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Modelling Forestry in Dynamic General Equilibrium

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Abstract

Adequately representing dynamic characteristics of land use change and forestry in computable general equilibrium models is challenging but essential if modellers are to provide credible assessments of policies that directly or indirectly influence these phenomena. In this paper, we show how a dynamic representation of planted or naturally regenerating forests may be integrated within a neoclassical, intertemporal general equilibrium model. We demonstrate the application of such a model to assess the impacts of including forestry within a hypothetical emissions trading scheme in the US, showing the resulting changes in land use and increases in the optimal rotation length.

Keywords

Intertemporal general equilibrium, optimal forest management, forest carbon credits

INTRODUCTION

Reducing deforestation and degradation, afforestation, reforestation, and forest management, management of harvested wood products and forest bioenergy supply are listed by the IPCC as key policies for short to medium term greenhouse gas (GHG) mitigation (IPCC, 2007). Policies and measures to limit forest carbon emissions and/or to increase forest carbon stocks are of considerable interest to policy-makers in many countries, not only for their potential mitigation benefits, but also for their food security and even energy security implications. However, to robustly quantify the impacts of such policies often requires accounting for interactions not only between agricultural and forestry sectors, but also energy and other sectors. At larger scales, these interactions may also involve linkages through international trade.

General equilibrium (GE) models are one of the few analytical tools that can represent interactions between all sectors and regions of the global economy, and can be used to assess the direct and indirect (sometimes counter-intuitive) effects of climate and other policies. While significant advances have been made in the representation of land use and land use changes in GE models, important challenges remain (Hertel et al., 2009). One important challenge is to adequately model forestry (Sohngen et al., 2009; Pant, 2010). In this paper, we discuss different ways of accounting for forest carbon and explain how these affect the economics of planted or naturally regenerating production forests. We then go on to show how the impacts of a hypothetical policy may be simulated using our GE model 'CliMAT-DGE', which includes an explicit representation of forest growth and dynamically optimal decisions in forestry (Lennox et al., 2011).

Dynamic models of timber supply are found in partial equilibrium models developed by forest economists. For example, the Global Forest Products Model (GFPM) (Buongiorno et al., 2003) provides a detailed representation of the supply of and international trade in timber and harvested wood products within a recursive dynamic partial equilibrium framework. The Global Timber Model (GTM) (Sedjo and Lyon, 1990; Sohngen et al., 1999) focuses on global timber supply and demand within an optimal dynamic partial equilibrium framework. The GTM is an intertemporal optimisation model in which forestry producers seek to maximise profits subject to various constraints associated with different forest management regimes.

Traditionally GE models that distinguish a forest sector have modelled it as any other sector. This overlooks the slow dynamic responses that result from the production of outputs using land and other inputs applied over preceding decades. However, recently there have been efforts to model forests and forestry more realistically. Golub et al. (2009b) extend a recursive dynamic version of the GTAP-AEZ model to model deforestation, using the input and output data of the GTM. Pant (2010) proposes a more comprehensive approach in a recursive dynamic framework, explicitly modelling (as relevant) activities of planting, growth and logging. In this paper we develop and demonstrate a multiregional intertemporal GE model that incorporates a bottom-up representation of forestry, similar to that used in the GTM. This framework allows us to endogenously model intertemporally optimal decisions in forestry. We demonstrate the model for several carbon trading scenarios.

While much international attention has rightly focussed on efforts to reduce deforestation and degradation of primary forests in developing countries, forestry does or could potential play an important role in mitigation in many developed countries too. In this paper, we provide examples for the US, where carbon stocks in forests were 46 Gt CO_2-e in 2010, with a further 2.5 Gt CO_2-e stored in HWPs (EPA 2011). Increasing afforestation and forest carbon management could significantly increase US removals of GHGs (Hertel 2009). The next section briefly describes our computational model 'CliMAT-DGE', focussing on the inclusion of forest growth dynamics and optimal management in an intertemporal GE framework. Following this, we review forest carbon accounting protocols and explain the economic incentives that may be associated with one particular accounting scheme. Finally, we present and discuss the results of an illustrative simulation study that involves the inclusion of forestry in a hypothetical US emissions trading scheme (ETS).

THE CLIMAT-DGE MODEL

Overview

Our computational framework CliMAT-DGE (Climate Mitigation, Adaptation and Trade in Dynamic General Equilibrium) is ultimately intended to consist of a number of tightly linked economic and biogeophysical models. The central component of this computational framework is a multiregional intertemporal general equilibrium (GE) model (Lennox et al., 2011). Each region has a single representative household. We assume households have perfect foresight and maximise the discounted sum of their instantaneous utilities, subject to a lifetime income constraint. Firms are assumed to be identical within each production sector and to operate with constant returns to scale in perfectly competitive markets. Regions are linked by bilateral trade flows, modelled under the Armington assumption, with imperfect substitution between domestic and imported products from different regions. International transport margins are associated with bilateral trade flows. Taxes and subsidies on output, factor inputs, intermediate and final consumption of goods are modelled, as are taxes and subsidies on bilateral trade flows.

Firms' technologies are described by nested constant elasticity of substitution (CES), Cobb-Douglas and Leontief production functions. Different nesting structures are used for agricultural and forestry sectors, each of the coal, oil, gas, oil refining and electricity sectors, and manufacturing and service sectors. All sectors in the model use intermediate inputs, capital and labour. Agricultural and forestry sectors also use land, while the primary energy sectors also use sector-specific and depletable resources. Capital, once installed, is also sector specific and depreciates at a constant rate. Capital stocks are increased through new investments.

Following Mathiesen (1985) and Lau *et al.* (2002), the model is formulated as a mixed complementarity problem (MCP) in GAMS™ and solved using the PATH solver (Ferris and Munson, 1998) with a five-year time-step. It is calibrated to the GTAP version 7.1 database (Narayanan and Walmsley, 2008), which we aggregate here to thirteen sectors and three regions: the United States (US), rest of OECD (ROECD), and rest of the world (RoW).

Integrating bottom-up forestry production

Forests are managed in many different ways, which may be more or less economically optimal with respect to timber and other values (e.g. carbon storage, recreation, biodiversity). To represent various types of forest and forms of management within a dynamic intertemporal general equilibrium model, we first need to describe them in a way that is sufficiently rich while remaining analytically tractable. Arguably, the GTM provides just such a description; indeed, it is presented in just this light by Sohngen et al (2009). In this paper, we limit our focus to planted or naturally regenerating (i.e. self-seeding) production forests comprising even-aged stands. Such forests dominate production in temperate regions.

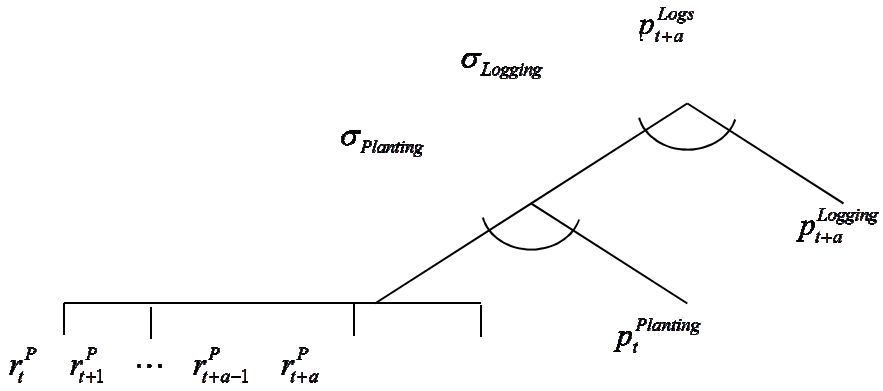
Our objective is to account for the optimal management of even-aged production forests, including determination of the optimal intensity of planting, management and harvesting, and the optimal rotation length (harvest age). In many developing, tropical and sub-tropical countries, a large fraction of timber supply is associated with harvesting or clearance of primary forests. This poses different modelling challenges that we will deal with in future research.

In the GTM, a biomass growth function gives biomass volume as a function of rotation length and management inputs associated with planting and silviculture. The equations are parameterised to reflect the growth and management of different species in different regions. In the GTM, the optimal rotation length is determined endogenously to maximise the present value of current and future rotations. The essential feature of this calculation is that there is a trade-off between the increased yields obtained from longer rotations, and the opportunity cost of delaying harvest of the current and future rotations. Non-timber values, such as forest carbon credits, can also be considered.

The problem is slightly different in a GE setting in which we have competing land uses (i.e. agricultural) and an explicit market for land. Recalling our earlier assumptions of competitive markets and constant returns to scale, we wish to choose the input proportions *and* a harvest age that will yield the maximum of zero pure profits and equalise (discounted) marginal revenues and costs. Similar to the GTM, our approach is to use complementarity conditions to determine endogenously the particular input proportions and rotation length(s) that achieve this.

We define production functions for forestry that combine land and other inputs to produce logs for some harvest age a. In these production functions, planting inputs (if relevant) are used in period t, together with land in periods t to $t+a-1$ and logging inputs in period $t+a$. Depending on the forest management regime, it may additionally be desired to model silvicultural management inputs (associated with, e.g. thinning) at one or more periods between t and $t+a$, and there may be associated secondary outputs (e.g. biomass available from thinnings). Non-timber secondary outputs (e.g. forest carbon credits) can also be modelled. The important restriction on this production function is that the land input is the same in all periods, as production of logs in period $t+a$ requires that trees remain on a given area of land up to this time. In Figure 1, we illustrate the structure of a single production function with planting, land and logging inputs. Calibration of this model and formulation of appropriate terminal conditions are described in Lennox *et al* (2011).

Figure 1: Nested Production Function for Forestry



For each forest type in a given region (or in the simplest case, for a single forest type representative of that region) several such production functions are defined, one for each allowable discrete harvest age *a*. These functions will differ in the number of time periods for which land is required and the proportions of non-land inputs. Output per unit of land as a function of *a* will reflect a yield curve for merchantable log output reflective of the forest type and region. Upper and lower bounds on *a* may reflect only the range required to accommodate likely variations in relative prices and demand, or may also reflect structural factors (e.g. a regulatory minimum harvest age). Complementarity between the negative profits and level of output of production functions for each allowable harvest is exploited to endogenously determine optimal rotation length(s) in any period.

FOREST CARBON ACCOUNTING

Accounting Protocols

There are two main elements to forest carbon accounting protocols implemented in voluntary and compliance carbon trading schemes. The first are the rules around what carbon pools are eligible and how they are counted. The second is the treatment of the potential non-permanence of forest carbon sinks. For example, the Chicago Climate Exchange issues credits for carbon in the live tree, below ground and optionally wood products remaining after 100-years. For the latter, credits are issued at the time of harvest. Up to 20% of credits are also deducted from carbon pools to account for uncertainty in the measurement of actual carbon sequestered in the biomass. Forest owners providing offsets are contractually required only to maintain carbon sequestration offsets through December 31, 2010, after which the sequestered carbon could be emitted (Chicago Climate Exchange 2007a,b).

Galik et al. (2009) and Erikson et al. (2011) provide useful reviews of carbon forestry accounting protocols in the US. The protocols they review differ in terms of:

a. Eligible pools of carbon; live tree above ground, live tree below ground, standing dead trees, litter, soil and harvested wood products
b. Tests for additionality

c. Treatment of carbon stored in harvested wood products (HWP)
d. Deductions from carbon pools to capture uncertainty of measurement, leakage and reversals

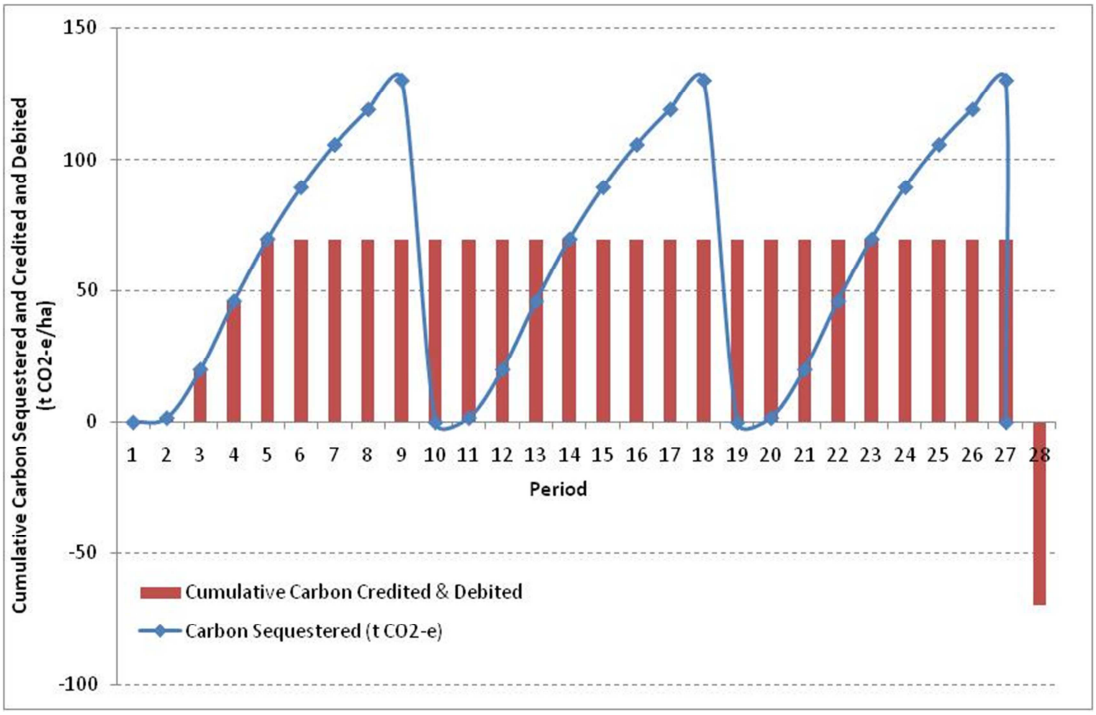
The term “leakage” is used with different meanings in relation to forest carbon. Firstly, leakage refers to displacement of emissions from inside the project boundary to outside the project boundary, as a result of project activities. For example, a reduction in harvests to increase carbon storage in a forest may result in increased harvests from forests elsewhere (Murray et al. 2004). Secondly, leakage may also refer to increases in fuel emissions resulting from use of equipment to carry out management activities. Most US accounting protocols consider the former, while Clean Development Mechanism protocols consider both (Lazarus et al. 2010).

For forest carbon sequestration projects “permanence” refers to the fact that the sequestration in forests can be reversed, through forest loss due to harvesting, fire, windthrow, etc., cancelling the GHG benefit achieved by a project. Permanence covers both the length of time a project is required to maintain GHG mitigation and rules for avoiding reversals in the case that sequestered carbon is emitted. For voluntary programs where limited enforcement can be expected, requiring permanent conservation easements is often used. For compliance programs, periodic assessment of continued carbon storage is often required and carbon credit owners are held liable for replacing reversed offsets. This may be by using other carbon credits, and/or a fraction of the sequestered carbon being held in reserve to cover emissions (Lazarus et al. 2010).

For example, New Zealand’s Permanent Forest Sink Initiative (PFSI) is implemented as a covenant between the Crown and the landowner, which lasts for at least 50 years, and places restrictions on harvesting of the forest for 99 years to create a continuous cover forest that forms a permanent forest sink. Under the PFSI, limited harvesting is permitted, but participants are liable for any net loss in the carbon stocks in their forest from harvesting or any other cause up to the net amount of carbon credits previously received for the forest (MAF 2011).

The issue of non-permanence of forest carbon sinks has lead to several suggested carbon crediting approaches for accounting for the emission of sequestered carbon; average stock, temporary credit, and stock change (Pajot 2007). The average stock approach was considered for afforestation projects where successive harvesting and replanting cycles would occur (Schroeder 1992, Schlamadinger et al. 2002, Baalman and O’Brien 2006), with credits given annually based on carbon stock increases up to the long-run average stock (Figure 2). This approach has been abandoned by all countries due to challenges in its implementation.

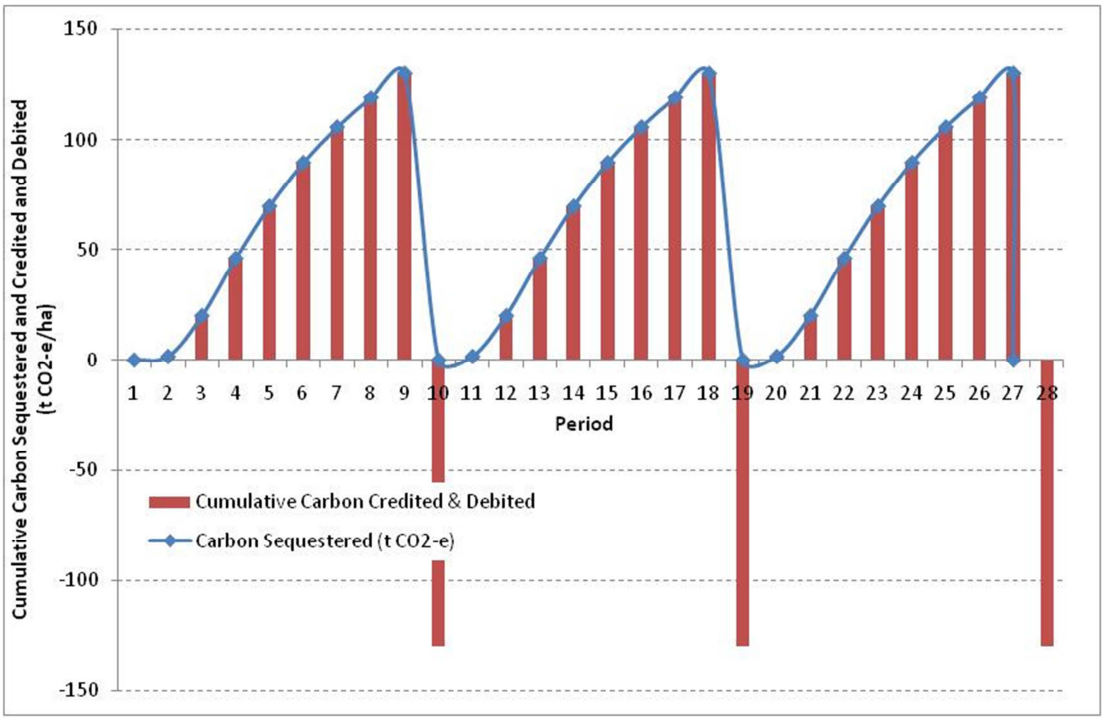
Figure 2: Above-Ground Carbon Sequestration Curve (blue), and Cumulative Carbon Credits Accrued to or Debited (red) per Hectare of Southern Natural Pine Forest Managed on a Forty Year Rotation under the Average Stock Approach



The temporary credit approach is used for carbon credits from forest plantations in non-Annex I countries under the Clean Development Mechanism, where an emitter temporarily purchases carbon credits associated with a forest plantation to offset their emissions. The forest owner is then liable for the emissions. At the end of the contract, liability for the emissions goes back to the emitter (Pajot 2007). These carbon credits may then be a temporary source of lower cost credits for offsetting emissions for emitters where the cost of directly reducing emissions or purchasing permanent carbon credits are too costly. For forest owners in non-Annex I countries it provides a temporary source of revenue from carbon sequestered in their forest.

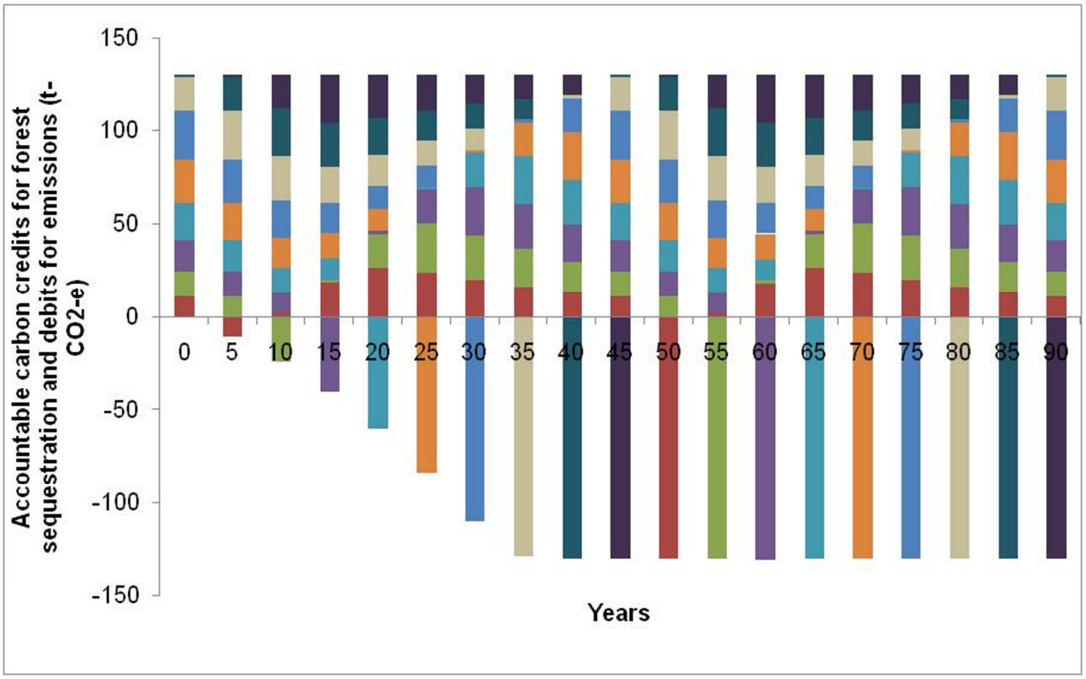
The stock change approach is used in Kyoto Protocol Annex I countries, with carbon credits attributed when carbon stocks increase, and debits paid when carbon stocks decrease (Schlamadinger et al. 2002) (Figure 2). The stock change approach is used in the New Zealand emissions trading scheme for post-1989 planted forests (MAF 2009) and the Permanent Forest Sink Initiative (MAF 2011).

Figure 3: Carbon Sequestration Curve (blue), and Cumulative Carbon Credits Accrued and Paid (red) per Hectare of Southern Natural Pine Forest Managed on a Forty Year Rotation under the Stock Change Approach



The baseline for forest carbon accounting is also important. If the initial carbon stock of a standing forest is grandfathered out, this can result in a substantial surplus of credits over debits in the initial decades. This is shown in Figure 4 for a forest of Southern natural pine with an equal area in each age class. Credits accrue for a growth increment in every age class. In the first period though, there are no debits, since all of the carbon in the harvested timber is grandfathered out. In subsequent periods, an increased fraction of the carbon associated with harvests is accounted for, until the credits and debits balance in each period (i.e. as one complete rotation is subject to the scheme. The cumulative surplus of credits over debits is reduced again if stands are not replanted.

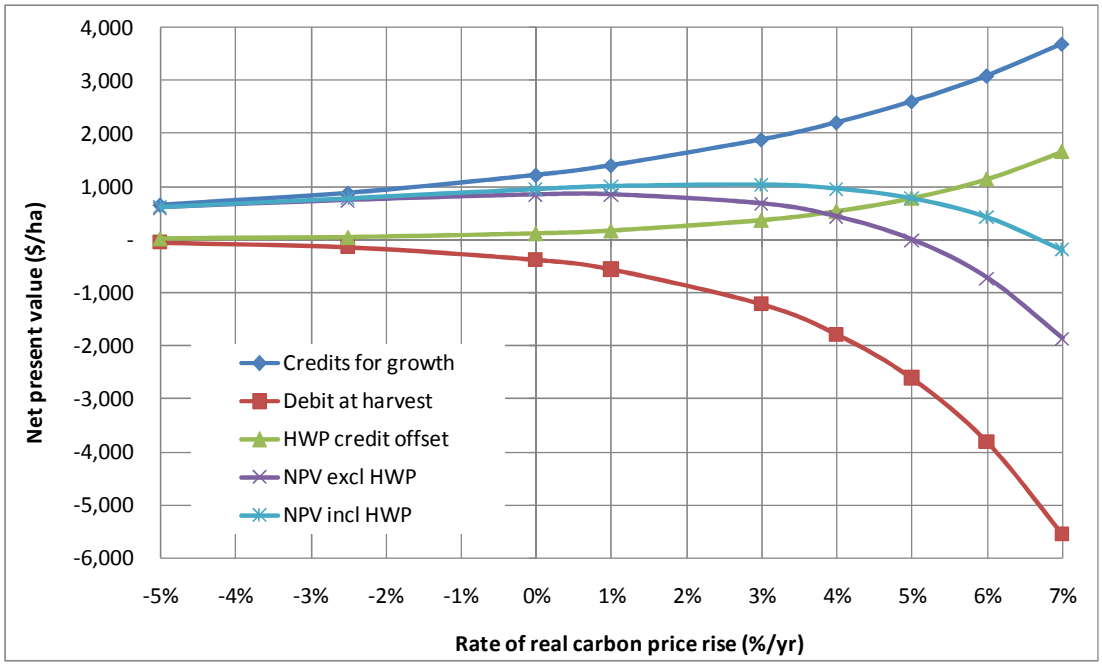
Figure 4: Carbon Credits (Sequestration) and Debits (Emissions) Over a Ninety Year Period for a Southern Natural Pine Forest Estate Managed on a Forty Year Rotation With Equal Areas in Each Age-Class



Economics of Forest Carbon with the Stock Change Approach

For a given rotation length and discount rate (δ) the PV of carbon credits and debits both increase with the rate of rise of the real carbon price (γ). Initially, the carbon NPV initially rises with γ. Assuming carbon neutrality over the rotation, the carbon NPV should reach a maximum at a point $0<\gamma<\delta$ then fall to become negative for $\gamma>\delta$. If credits are earned for carbon storage in HWPs, these partially offset debits at harvest. Consequently the carbon NPV curve is shifted upwards and the point at which the carbon NPV is zero shifts rightward. The case in which $\gamma=\delta$ is of particular interest, as if emissions are constrained, but unlimited banking and borrowing are allowed, the carbon price should increase at the discount rate. Below, we model a scheme in which in the long run, $\gamma=0$. This choice is arbitrary and probably less realistic in the long run than a value of γ closer to δ. However, we make it for reasons of technical simplicity and to provide an interesting case in which there are strong incentives to store carbon in production forests.

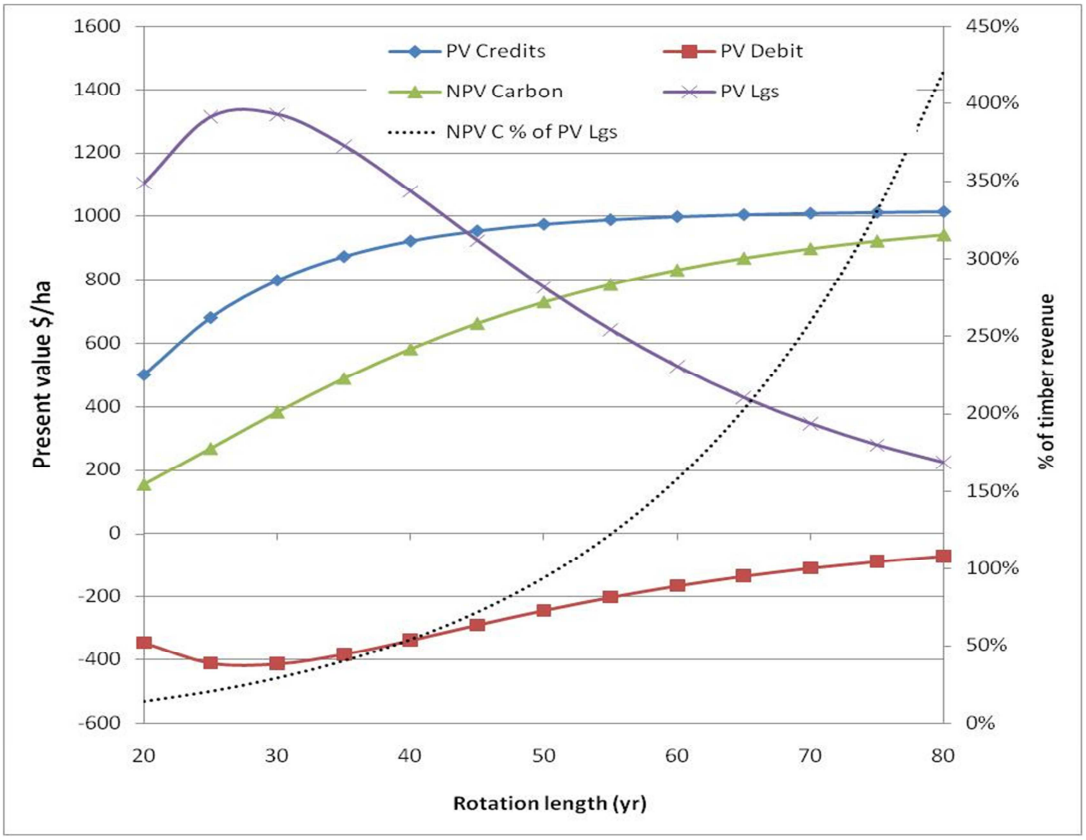
Figure 5: Present Value per Hectare of Carbon Credits and Debits over a Single Forty Year Rotation of Southern Natural Pine (US) With 5% Discount Rate



For a constant real carbon price, figure 4 shows the present value (PV) of revenue from logs harvested (purple line), which peaks around a 30 year rotation, and then declines due to the effect of discounting. To determine the economically optimal rotation length for timber production, the PV of planting, management and logging costs (not shown in the figure) must also be considered. Figure 4 also shows for the stock change accounting approach, the PV of carbon credits for forest growth (blue line), debits at harvest (red line) and the carbon net present value (NPV) for the stand (green line). This applies to new plantings and to existing forests with grandfathering of initial carbon stocks, as explained above.

The PV of carbon credits increases with rotation length, but the rate of increase slows due to the combined effect of the incremental carbon sequestered becoming smaller in older stands (Figure 2) and the effect of discounting future revenues. The PV of carbon debits initially becomes larger (more negative), but then becomes smaller beyond a 30 year rotation, due to the combined effect of discounting the debit over a longer period and the carbon liability at harvest increasing in successively smaller increments (Figure 2). The overall effect is that the carbon NPV rises with rotation length and becomes an increasingly large share of total PV revenues (black line, right-hand axis).

Figure 6: Present Value per Hectare of Timber, Carbon Credits, Debits and Carbon Over a Single Rotation of Different Lengths of Southern Natural Pine (US) With 5% Discount Rate and Constant Real Carbon Price



SIMULATIONS FOR A US ETS INCLUDING FORESTRY

Baseline and Policy Scenarios

To show how the CliMAT-DGE model may be used to analyse the dynamic general equilibrium effects of policies affecting forests and forestry, we simulate the introduction of a measure to include forestry within a hypothetical US emissions trading scheme (ETS). We compare the impacts of this policy against a baseline in which the US implements an ETS to make a once-off 20% reduction relative to its business-as-usual emissions (i.e. emissions are cut 20% immediately, but then rise at the same rate as before). In the baseline, this ETS covers all CO_2 emissions and industrial emissions of non-CO_2 GHGs. We assume that agricultural CH_4 and N_2O emissions are exempted, therefore the baseline does not involve large impacts on either agriculture or forestry compared to business as usual.

In both baseline and policy simulations we include a once-off 20% reduction of emissions in the ROECD region, also achieved using an ETS that does not include agriculture or forestry and separate from the US scheme (i.e. without international emissions trading). No limits are imposed on emissions of the RoW region. As our concern here is only with the *additional* impacts of the forestry measure in the US, the baseline is not designed to be realistic, but it does have two useful features. Firstly and most importantly, it allows us to embed the US forest sector within a

large ETS that creates a demand for carbon credits. Secondly, simulating an ETS for the ROECD region avoids having emissions leakage from the US to the ROECD region, which includes many countries that have now and seem likely to have in the future more stringent climate policies than the US.

In the policy scenario – US ETS including forestry – forest owners receive credits for 5-yearly incremental carbon sequestered in their forests, but must also surrender credits associated with logs harvested; the stock change approach. Carbon initially stored in forests is grandfathered. We consider only the carbon content of living trees, ignoring entirely potential changes in other forest carbon pools. We assume that a third of potential forestry carbon credits and debits are bought and sold in the carbon market, while the remaining two-thirds are unavailable due to non-participation and/or forest owners retaining credits to offset their harvest liabilities.

In the US and ROECD regions we model a single forest type with an initial harvest age of sixty years. Since we have not yet implemented an explicit representation of deforestation, we model forestry in the RoW region like agriculture; using land to produce logs within a single period. This permits immediate conversion of forest to agricultural land in those regions.

Impacts on the US Forest Sector, Agricultural Sectors and Carbon Price

In the baseline, the US carbon price begins at almost \$27/t CO_2-e and falls (in constant dollar terms), but soon reaches an equilibrium level of \$22/t CO_2-e. The higher initial price is due to the initial lock-in effect of sector-specific capital stocks. As explained in the discussion of forestry under a carbon stock change scheme, this significant (albeit not high) and more-or-less constant real carbon price provides a strong incentive to increase forest plantings to shift to longer rotations.

The direct impact of including forestry in the US ETS is an immediate increase in planting and the area of forestland increases by almost 50% within the first five-year period (Figure 7). Over time, this wave of new planting works its way through the forest age structure, but it is not until year 55 that output begins to increase (Figure 8). Output rises rapidly from 55 to 75 years then moves slowly to a new equilibrium growth path 27% above the baseline. The increase in forestland reflects both a higher level of output and an increased rotation length. With a longer rotation, yield per harvested hectare increases, but yield per hectare of forestland per annum falls. A second and less intuitive effect of the increased rotation length is a decline in productivity at harvest. This results from our linking of baseline forestland productivity increases to the date of planting of each rotation. In reality, productivity increases in the forestry sector are associated with various stages from planting (e.g. genetic improvements), to management (e.g. herbicides), to harvest (e.g. improved machinery). Logging and log transport technologies are also linked to technologies used in timber, chip and pulp mills. In its current form, our model therefore overstates this vintage effect on forest productivity.

Figure 7: Productivity-Adjusted Relative Areas of US Forestland by Age-Class

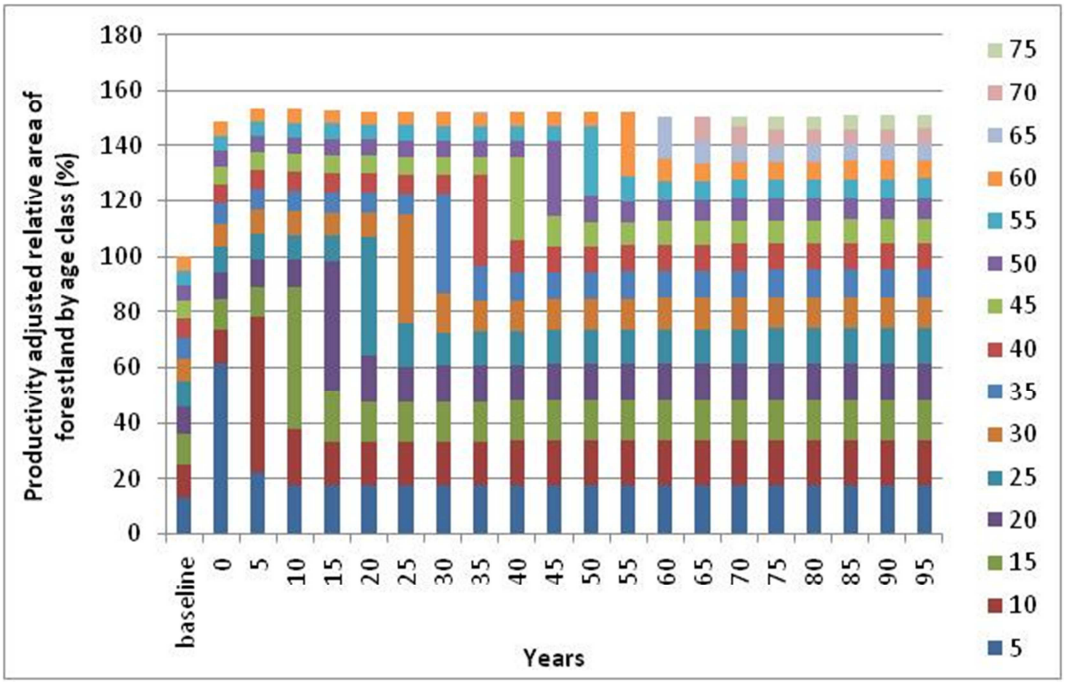
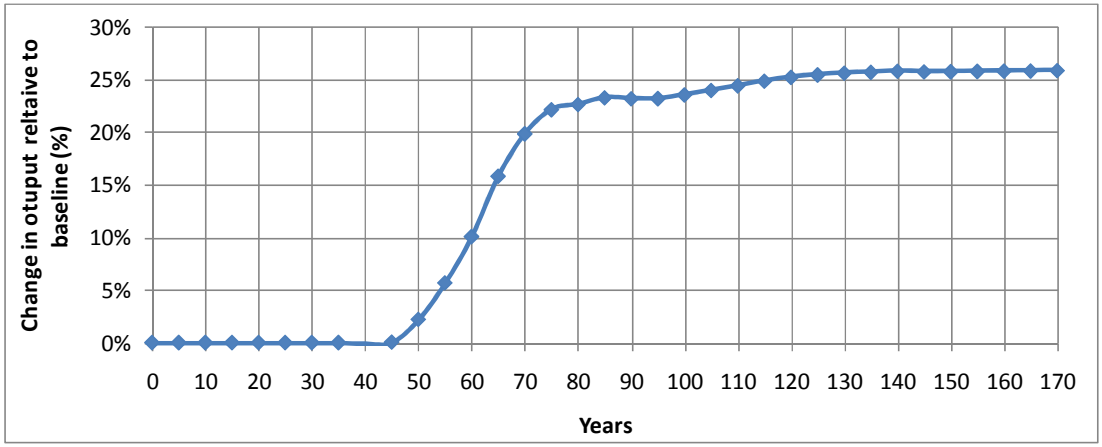


Figure 8: US Forest Sector Output Over Time



The increase in forest land comes at the expense of both crop and grazing lands (Table 1), although the decrease in each of these land uses is very modest. Note that the percentages in the table refer to baseline land values and not to actual land areas. The average price of forestland is relatively lower than that of cropping or pastoral land, hence shares for forestry are lower in terms of value than in terms of absolute area.

Table 1: Long Run Percentage Changes in Shares of Land Use in the US (by Baseline Land Value)

	Baseline %*	Policy %	Difference %	% Change of Effective Area for the Sector
Cropping	79.8%	78.4%	-1.35%	-1.7%
Livestock	17.2%	17.0%	-0.19%	-1.1%
Forestry	3.1%	4.6%	1.55%	50.1%

*Percentages in this column do not sum to 100% due to rounding

Newly planted forestland yields an increasingly large supply of credits as these forests grow, thereby lowering the carbon price by \$2.75/tCO_2-e after 30 years. As these forests begin to be harvested, the net supply of credits is reduced, but it remains positive and lowers the carbon price by \$1.70/tCO_2-e in the long run.

Other Sectoral Impacts and International Emissions Leakage

Table 2 shows how inclusion of forestry in the US ETS affects output in all sectors and regions in the long run. We see that the large increase in output of US forestry is accompanied by some reductions in output of the other two regions. US cropping and livestock output decreases, but significantly less than proportionally to the reductions in area shown in Table 1, implying land use intensification in both these sectors. Again we see opposing although much smaller changes in the other two regions. Due to the slightly lower US carbon price, the impacts of the US ETS on US emissions-intensive production and US demand for domestic and imported fossil fuels are reduced by the inclusion of forestry. Output of these sectors is therefore slightly higher. The increased supply of timber in the US reduces the US log price, benefiting the US HWP sector (as it can source cheaper inputs), while output of this sector falls slightly in the other regions.[1]

[1] It should be noted that the increased output of forestry does not require an increase in HWP output of the same proportion in the model. Firstly, a significant fraction of forestry output is consumed by sectors other than HWP. Secondly, substitution possibilities in the HWP sector allow that a cheaper feedstock will result in substitution away from other inputs. In physical terms, this may correspond to production of a higher volume but lesser quality of wood and paper products and increased production waste.

Table 2: Long-run Impacts on Sectoral output

	US	ROECD	RoW
Cropping	-0.9%	0.3%	0.0%
Livestock	-0.2%	0.1%	0.0%
Forestry	26.6%	-2.6%	-0.1%
Coal	1.1%	0.0%	0.0%
Oil	0.4%	0.1%	0.1%
Gas	0.8%	0.3%	0.1%
Refining	0.7%	0.0%	0.0%
Electricity	0.5%	0.0%	0.0%
Food	0.0%	0.0%	0.0%
HWPs	0.8%	-0.1%	-0.2%
EMT*	0.4%	0.0%	0.0%
NEM**	0.1%	0.0%	0.0%
Services	0.0%	0.0%	0.0%

*Energy intensive manufacturing & transport
** Non-energy-intensive manufacturing

Total net US emissions are capped therefore the policy results in 100% leakage to other sectors in the US. The benefit of including forestry in the ETS is primarily to lower mitigation costs, as indicated by the reduction in the carbon price. Since ROECD emissions are also capped, there can be no emissions leakage at the aggregate level from the US to the ROECD. However, RoW emissions are uncapped, and there may be emissions leakage from the US directly; or indirectly via the ROECD. Considering RoW emissions excluding those from land use change and forestry, our results show no significant changes in aggregate emissions. Note that we have not modelled emissions from deforestation in the RoW region, but, given that RoW forestry output decreases slightly, we can deduce that the US policy does not cause emissions leakage to the RoW region.

CONCLUSIONS AND FUTURE RESEARCH

We have developed and demonstrated the integration of bottom-up representations of planted or naturally regenerating production forests within a top-down intertemporal GE framework. Using multiperiod production functions and complementarity conditions, we can account for the optimal intensity of planting, management and harvesting and the optimal harvest age for age-structured forests. A comparable bottom-up treatment of timber production from and clearance of primary forests is the subject of ongoing research. These dynamic representations of forestry will allow for more robust assessments of policies such as domestic GHG emissions trading schemes or reducing emissions from degradation and deforestation Plus (REDD) in developed and developing countries.

An illustrative scenario using a four-region version of our CliMAT-DGE model with bottom-up forestry showed the effects of including forestry in a hypothetical US ETS. In the rather favourable context for forestry of a nearly constant real carbon price, our results showed a significant expansion of forestland and output in the US, and changes in the age structure of the forest estate and harvest ages over many decades. While flow-on effects to other sectors and regions in our simulations were quite small, larger effects could be expected for policies affecting a larger part of global forest production or in regions where forestry accounts for a larger share of economic activity.

Computational considerations limit the number of regions and the level of bottom-up detail achievable through direct bottom-up integration. However, larger models should be solvable with the aid of decomposition techniques, which allow tight and theoretically consistent linking of a top-down model with bottom-up sub-models. This is another focus of our own-going research.

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