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ASSESSING THE ECONOMIC APPROACHES TO CLIMATE-FOREST POLICIES: A CRITICAL SURVEY

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ABSTRACT

The linkage between global climate change and forests have assumed political prominence as forest sinks are now acknowledged as a means for off-setting carbon dioxide (CO_2) emissions under the Kyoto Protocol targets. As such, policies to stimulate forest carbon sequestration in an open economy will require varying levels of economic information to allow for decisions that are both efficient and sustainable. This paper reviews the various economic approaches that have been recently used to examine the impacts of climate-forest policies, and discusses their usefulness for policy analysis. A suite of integrated economic-ecologic models is also reviewed to contrast with the shortcomings of static single sector studies, and a series of guidelines for future integrated research in this area are highlighted.

1 INTRODUCTION

The international climate negotiations in Marrakech (November 2001) finally brought into agreement a framework for implementing the 1997 Kyoto Protocol. With the "Marrakech Accord", countries were able to resolve their disagreements over the role of forests and agriculture as carbon sinks, a thorny issue that had derailed earlier negotiating sessions. Land-use, land-use change and forestry activities will receive credits during the first commitment period (2008-2012) for all human-induced forest, cropland and grazeland management and re-vegetation activities since 1990 (UNFCCC, 2001). As the dust settles from Marrakech, those countries with significant forest carbon opportunities and who have lobbied extensively on this issue, such as Canada, Australia and the Russian Federation[1], are likely to implement domestic climate forest policies as a significant part of their national climate change action plans.

The climate-forest linkage is complex. Forests play a prominent role in the global carbon cycle by absorbing atmospheric carbon dioxide (CO_2) through photosynthesis and storing carbon in the form of biomass. As such, a strategy for mitigating climate change can be achieved by sequestering CO_2 from the atmosphere through afforestation or replanting activities, and by slowing the loss of carbon from plants and soils through reduced rates of deforestation. The latter is particularly critical as increasing land scarcity due to population and development pressures is driving forest clearing around the world – land use change accounts for about one-third of total anthropogenic CO_2 emissions (those that are produced, induced or influenced by human activity) into the atmosphere (IPPC, 2000). In turn, there is a feedback effect where global warming threatens to emerge as a driving factor for forest loss in the future, leading to potentially even greater CO_2 emissions. As such, the use of forests as a carbon sink will generate even more scrutiny in the coming years.

1.1 Objective

Following the Kyoto Protocol in 1997, academic literature on the economics of climate change has grown tremendously (Toman, 2001). Economic ideas have played an influential role in shaping international policies for reducing greenhouse gases (GHG); examples include the design of economic incentives for developing renewable energy technologies, and international trading of carbon emissions rights. Similarly, economic approaches have been used extensively to evaluate the costs and benefits of climate policy impacts (see Kolstad and Toman, 2000 for a review).

Using forests to mitigate CO_2 emissions will obviously have direct impact on forest areas, timber harvest levels, rotation lengths and levels of management intensity (Solberg, 1997; van Kooten et al., 1995; Plantinga and Birdsey, 1994). In turn, this will affect forest product prices, consumption and trade, forest sector employment and income, and other economy-wide effects. There is a substantial body of policy studies centered on assessing the economic impacts to timber production and markets, with

[1] The U.S. has indicated that it will not ratify the Protocol, but will not prevent other countries from going ahead with the Protocol "so long as they do not harm legitimate U.S. interests" (IISD, 2001).

varying economic theories and degrees of coverage. Most are, however, limited in capturing costs outside of the forest sector, non-market or ecological values of the forest, or for reflecting the interactions between climate change processes and the forest ecosystem (Binkley and van Kooten, 1994).

This paper is a review of the different economic methodologies used to examine the effects of climate-forest policies – ranging in scope from stand-level landowner perspectives to global trade models, and from single-sector to macro-economic models. The advantages of economy-wide and dynamic economic-ecologic models are reviewed to contrast with the shortcomings of single sector models and to emphasize their role in supporting prudent policy choices. Finally, opportunities for future integrated research are highlighted.

2 ECONOMIC ANALYSES OF CLIMATE-FOREST POLICIES

Forestry activities are long thought to be a low-cost option for mitigating climate change (Parks and Hardie, 1995; Moulton and Richards, 1990). Climate-forest policies generally fall into one of three categories: to increase the standing inventory of forest biomass, to extend the life storage of carbon in forest products, and to substitute wood products for other materials that emit more CO_2 in their manufacture, use or disposal (Sampson and Sedjo, 1997). This paper focuses on the first category, policies that reduce deforestation, increase afforestation, or influence forest management practices to reflect the value of carbon sequestration.

Figure 1 illustrates how a climate-forest policy could impact the flux of carbon. Government policy affects these flows in the market, which acts as an information conduit for converting policy changes into price signals. A carbon policy in the form of carbon taxes and/or credits will influence the optimizing behavior of private forest owners, and over the longer term, impact wood supply, prices, trade, consumption, and efficiency in the use and manufacture of wood products. This could also lead to potential fluctuations in the size of forestlands, land-use change between forestry and other sectors, and the standing stock of timber (and carbon).

A policy to induce change in forestry practices raises a myriad of questions:

a) What are the incentives for enticing forest owners to manage their forests for both timber and carbon?
b) Which lands can be converted to forests?
c) What is the long-term impact on the forest sector market?
d) Or on carbon stocks and fluxes?

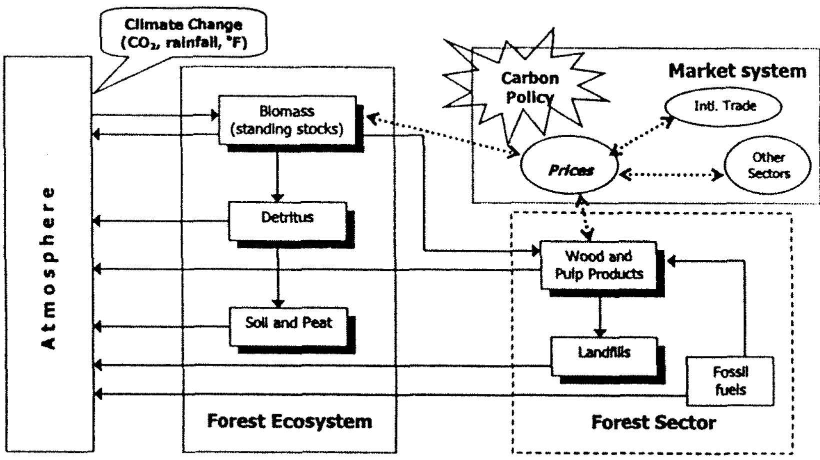

Figure 1 Forest carbon (C) cycle

The solid arrows represent C flows. Primary C reservoirs are in the atmosphere, forest ecosystems (left), and forest products. The release of fossil fuel C in the forest sector, and its displacement by direct and indirect means, are shown as components of the forest product pool. Releases of C to the atmosphere from the forest ecosystem include all forms of decomposition, combustion and respiration from vegetation biomass. Uptake of C from the atmosphere occurs only though photosynthesis, a process that is affected by changes in the climate and atmospheric CO_2 concentration. The market system (top right) acts as a conduit for converting a C policy shock into price signals (represented by dashed arrows) that will result in adaptation in forestry practices, which will, in turn, affect the standing stock of timber in forests and over the longer term, affect prices, trade, local consumption, and use/manufacturing efficiency.

e) What are the economy-wide impacts?
f) What are the distributional consequences? and
g) What is the policy's efficiency in mitigating overall CO_2 emissions?

Current capacity to adequately answer all these questions is still lacking.

We begin by describing the literature on use of micro or stand level assessments to analyze either climate change effects or specific carbon-related policies. These studies examine the adaptive behavior of forest owners using the Faustmann principle for determining optimal rotation ages. The next class of studies builds on the previous by incorporating endogenous adaptation at the stand-level to regional or national assessments. These are commonly static simulations of timber market models using spatial equilibrium methods, although few have integrated dynamics and ecological elements into the framework. Studies with a global scope are similarly constructed as the regional models, but with the incorporation of timber trade data between regions. The final group of studies is those with economy-wide linkages and/or a macro-economic perspective. These different classes of models are then compared in their ability to provide a holistic analysis of a climate-forest policy.

2.1 Micro (or Stand)-level Studies

Since carbon sequestration is perceived as a positive externality to timber production (a public good), there is little incentive for private investments in the production of carbon storage within a market economy (Solberg, 1997). Policies to ensure for a desired level of carbon stock in the economy will have to provide incentives to, or impose taxes on, private landowners to internalize carbon costs and benefits in their forestry practices. This will have significant impact – forestry practices that incorporate carbon storage benefits have longer harvest rotations than those that merely maximize timber revenues (Stainback and Alavalapati, 1999; Solberg, 1997; van Kooten et al., 1995).

van Kooten et al. (1995) were among the earliest to develop a methodology for internalizing the carbon sequestration benefits of growing trees into the Faustmann model. The Faustmann principle for choosing the optimal rotation age for a commercial forest plantation is based of the criteria of maximizing net present value of timber income. van Kooten et al.'s extended Faustmann model, thus, takes into account both commercial timber and carbon uptake values (carbon credits), and provides the opportunity to impose a penalty for releasing carbon into the atmosphere at harvest (carbon taxes). Their primary conclusion is that rotation ages in the U.S. Pacific Northwest are likely to increase by about 20% for the most likely range of carbon credits and taxes, but that it may be worthwhile to never harvest old-growth forests to avoid releasing the large stocks of biomass carbon into the atmosphere.

Numerous studies have applied variations of the Faustmann model to different forest types and regions, and for different objectives – Stainback and Alavalapati (1999), for example, examined the consequences of a carbon policy on management of slash pine forests in Florida. Huang and Kronrad (2001) used the difference between the Faustmann's soil expectation value of the economically optimal rotation and the biologically optimal rotation to determine the amount of annual compensation required to motivate private landowners to sequester higher levels on carbon on their forestlands in the U.S. South.

A slightly different slant was used by Hoen and Solberg (1994) in comparing the economic efficiency of sequestering CO_2 in Norwegian boreal forest stands under various forest management prescriptions. Although still within an optimizing framework, they used a linear-programming model to maximize utility from a multi-input/double-output forest production function (timber and carbon). Holding harvesting levels fixed, this approach allows the timber producer to adjust his management intensity and timing of treatments (such as fertilization, thinning, clear felling, etc.) in order to maximize carbon sequestered on the stand.

2.2 Regional or National-level Studies

Early regional assessments of climate change on the socio-economic aspects of the forest sector were centered on the forest products markets – where the forest forms one component of the production function. Climate-forest policies are translated into changes in production costs, harvest rates or product prices in the timber supply function, and their movements tracked to consequent implications on the forest markets and trade. These models represent the forest sector as stock-accounting equations for changes in forest inventory or use area-based models that track land use changes in land units.

An example is Haynes et al.'s (1994) study, which used TAMM (Timberland Assessment Market Model), a forest sector model for the U.S., and ATLAS (Mills and Kincaid, 1992), the Aggregate Timber Land Assessment System, to compare the impacts of several forest carbon options. TAMM was built on earlier econometric and linear programming studies to solve spatial market concerns, and provides an integrated structure for considering the behavior of regional prices, consumption and production in both the stumpage and wood product markets. ATLAS was used to make inventory projections for all private timberland in the U.S. The study examined combinations of possible carbon policies (such as afforestation programs, recycling and reduced harvests from National Forests) and projected inevitable price increases in solid-wood products and sawtimber, large-scale expansion of softwood supply in the U.S. South, and an increase in relative importance of hardwoods as a result of higher demand for fiber products.

Further developments expanded to include the agricultural sector because of their shared land base. Adams et al. (1993) linked a price-endogenous spatial equilibrium model of the U.S. agricultural sector (ASM) and TAMM to quantify the social costs of tree planting programs on agricultural land, and their effects on prices and welfare of economic agents in the agricultural and forest sectors. The model simulates competition between carbon sequestration and traditional crop or livestock activities for available land under the different carbon policy targets. The social cost associated with each target, or shadow price of carbon, is the marginal subsidy that would induce farmers to plant trees instead of crops under specific CO_2 targets. The analysis shows that the social costs are relatively low if the policy target is to sequester 10-20% of annual U.S. CO_2 emissions but these costs increase dramatically for higher CO_2 targets, suggesting that the use of agricultural land to sequester substantial amounts of carbon may be more expensive than previous estimates.

The Forest and Agricultural Sector Optimization Model, FASOM (Adams et al., 1996; 1999), takes the research further by incorporating endogenous adaptation and dynamic stock adjustments. FASOM is a non-linear model of the forest and agricultural sectors - it has a joint spatial equilibrium market structure with the linked sectors competing for a portion of the land base. FASOM is dynamic in that it jointly solves for the equilibrium in the different markets (land, agriculture products and logs) for each model time period. Prices for agricultural and forest commodities and land are endogenously determined given demand functions and supply processes. Unlike TAMM, forestry investment decisions in FASOM are endogenous - forestland owners implement management activities to maximize their present net welfare, where the intertemporal impacts of their activities are known with certainty. The model examines the consequences of these management decisions and the market implications of "least social cost" carbon policies on forest carbon storage, fluxes and costs. FASOM results suggest that land use shifts account for the largest adjustments to meet policy targets (although these changes need not be permanent) and forest management changes involve higher intensity management and lesser forest type conversion.

An alternate method to examine land use distribution between forest and agricultural sectors under carbon subsidy programs is by using econometric land use models (Plantinga et al., 1999). This model structure has several advantages over the "engineering" or spatial equilibrium approach by capturing elements of landowner behavior such as the irreversibility of investments under uncertainty, decision-making inertia due to high costs of acquiring forest management skills and knowledge, and other private, non-market benefits derived by landowners, such as recreation. Their study of Maine, South Carolina and Wisconsin compares the marginal costs of sequestering carbon from converting up to 25% of a state's agricultural land (upper limit) and finds that the costs are cheaper where there is lesser pressure on land conversion to urban uses, and in scenarios where harvesting is permitted, more valuable timber species. These results can be used to identify regions or states where land can be converted for forest carbon sequestration activities at lowest costs.

In a similar approach, Newell and Stavins (2000) drew on econometrically estimated parameters of a land use model, and layer it upon a model of relationships that link changes in land use with changes in the time parts of CO_2 emission and sequestration. They used their model to compute the sensitivity of marginal carbon sequestration costs to changes in relative prices (between forest and agricultural products), discount rates, forest management regimes and tree species. They draw four major conclusions; first, marginal sequestration costs are greater for cases with periodic timber harvests relative to cases of permanent stands. Second, changes in the discount rate have counter-effects on the marginal costs of sequestration and quantity of induced carbon sequestration. Third, marginal sequestration costs increase monotonically and non-linearly as agricultural prices increase because the opportunity cost of land increases; and fourth, there is asymmetry between marginal costs of carbon through forestation and retarded deforestation. The last point suggests that attention should be focused on efforts to reduce rates of deforestation, particularly in the tropics.

A different method in regional studies is to explore the effect of climate change on forest productivity, and then, trace the implications on regional timber markets assuming constant demand. Integrated climate-forest assessments provide an opportunity to characterize the linkages between climate and the forests that are typically defined away or treated parametrically in traditional economic research. Bowes and Sedjo's (1993) study of the MINK region (Missouri, Iowa, Nebraska and Kansas) is an early example. The study used a stochastic model of forest growth and succession, to simulate forest development under climate conditions in the 1930s, and qualitatively measured the impacts of a 2 X CO_2 climate on the regional economy. A warmer and drier climate is generally projected for the region, leading to declines of 25% - 60% in forest biomass. Given the originally low productivity of forests in the area, the authors concluded that potential for active adaptation in forest management was unlikely unless a market for carbon exists to substantially increase the economic value of these forests. As such, these results cannot be extrapolated to other regions even though a legitimate ecological model was used to measure the effects of climate change.

Along a similar vein, Joyce et al. (1995) used the TAMM-ATLAS model to examine market effects of forest productivity under various climate scenarios projected by General Circulation Models (GCMs). Integrating FORCARB (Birdsey and Heath 1996), a model of the U.S. carbon budget, provides the advantage for examining changes in forest carbon storage and flux, projected changes in forest productivity and wood product prices on the level of forest carbon sequestration in the future. Wood product markets adapt to shifts in forest productivity, inventories and harvest levels by solving for equilibrium stumpage prices and harvests based on the interactions between demand for standing timber and projected timber supply.

The more complete integrated assessments include the two expected effects of climate change on forest ecology. One is the biogeochemical effect addressed by Bowes and Sedjo (1993) and Joyce et al. (1995) - where increases in average temperatures and atmospheric CO_2 concentrations are expected to impact forest growth productivity (i.e. the photosynthesis and respiration rates), and the net gain in carbon exchange with the atmosphere[2]. Second is the biogeographical effect – simulated changes in seasonal weather patterns due to climate change could result in shifts in the geographical distribution of forest types. For the latter, Sohngen and Mendelsohn (1998) predicted a substantive shift from northern white pines to southern loblolly pines for the U.S., the relative size[3] is projected at between 1.54 to 1.98 for loblolly pine, and 0.10 to 0.26 for white pine (based on results from three GCMs).

A second advancement by Sohngen and Mendelsohn (1998) is the incorporation of a dynamic adjustment pathway for ecological change to climate effects, and market adaptation to these stimuli in the short and long run. A "natural change" ecological scenario was compared to an integrated model that incorporated the dynamic optimizing behavior of U.S. timber markets to illustrate how the industry endogenously adapts to minimize economic and carbon losses. The study used a GCM to model climate change, which predicts a 6.73° C temperature change and a 15% average increase in precipitation across the U.S. by 2060. These parameters were assumed to increase linearly. Combinations of biogeographic (BIOME2 and MAPSS) and biogeochemical models (TEM and BIOME-BGC) were used to depict the forest's ecological impacts. The natural model predicted a release of between 2.5 to 6.3 Pg[4] carbon during the forest dieback and re-distribution process, whilst the integrated model anticipated that human responses will mitigate or even reverse these fluxes by changing the timing of harvests, salvaging timber from dieback and replanting new forest types. A similar approach (Sohngen et al., 1996) expanded the geographical scope to include nine different timber supply regions in the world.

2.3 Global Studies

Restricting analysis to within the region or country of study discounts the potential impact of climate-forest policies in one country on other timber-producing countries. Creation of the Kyoto Protocol is, in part, driven by issues of distribution and scale, and a global perspective is

[2] Early experiments into CO_2 fertilization suggest that tree productivity will indeed increase in the short-run (Eamus and Jarvis, 1989; Norby et al., 1996). It has yet to be proven whether this positive net gain can be maintained in the long-run, since other environmental factors such as nutrients, nitrogen or water may be limiting (Norby et al., 1992; DeLucia et al., 1999). The process-based terrestrial ecosystem model (TEM) by Melillo et al. (1993, p. 239) estimated that global net primary productivity of forests would increase by 20 - 26% in response to GCM-generated climate change scenarios and 2 X CO_2 conditions. Responses are most significant in tropical and dry temperate forests and least in the northern temperate ecosystems. VEMAP (1995) provides a useful review of biogeochemistry and biogeography models, and compares results obtained from these models for simulating change in the continental U.S.

[3] "Relative size" is the ratio of the final (simulated) steady state forest area divided by the area of the initial (current) steady state (Sohngen and Mendelsohn, 1998, p. 700).

[4] $1 Pg = 10^{15}$ g

required to adequately capture those impacts. In addition, changes in the production, demand and prices of wood products in the U.S. may have implications on the international timber trade, as the U.S. is one of the world's largest importer and consumer of wood products. The single sector or partial equilibrium studies discussed earlier do not address such regional trade effects.

An early study to integrate climate impacts into a global forest assessment was carried out by Binkley (1988). Binkley used a regression model of the relationship between heat sum and forest growth to predict the effects of a 2 X CO_2 climate scenario on the growth of the world's boreal forests. Kallio et al's (1987) Cintrafor Global Trade Model was then used to predict the production, consumption, price and trade effects of the simulated climate change. The simulations projected gains for some regions and losses for others, shifts in timber revenues ranged from - 25.5% to +22.4% relative to the base case. However, the study is limited in that it ignored endogenous adaptation and changes in forest growth outside of the boreal region.

Similar to Joyce et al.'s (1995) study for the U.S., Perez-Garcia et al. (1997) linked climate change scenarios from GCMs with a model of global vegetation, TEM (Terrestrial Ecosystem Model; Melillo et al., 1993) to examine changes in forest productivity, and used the Cintrafor Global Trade Model to examine shifts in forest product markets. The study projected substantial shifts in global trade patterns of wood products. Under all GCM climate scenarios, Canada, China, and other consumer Asian countries are expected to enjoy significant gains in forest productivity as increased production of pulpwood and residual chips in these countries displace pulpwood production in the Oceanic region. The U.S., on the other hand, will gain a significant cost advantage in the production of structural panels. Higher log output in the U.S. and China reduces log production in the former Soviet Union and European consumer countries, and in the process, redirects the trade flows of lumber to reduce lumber manufacturing activities in the Middle Asia, Africa and Oceanic regions.

2.4 Economy-wide Approaches

The studies previously discussed have a rigorous approach to details in the forest sector and in some, a rather well-integrated structure for ecological economic analysis. They remain somewhat limited for policy analysis, however, because they do not capture the overall effectiveness of a forest carbon policy beyond its impacts in the forest sector. In a national economy, the producing sectors are linked through markets in their purchase of production factors (capital, labor, and inputs) and sale of finished goods to households. Figure 2 illustrates how the forest sector is linked to the other sectors and households in an economy. Changes in the

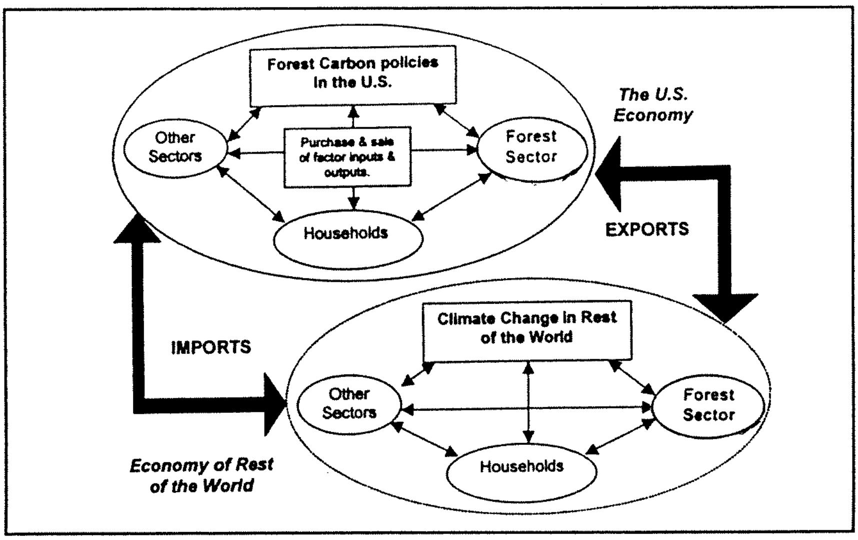

Figure 2 Inter-sectoral and inter-regional model of a climate-forest policy

forest sector will have implications for other producing sectors and households in the economy. An economy-wide perspective has considerable merit for public decision-making as it allows for a coherent examination of multiple objectives in identifying policy criteria and hence, provides a firm basis for making judgments on social welfare. Changes in prices (or other market conditions) can be translated into changes in aggregate well-being of consumers and producers in order to discern distributional consequences for the different groups in society.

The Future Agricultural Resources Model (FARM) by Darwin et al. (1996; also Darwin, 1999) addresses the issue with a computable general equilibrium (CGE) model. FARM is composed of a geographic information system (GIS) which links climate variables with land and water resources, and a CGE economic model which links land, water, and primary resources with regional production, trade and consumption. FARM's CGE model simulates interactions between farmers and downstream consumers (both domestic and foreign) and so, accounts for all responses by economic agents under climate change or policy scenarios. Climate change is simulated by allowing land to shift from one land class productivity to the other based on changes in length of growing season (primarily determined by regional rainfall and soil temperatures), and by changing regional water supplies.

FARM results indicate that climate change will have adverse effects on the health and integrity of tropical forests in Southeast Asia, Latin

America and Africa; decreased forest land areas were a result of climate-induced effects and competition from crop production (Darwin et al., 1996). In addition, estimated changes in Ricardian rents indicate likely detrimental effects in Latin America and Africa, beneficial effects in the former Soviet Union, and mixed impacts on eastern and northern Europe and western and southern Asia (Darwin, 1999). Benefits and losses associated with these changes are passed on to consumers. The FARM model has also been applied towards examining land-use issues as a result of policies to induce forest carbon plantations (Wong et al., 2001).

The Global Impact Model, GIM (Mendelsohn et al., 2000; Mendelsohn and Schlesinger, 1999) uses an econometric[5] approach to measure the economic effects of climate change by country and market sector. GIM combines two empirical methods to construct climate response functions for each of five market sectors (agriculture, forestry, coastal resources, energy, and water) – a process-based analysis based on experimental approach (bottom-up) and a "Ricardian" approach using cross-sectional data (top-down).

For the forestry sector, the process-based analysis relies on a set of ecological models (both biogeochemical and biogeographic) and GCM simulations to construct a reduced-form model that links climate scenarios and sectoral welfare impacts to temperature and precipitation. The second method is based on a cross-sectional analysis of the effect of climate on the present value of timber grown. The GIM's advantage is that it represents strengths from both the bottom-up and top-down approaches. The first captures the response sensitivity of trees to different climates, while the cross-sectional approach includes adaptation based on where people live. Because each of the response functions is concerned with just one sector in one country however, GIM is essentially still a partial equilibrium model.

3 COMPARISON OF MODEL STRUCTURE AND RESULTS

The varied approaches to analyzing climate-forest policies raise two interesting questions: (1) what are the predominate theoretical and structural differences at the different scope levels; and (2) how do the theoretical differences affect predicted results? The first question is answered to some extent in the description of the different approaches in the previous section. Table 1 presents some of the general structural points for the more prominent models.

[5] Adams (1999) discussed the advantages and shortcomings of the two economic methodologies – econometric assessments vs. mathematical optimization – with particular reference to FARM and GIM.

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Table 1 Comparison of select models over several structural components

	Van Kooten et al. (1995)	ASM-TAMM (Adams et al., 1993)	FASOM (Adams et al., 1999)	Perez-Garcia et al. (1997)	Sohngen and Mendelsohn (1988)	FARM (Darwin et al., 1996)	GIM (Mendelsohn et al., 1999, 2000)
Theory	Optimization (extended Faustmann)	Spatial equil.	Spatial equil.	Spatial equil.	Dynamic optimization	General equilibrium	Cross-sectional analysis
Projection method	Static	Static	Dynamic (recursive)	Static	Dynamic – optimal control	Dynamic (recursive)	Static
Scope	Stand-level (Pacific NW)	U.S.	U.S. (11 regions)	Global (9 regions)	U.S. (4 ecosystem types)	Global (8 regions)	Global (7 regions)
Sectors	Forestry	Forestry-agriculture	Forestry-agriculture	Forestry	Forestry	Economy-wide	5 sectors (incl. forestry-agric)
Integrated climate scenarios	No	No	No	Yes	Yes	Yes	Yes
Policy scenarios	Yes	Yes	Yes	No	No	Yes	No
Endogenous management	Yes	No	Yes	No	Yes	Yes	Yes
Timber inventory	Yes	Yes	Yes	Yes	Age-delimited	No	No
Carbon flux details	Yes	Yes	Yes	No	Yes	No	No

Table 2 Comparison of select models on their main results

	Van Kooten et al. (1995)	ASM-TAMM (Adams et al., 1993)	FASOM (Adams et al., 1999)	Perez-Garcia et al. (1997)	Sohngen and Mendelsohn (1988)	FARM (Darwin et al., 1996)[g]	GIM (Mendelsohn et al., 2000)
Policy scenarios	P_c = \$20/mt[a] P_t = \$15/m^3	C stock targets	C flux and stock targets	N/A	N/A	N/A	N/A
Climate scenarios	N/A	N/A	N/A	+ 2.8 – 4.2 °C 2 X CO_2	+ 3.0 – 6.7 °C 2 X CO_2	+2.8 – 5.2 °C 2 X CO_2	+ 2°C 2 X CO_2
Rotation age	+ 20% longer	N/A	+ 0.4 – 2.4% longer	Constant	N/A	N/A	N/A
Timber prices	Constant	Constant	N/A	N/A	Decrease	+ 0.8 – 3.1%[h] + 1.7 – 5.8%[i]	Constant
Land-use change into forestry (in US)	Constant	+ 49.4 – 274.4 mil acres	+ 14 – 28 mil acres	Constant	Constant	- 4.5 – -16.4%	N/A
Carbon storage	Small increase	140 – 700 mil short tons C/yr	+ 440 – 800 mil mt	N/A	N/A	N/A	N/A
Carbon costs	N/A	\$18 – 55/ton	\$22 – 37/mt[c]	N/A	N/A	N/A	N/A
Welfare measures for the US	N/A	- \$1.3 – -2.3 (producers) - \$7 – +0.2 (consumers)[b]	+ \$0.5 – 1.3 (producers) - \$0.7 – -1.6 (consumers)[d]	+ 1 bil/yr to 2040[e]	+ \$2.6 – 30.1 (ecological change)[f] + \$3.9 – 31.2 (endog. mgt)	N/A	+ 56 – 87 bil[j] (+ 4 – 9 bil in forestry sector)
Distributional effects	N/A	N/A	N/A	+ Canada, US, Japan; - Chile, NZ	N/A	N/A	+ North Amer, Asia, East Europe; Rest uncertain

Notes: [a] mt = metric tonne; P_c = price of carbon; P_t = price of timber; [b] in billion US dollars. Welfare measures reported are for the case where timber harvesting from carbon plantations is permitted. [c] Average cost, carbon is discounted. Marginal cost = \$11–15/mt/yr; [d] in billion 1990 US dollars, simulation from 1990-2039. Welfare measures reported are for the forestry sector only. [e] in 1980 US dollars, simulation from 1990-2040. [f] in billions 1982 US dollars, relative to base case, 2060. [g] Although the FARM model has a global scope, the results reported in Darwin et al. (1996) are for the Southeast Asian region. [h] change in export prices. [i] change in timber harvest rate. [j] in 1990 US dollars. The expected welfare benefits reported here are for the North America region, and are approximately 0.53 – 0.83% of GDP.

Table 2 presents a summary of the major results from the select models under their different policy and/or climate scenarios. These results are not directly comparable given differences in model structure and features. It is not the intention to find the *best* model for economic theory and modeling is unlikely ever to find the perfect predictive tool, and we do not have the benefit of a historical perspective. Instead, the intention is to compare and contrasts the theoretical underpinnings and empirical results to guide future endeavors. It is useful to note that the appropriate model is one that addresses the objective at hand. A balance has to be made between the types of information gained from detailed sector analysis at the expense of those generated by broader economy-wide or integrated analyses, and vice versa. The trade-off is always driven by the question(s) that one is attempting to answer.

There are two points to clarify with regards to predictions from economic assessments. First, in addition to differences in model structure and features, the quality of regional climate forecasts contributes considerable noise to results. The science of climate change remains relatively unknown at this point, and this problem may disappear as the quality of climate information improves. Second, it should be noted that projections from economic assessment models are more accurate for short-term events. It is impossible to estimate or predict all the changes in the myriad of factors involved in shaping forestry and climate over the century, and numerical results should only be treated as useful guides.

Finally, the studies reviewed in this paper are largely focused on market goods in their evaluation of policy impacts. Non-market aspects dominate the social values of many forests, particularly on remote or unmanaged lands where the impacts of climate change may be significant (Binkley and van Kooten, 1994, p. 97). Non-market benefits can be examined in the different biophysical impacts of climate change on forests, and in the valuation of those impacts. For example, changes in forest cover could affect recreational and aesthetic values, changes in forest health could affect biodiversity and wildlife habitats, and changes in vegetation could affect regional water flows. Admittedly, the incorporation of non-market values into the policy process is a daunting one and as such, policy impacts related to these issues are the least understood.

5 CRITERIA FOR FUTURE RESEARCH

A challenge for economic research is to provide policy makers with succinct information to make socially equitable, and economically and ecologically sound decisions. Research that fails to conceptualize multiple concerns or fails to generate information at the level appropriate to the problem at hand will provide biased results and hence, inefficient policies. From our reviews of previous research, we identified the following criteria as crucial for analysis of any climate-forest policy:

- *An integrated linkage between the forest and climate systems.* Ecological and social systems co-evolve through time, each providing feedbacks on the other. As shown by Sohngen et al. (1998, p. 514), the integrated ecologic-economic analysis can provide insights that contradict results from the simple ecologic assessment.
- *An objective of any policy analysis is to discern the economy-wide impacts of a climate policy.* As such, economic assessments should link forest sector impacts to the larger macroeconomic picture, as climate change does not impact the forest in isolation from the rest of the economy. Intersectoral linkages allow for a comparison of relative impacts incurred by different groups within a society. Also, studies concerned with distributive justice should also have a global scope in order to discern welfare effects between developed and developing, and forested and non-forested countries.
- *A dynamic analysis.* Given the large capital stock involved, the dynamic nature of ecological changes and adaptive market response, static comparisons provide poor approximations of the resulting adjustment path and their welfare outcomes. A dynamic analysis can also account for issues of timing and lagged effects with regards to policy implementation and adaptation by producers.
- *The economic framework should be linked to a carbon cycle model.* In this way, CO_2 emissions are tied to levels of economic production and energy consumption, and CO_2 sequestration to growing forests. This information is useful for estimating cumulative gains (or losses) in carbon storage over the long term, and for comparing the overall efficiency of different forest management activities in mitigating CO_2 emissions.
- *The treatment of uncertainty is crucial,* given the lack of scientific consensus and the non-linear linkages between the climate and terrestrial systems. The two types of uncertainties that should be made explicit are: 1) uncertainties in model structure and parameter values; and 2) structural uncertainties because of expert disagreement of climate change processes. Sensitivity analyses should be carried out to account for some of the randomness in parameter values and to increase confidence in the model results.
- Although a rather daunting challenge, economic studies should, nonetheless, attempt to include some aspects of the non-market flows for a holistic analysis of environmental impacts.

Thus, given all our criteria, a suitable research path is to integrate climate and ecologic models with a forest sector model into a dynamic general equilibrium framework. The general equilibrium framework accounts for intersectoral linkages in an economy and can expand to include inter-regional trade within the global economy to examine the distribution of impacts among regions. Recent developments such as the FARM model (Darwin et al., 1996), integrated efforts by Sohngen et al. (1996, 1998, 2000), and the Global Impact Model (Mendelsohn et al., 2000) each have certain desirable elements, but there remains work to be carried out towards a truly integrated policy analysis effort.

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