattle, sheep, goats and horse sector and the other animal products sector. In the absence of detailed information, methane emissions from these sectors are linked to respective sectoral output.

Farming and livestock waste are the major sources of nitrous oxide emissions. The main sources of direct nitrous oxide emissions from agricultural soils include application of synthetic fertiliser to agricultural soils, animal faeces deposited on the land and the mineralisation of organic nitrogen compounds in the soil, while the indirect sources include nitrous oxide converted from the atmospheric deposition of nitrogen and from nitrogen leaching and runoff (NGGIC 1998; IPCC 1996). Emissions of nitrous oxide attributable to fertiliser application are directly linked to the corresponding inputs (namely, chemicals, rubber and plastic) in GTEM. Nitrous oxide emissions from animal waste are a function of the type of animal, the intake of dry matter by the animal, the nitrogen content of the animal's diet and of how the waste is treated. Due to the lack of data, emissions are linked to livestock outputs in GTEM. Nitrous oxide emissions from soil disturbance have been linked to the area of land used for agriculture in each GTEM region. As for the indirect emissions of nitrous oxide from fertiliser and manure nitrogen runoff into the water system, it is assumed that 30 per cent of fertiliser and animal deposited nitrogen runs off or is leached into the water system, as recommended by IPCC (1996).

Currently GTEM does not account for emissions from burning savannas and agricultural residues.

Carbon sequestration in forestry

Through the process of photosynthesis, plants withdraw carbon dioxide from the atmosphere. Together with other elements, the carbon atom from each carbon dioxide molecule is incorporated in plant tissue. In view of this, any carbon gain by plants can be taken as a measure of the amount of carbon dioxide absorbed from the atmosphere. Carbon is also lost from plants and returned to the atmosphere as carbon dioxide through plants' respiration as well as through the respiration of the animals that eat parts of the plants, and also by decay of plants and animal organic matter in soils and litter.

Without human interferences, the gross fluxes (that is, the amounts of carbon moving per year from the terrestrial biosphere to the atmosphere or vice versa), although significant, are reasonably in balance. Accordingly, undisturbed natural forests are considered to be neither an emissions source nor a sink. However, management of forests for timber production and/or fuelwood that involves plantation, controlling forest growth, timing of harvest, etc., may alter the carbon dioxide flux. The net removal of carbon dioxide from the atmosphere by managed forest depends on the nature and timing of harvest and regrowth and also on the time scale over which forest activities are measured.

Capturing forest management dynamics in a computable general equilibrium model and, hence, estimating the amount of carbon stored in forests within such a modeling framework is difficult (Wong et al. 2003). To start with, the forestry sector in most input-output tables (a major component of, for example, GTAP and GTEM databases) comprises plantation and logging activities as well as services to forestry. Ideally, they should be separated for the current modeling purpose. Otherwise, one has to presuppose input-output separability in production whereby the optimal mix of outputs (of plantation, merchantable logs and forestry services) is set independently of the optimal mix of inputs (land, labor, energy, capital and other materials) and, hence, of input prices. One significant limitation of this approach is that it is based on the restrictive assumption that individual inputs are nonspecific to individual outputs so that no input has a comparative advantage in the production of any particular output. Furthermore, the way that forestry activities are typically modeled in a recursive dynamic computable general equilibrium model (such as GTEM and other global models discussed earlier) can best be described as representing some sort of 'long run average' or 'steady state' supply responses. While incorporating the key forestry dynamics within the current recursive dynamic GTEM framework could be quite demanding, its new land use modeling (discussed earlier) can easily be complemented with a detailed forestry inventory modeling. By taking account of changes in forest inventory, one can estimate carbon sequestration in forestry.

The approach to modeling changes in forestry inventory in GTEM can be described as follows. Forest stocks in a GTEM region are differentiated by age, by management type and by land class. Because forestry data for the one-yearly age cohorts are not available,

existing forest stocks are classified into ten 10-yearly age cohorts. Tree species are not modeled explicitly. As a result, an average relationship between plant growth rate, management type and age class is used. Although the age at which the maximum growth of a plant occurs may vary with species and environmental conditions, the rotation periods are assumed to be about thirty years across the board.

The annual changes in the GTEM forestry composition arise from three sources: (i) land shifting between agriculture and forestry activities; (ii) aging of forestry; and (iii) forest stock harvesting and reforestation. Plantation is assumed to take place immediately in any land transferred from agriculture to forestry. The additional forest land is accordingly accounted for in the first forest age cohort while any shift of land from forestry to agriculture is assumed to come from the age cohorts over 30 years. As forest stocks age, a certain fraction of forest stock from one age cohort is assumed to shift to the next. Finally, logging activities are assumed to occur only in the age cohorts older than 30 years. The harvested forest land area, unless transferred to other land using activities such as agriculture, is used for reforestation and, hence, added to the first forest age cohort. Based on the above assumptions, A_{alm}^+ — the end-of-the-year area of particular land type l with particular forestry stand of age cohort a under management type m — is estimated in GTEM. For the equation system determining the annual changes in forest inventory, see appendix A.

Following Sohngen and Tennity (2004), carbon stock associated with each age cohort of forestry under specific management in a particular land type can be estimated as the product of forest land area, yield per hectare of land and carbon conversion factor:

$$C_{alm}^+ = A_{alm}^+ \times Y_{alm} \times \alpha_m,$$

where C_{alm}^+ denotes the carbon stock measured, say, in tonnes of carbon and associated with forest age class a in land type l under management type m ; A_{alm}^+ is as defined before and is measured in hectare; Y_{alm} denotes the forest stock measured as cubic metres of wood per hectare of land type l with forest of age class a under management m ; and α_m is the carbon conversion factor for forest stock (tonnes of carbon per cubic meter of wood) under management type m . As noted in Sohngen and Tennity (2004), the carbon conversion factor may vary across timber types, age classes as well as land types. However, the carbon conversion factor is taken to vary with management type only and not across land types and age because of the lack of detailed information.

The sum of forest carbon stocks over all age cohorts, land types and management types provides the total carbon stored in forest in a particular year: $C^+ = \sum_a \sum_l \sum_m C_{alm}^+$. The estimate of the carbon sequestration in forestry is the additional carbon stock accumulated in the particular year: $\Delta C = C^+ - C^0$, where C^0 denotes total forest carbon stocks at the beginning of the year. This can be converted to carbon dioxide uptake by multiplying the value for carbon, ΔC , by the ratio (44/12) of the molecular weight of carbon dioxide to the atomic weight of carbon.

The land use and emissions database

Recently, Lee et al. (2005) developed land use and greenhouse gases emissions databases for GTAP (Global Trade Analysis Project) with the sponsorship of US Environmental Protection Agency (EPA). The databases are suitable for global computable general equilibrium models.

The land use databases have been compiled from two sources: the acreage and yield data of cropland and pasture land from Ramankutty et al. (2004), and the timberland acreage from Sohngen and Tennity (2004). For each region, the GTAP–EPA land use database identifies eighteen land types corresponding to eighteen agro-ecological zones that, in turn, are based on three climatic zones and six different lengths of growing period. The land use information from the above two sources has been used by Lee et al. (2005) to calibrate the user costs (land rentals) for twelve GTAP agricultural (crops and livestock) sectors and one forestry sector, for the year 2001. Furthermore, the timberland inventories are available for three broad forest species (coniferous, broadleaf and mixed), fourteen management types, ten 10-yearly age cohorts and eighteen agro-ecological zones.

In addition, the GTAP–EPA databases contain emissions data for six greenhouse gases — carbon dioxide, methane, nitrous oxide and three f-gases. The carbon dioxide emissions data are for the year 1997 and are associated with fossil fuel combustion only. They do not account for the noncombustion emissions associated with oil and gas extraction, and cement and aluminium production. Emissions of non carbon dioxide gases have been sourced from the US Environmental Protection Agency for the years 1990, 1995 and 2000, and have been allocated to GTAP sectors as appropriate. Finally, the carbon stock associated with the total timberland has been sourced from Sohngen and Tennity (2004) and is available for various land classes, age cohorts, management types and tree species, for the year 2000.

For modeling the land use change and forest inventory in GTEM described earlier, a consistent GTAP–EPA database for land class, land use and emissions for the year 2001 can be used. The relevant forest yield functions (yielding Y_{alm}) and carbon conversion factors (α_m) can be obtained from Sohngen and Tennity (2004). Data for A_{alm}^0 — the base year area and composition of the managed forest land underlying the GTAP land rents — are required for modeling the land shifting and forest aging components of the forest inventory module (see appendix A). Also, the base year data for the area and composition of harvested forest land (H_{alm}^0) need to be estimated so that they are consistent with the GTAP core economic data. The data are required for the harvesting component of the forest inventory module (see appendix A). Unless available from original sources, these data can be calibrated using the GTAP land rents data and the data from Sohngen and Tennity (2004) on the timberland inventory and associated rents, and the annual forest area harvested.

Concluding remarks

The GTEM land use change and forest sinks modeling approach presented in this paper is a work in progress. The preliminary attempts to model land use change and forest sinks using the GTAP–EPA database need to be further improved and refined, on both theoretical and data fronts.

At the theoretical level, it is important to capture the short run as well as the long run forestry dynamics in the CGE framework. Because the greenhouse gas concentration in the atmosphere at a particular point in time is emissions path dependent, accounting for the short run fluctuations in forest sequestration is important.

On the data front, the forestry and logging sector in GTEM — currently representing plantation, logging and forestry services — needs to be disaggregated for better land use change and emissions modeling. Also, given the sensitivity of land use change to the values of some key parameters (namely, the CET and CES parameters on the land allocation and demand specifications respectively), it is critical to assign appropriate values to those parameters. Currently, to model forestry inventory and forest sinks, the area and composition of the managed and harvested forest are calibrated for GTEM. However, the model estimate for the forest sinks is sensitive to the base year forest inventory, which should fully conform to the core GTAP economic data.

Appendix A:

An overview of GTEM with forest inventory

Standard GTEM was derived from the original MEGABARE model (ABARE 1996) and the static GTAP model (Hertel 1997), with several important features added and/or improved to enhance GTEM's analytical capacity in energy and climate change areas. The distinguishing features of GTEM include dynamic characteristics, allowance for interfuel and factor–fuel substitutions, use of the ‘technology bundle’ approach in modeling energy intensive industries, endogenous determination of population and labor force growth, accounting for greenhouse gas emissions, and representation of an international quota market and quota banking that is characterised by forward looking behavior. A detailed description of the theoretical structure of GTEM can be found in Pant (2002); the key structural features of GTEM are also documented in Pezzey and Lambie (2001). This appendix presents an overview of the core GTEM framework and the new forest sinks modeling.

An overview of GTEM

The core theoretical structure of GTEM can be summarised as follows. For any regional economy, there are $T+N$ goods — which are defined to include services and factors of production, of which the first T are traded (all produced commodities) and the last N are nontraded (primary factors of production). Let $\mathbf{P} = \{\mathbf{P}^t, \mathbf{P}^n\}$ be the vector of prices faced by firms, where \mathbf{P}^t and \mathbf{P}^n are the subvectors for traded and nontraded goods defined by $\mathbf{P}^t = \{P_1, P_2, \dots, P_T\}$ and $\mathbf{P}^n = \{P_{T+1}, P_{T+2}, \dots, P_{T+N}\}$. The vector of consumer prices, \mathbf{Q} , faced by the representative regional household is defined analogously: $\mathbf{Q} = \{\mathbf{Q}^t, \mathbf{Q}^n\}$. Let $\boldsymbol{\gamma} = \{\boldsymbol{\gamma}^t, \boldsymbol{\gamma}^n\}$ be a vector of per unit production taxes and $\boldsymbol{\theta} = \{\boldsymbol{\theta}^t, \boldsymbol{\theta}^n\}$ a vector of per unit consumption taxes. In addition to these ‘explicit’ taxes, there are taxes on trade whose per unit amounts are denoted by the vector $\boldsymbol{\tau}$. In the case of an import, a positive tariff is represented by a positive element of $\boldsymbol{\tau}$; in the case of an export, a positive export tax is denoted by a negative element of $\boldsymbol{\tau}$. Let $\mathbf{v} = \{\mathbf{v}^t, \mathbf{v}^n\}$ and $\boldsymbol{\phi} = \{\boldsymbol{\phi}^t, \boldsymbol{\phi}^n\}$ denote the total per unit production and consumption taxes. For nontraded goods, $\mathbf{v}^n = \boldsymbol{\gamma}^n$ and $\boldsymbol{\phi}^n = \boldsymbol{\theta}^n$, but since tariffs are equivalent to production subsidies and consumption taxes, the total taxes on traded goods are given by $\mathbf{v}^t = \boldsymbol{\gamma}^t - \boldsymbol{\tau}$ and $\boldsymbol{\phi}^t = \boldsymbol{\theta}^t + \boldsymbol{\tau}$. Let \mathbf{R}^t be the vector of world prices of the traded goods, and define $\mathbf{R} = \{\mathbf{R}^t, \mathbf{R}^n\}$ where \mathbf{R}^n is the vector of tax-exclusive market prices of nontraded goods. Provided that domestic and world prices are measured in the same currency (or, equivalently, that a unit of the domestic currency is defined as the amount whose market value is equal to one unit of foreign exchange) these notational conventions imply that:

$$\mathbf{P} = \mathbf{R} - \mathbf{v}, \quad (1)$$

$$\mathbf{Q} = \mathbf{R} + \boldsymbol{\phi}. \quad (2)$$

The representative regional household's consumption of traded goods is given by the vector \mathbf{C}^t . The net output of traded goods produced by domestic firms is \mathbf{Y}^t and net imports are \mathbf{M}^t . The corresponding vectors of nontraded goods are \mathbf{C}^n , \mathbf{Y}^n and \mathbf{M}^n , where by definition $\mathbf{M}^n = \mathbf{0}$, and the corresponding vectors for all goods are \mathbf{C} , \mathbf{Y} and \mathbf{M} . The identity relating sources and uses of goods (also known as the market clearing condition) then becomes:

$$\mathbf{C} = \mathbf{Y} + \mathbf{M}. \quad (3)$$

GTEM is a dynamic model in which investment in one period is treated as an input in the production of output in subsequent periods. It is assumed that there is perfect competition both in product and factor markets.

The budget constraint of the represented regional household is:

$$E(\mathbf{Q}, U) = \pi(\mathbf{P}) + \phi \cdot \mathbf{C} + \mathbf{v} \cdot \mathbf{Y} - A, \quad (4)$$

where $E(\mathbf{Q}, U)$ is the minimum expenditure needed to reach utility level U when consumer prices are \mathbf{Q} and $\pi(\mathbf{P})$ is the maximum profits of firms when producer prices are \mathbf{P} ; $\phi \cdot \mathbf{C}$ and $\mathbf{v} \cdot \mathbf{Y}$ are the inner products of the vectors indicated; and A is the net transfer to the rest of the world made by the regional household.

If the regional household's budget constraint is satisfied, the balance of payments must also be satisfied: transfers abroad, A , must equal the BOT surplus. This can be confirmed by substituting $\mathbf{Q} \cdot \mathbf{C}(\mathbf{Q}, U)$ for $E(\mathbf{Q}, U)$ and $\mathbf{P} \cdot \mathbf{Y}(\mathbf{P})$ for $\pi(\mathbf{P})$:

$$A + \mathbf{Q} \cdot \mathbf{C}(\mathbf{Q}, U) = \phi \cdot \mathbf{C}(\mathbf{Q}, U) + \mathbf{P} \cdot \mathbf{Y}(\mathbf{P}) + \mathbf{v} \cdot \mathbf{Y}(\mathbf{P}). \quad (5)$$

Therefore

$$A + (\mathbf{Q} - \phi) \cdot \mathbf{C}(\mathbf{Q}, U) = (\mathbf{P} + \mathbf{v}) \cdot \mathbf{Y}(\mathbf{P}). \quad (6)$$

Equations 1 and 2 imply that $(\mathbf{Q} - \phi) = (\mathbf{P} + \mathbf{v}) = \mathbf{R}$ and equation 3 implies $(\mathbf{C} - \mathbf{Y}) = \mathbf{M}$. Since the elements of \mathbf{M} corresponding to nontraded goods are zero, equation 6 therefore implies that international payments are in balance:

$$A + \mathbf{R}^t \cdot \mathbf{M}^t = 0. \quad (7)$$

In GTEM each region enjoys some degree of market power associated with the Armington product differentiation assumption (Armington 1969a,b). Accordingly, the world prices of the traded goods can be expressed as:

$$R_i = \zeta^i(\mathbf{M}^t, \mathbf{Z}^*), \quad i = 1, 2, \dots, T, \quad (8)$$

where \mathbf{Z}^* is a vector of variables representing demand and supply conditions in the rest of the world markets.

The regional economic model, defined above by the sets of equations 1–4 and 8, contains $3(T+N) + T + 1$ individual equations.⁷ With \mathbf{Z}^* and A determined outside the above regional economic system, there are equal numbers of endogenous variables in the regional system. For each of the $T+N$ goods, there are three endogenous variables: the consumer price, the producer price, and either net imports (if the good is traded) or the tax-exclusive price (if it is nontraded). Also, there are T endogenous world prices and the variable U . Thus, the regional economic system is closed. Let vector \mathbf{Z} denote the equilibrium outcomes in the regional economy for given \mathbf{Z}^* and A .

Each individual GTEM region, in isolation, can be characterised by the above equation system. In GTEM, however, all regional economies are interlinked through trade in goods and services. It is convenient to think of a global economy comprising a region in question and the rest of the world. Then, in terms of the above notations, the vector of variables representing demand and supply conditions in the rest of the global economy, \mathbf{Z}^* , are determined endogenously for given \mathbf{Z} and A^* , where A^* is the rest of the world equivalent of A . With the specification of a global financial market and the global constraint of $(A + A^* = 0)$, GTEM solves for both \mathbf{Z} and \mathbf{Z}^* — the global general equilibrium.

The model structure described above is deliberately kept simple for expositional convenience. GTEM is much more detailed and disaggregated, and has many more features including a greenhouse gas emissions accounting module and population module. The model is specified in log-change form and the model solutions provide, among other variables, the growth in forestry output (an element of vector \mathbf{Y}^t defined above) and, due to the new land use change model described earlier in the paper, the growth in various types of land used in forestry (represented by an element of vector \mathbf{C}^n). As discussed below, these results are fed into the GTEM forest inventory to determine forestry sinks.

Accounting for forest sinks in a GTEM region⁸

As already discussed, the forest inventory in a GTEM region is classified by age, by land class and by management type. Rather than yearly age cohorts, existing forest stocks are classified into ten 10-yearly age cohorts because of data availability. Let A_{alm}^0 be the beginning-of-the-year area (in hectares) of managed forestry in age cohort a ($a = 1, 2, \dots, 10$) on land type l ($l = 1, 2, \dots, 18$) and under management m ($m = 1, 2, \dots, 14$) in a GTEM region. This defines the forestry inventory in GTEM at the beginning of the year. Because tree species are not modeled explicitly, average relationships between plant growth rate, management type and age class are used. Let Y_{alm} denote the average forest stock (measured as m^3 of wood per hectare) on land type l with forest of age

⁷ Note that equations 5, 6 and 7 do not provide independent restrictions on the variables, since they are derived from equations 1 to 4.

⁸ The equation system described in this section is identical for all GTEM regions, and the regional subscript (usually, r) is suppressed to avoid notational cluttering.

cohort a under management m ; and α_m is the carbon conversion factor for forest stock (tonnes of carbon per m^3 of wood) under management type m . The product of the last two ($Y_{alm} \times \alpha_m$) determines the amount (in tonnes) of carbon stock per hectare of forest land of type l under management m holding forest of age class a . These can be labeled as ‘sequestration coefficients’. The beginning-of-the-year carbon stock inventory (in tonnes of carbon) is thus given by ($A_{alm}^0 \times Y_{alm} \times \alpha_m$), a , l , and m .

Let ΔC denote additional carbon stock accumulated during the year in the managed forest. Assuming that Y_{alm} and α_m do not change over time, the total sequestered carbon by the end of the year can be estimated as:

$$\Delta C = \sum_a \sum_l \sum_m \Delta A_{alm} \times (Y_{alm} \times \alpha_m), \quad (9)$$

where $\Delta A_{alm} (= A_{alm}^+ - A_{alm}^0)$ denotes the change in forest land area of type l with forest stock of age class a under management m , by the end of the year. As already defined in the text, A_{alm}^+ denotes the end-of-the-year area (in hectares) of managed forestry in age cohort a on land type l and under management m .

Changes in the forest inventory at the end of the year, ΔA_{alm} , associated with the three sources described in the text — forest stock harvesting and reforestation, forestry aging, and net land shifting into forestry — can be derived as follows.

1. Changes in the forest inventory due to logging

It is assumed that forest stocks over 30 years of age are logged. The harvested forest land area is assumed to be reforested and hence, added to the first forest age cohort. Accordingly, changes in forest inventory due to logging are estimated as:

$$\begin{aligned} \Delta A_{alm}^H &= -H_{alm}^0(1+y) && \text{for } a = 4, 5, \dots, 10; \text{ and } l, m; \\ \Delta A_{alm}^H &= -\sum_{a=4}^{10} \Delta A_{alm}^H && \text{for } a = 1; \text{ and } l, m; \end{aligned}$$

where ΔA_{alm}^H denotes changes in forest inventory due to logging (superscript H for harvesting or logging); H_{alm}^0 denotes the area harvested in the previous year; and y is the average growth in logging in the current year relative to the previous year.

2. Changes in the forest inventory due to aging

It is assumed that one-tenth of the forest stocks in each age cohort, which have survived the annual harvest, shifts to the next. However, nothing can be shifted from the final age

cohort of over 90 years. That is, changes in forest inventory due to forestry aging can be estimated as:

$$\begin{aligned} \Delta A_{alm}^A &= - A_{alm}^0 / 10 && \text{for } a = 1; \\ \Delta A_{alm}^A &= (A_{(a-1)lm}^0 - A_{alm}^0) / 10 && \text{for } a = 2, 3; \\ \Delta A_{alm}^A &= (A_{(a-1)lm}^* - A_{alm}^*) / 10 && \text{for } a = 4, \dots, 9; \\ \Delta A_{alm}^A &= A_{(a-1)lm}^* / 10 && \text{for } a = 10; \end{aligned}$$

where ΔA_{alm}^A denotes changes in forest inventory due to forestry aging (superscript A for aging) and A_{alm}^* ($= A_{alm}^0$ for $a = 3$; and $= A_{alm}^0 - H_{alm}^0 (1 + y)$ for $a \geq 4$) denotes the beginning-of-the-year forest land adjusted for forest area harvested during the year.

3. Changes in forest inventory due to land shifting between forestry and agriculture

Plantation is assumed to take place immediately in any land transferred from agriculture to forestry. The additional forest land is accordingly accounted for in the first forest age cohort. Also, for accounting convenience, any shift of land from forestry to agriculture is first taken away from the first age cohort, which will be subsequently adjusted for land becoming available for reforestation (associated with forest harvesting). That is, changes in forest inventory due to land shifting are given by:

$$\Delta A_{alm}^S = \sum_{a=1}^{10} A_{alm}^0 (l_i) \quad \text{for } a = 1; \text{ and } l, m.$$

where ΔA_{alm}^S denotes changes in forest inventory due to land shifting (superscript S for land shifting) between forestry and agriculture; l_i is the average growth in forest land of type l , in the current year relative to the previous year; a positive value for l_i is associated with agricultural land converted to forest and a negative value indicates the conversion of forest land to agriculture.⁹

4. Changes in the forest inventory due to all three aspects

The end-of-the-year overall changes in forest inventory are given by the sum of the above three groups of changes as:

$$\Delta A_{alm} = \Delta A_{alm}^A + \Delta A_{alm}^H + \Delta A_{alm}^S \quad a, l, m.$$

⁹ To achieve the required forest land conversion to various agricultural uses, forest land can be withdrawn from higher age cohorts if the end-of-the period forest land in age cohort 1 is not sufficient.

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