CARBON SEQUESTRATION BY FORESTRY – EFFECTS OF TIMBER MARKETS

Report Number PH3/10
June 1999

This document has been prepared for the Executive Committee of the Programme.
It is not a publication of the Operating Agent, International Energy Agency or its Secretariat.

Title: **Carbon sequestration by forestry - effects of timber markets**
Reference number: **PH3/10**
Date issued: **June 1999**

Other remarks:

Background to the Study

Forestry has the potential to reduce the atmospheric concentration of CO_2 by sequestering carbon in above ground timber and below ground roots and soil. This potential has been noted in the Kyoto Protocol, which identified forestry activities for which carbon sequestration credits could be obtained. Forestry can also contribute to greenhouse gas abatement by producing biofuel to displace fossil fuels, but this is outside the scope of this study.

Most carbon sequestration forestry efforts to date have been undertaken on a small scale but proposals are being considered that would result in large areas of new forests. Sequestration forests are only likely to survive in the long term if they generate some employment and income for the local inhabitants. An important way of providing local benefits, and also reducing the net cost of the forestry schemes, is to harvest some timber and plant replacement trees. This was recognised in an earlier study of the potential for large scale sequestration forestry in the Chiapas region of Mexico, carried out by the IEA Greenhouse Gas R&D Programme[1]. Even though harvesting would reduce the average amount of carbon stored on the land, more carbon would be stored than if the land had remained un-forested. Concerns are expressed, however, that large-scale sequestration forests might have impacts on the world timber market affecting traditional suppliers of timber, and reducing their incentive to invest in forest management and new production. Such a "crowding out" or "leakage" effect, as it is called in the literature, may negate all or a portion of the sequestration achieved by the afforestation.

The aim of this study is to examine such effects on carbon sequestration forests, by quantifying the likely impacts of timber from sequestration forests on the world market and on commercial forestry. The study was carried out by Dr Roger Sedjo and Professor Brent Sohngen in the USA.

Approach Adopted

An existing timber market model was modified and used to simulate the effects of adding sequestration forestry. A base case scenario was developed, in which timber supply, costs and carbon sequestration over the next hundred years were predicted for normal commercial forestry activities. Forest planting, management and harvesting in the base case takes place in the model to maximise financial returns from timber sales. A series of scenarios was then developed, involving addition of carbon sequestration forests. These forests were assumed to be established without regard for the financial return from their timber production.

The sequestration scenarios involved establishment of high or low levels of sequestration forests (50 or 10 million hectares) over the next 30 years, in temperate or sub-tropical regions. These areas of forests were considered to be significant, but not overwhelming, in comparison to current commercial forests. The sequestration forests were assumed to be replanted after harvesting. Three harvesting options were modelled:

[1] Assessment of the Cost of Large Scale Forestry for CO_2 Sequestration, IEA Greenhouse Gas R&D Programme, report number PH2/15, February 1998.

- Harvesting with relatively short rotation times to optimise the economic return from timber sales.

- Harvesting with longer rotation times, which may be appropriate if some of the income to the forest owner is related to the amount of carbon sequestered.

- No harvesting, with forests allowed to grow to maturity.

A key uncertainty in the modelling is the elasticity of demand for timber, i.e. to what extent the price of timber would have to fall to create extra demand. Further scenarios were therefore modelled to assess the sensitivity to assumptions about elasticity in demand.

The model used for this study is an existing dynamic timber market of the world, adapted to account for carbon stocks and non-economic carbon sequestration forests. The model includes 9 geographical regions and 46 timber types, each with different growth rates and costs. The model itself determines the level of commercial timber planting, management and harvesting, based upon generating an optimum financial return. The model does not include conversion of tropical forests to other uses, e.g. cropland or grazing areas, that are not driven by timber markets.

In the base case, global timber demand is projected to increase at 0.75% initially, this rate declining exponentially to zero by 2190. This is consistent with recent trends: the rate of growth of timber demand has been less than the overall economic growth rate, because of substitution in construction and packaging, stagnant newspaper production and increased recycling. If the rate of timber demand were to continue increasing, this would affect the base case predictions but is expected to make little change to the predicted effects of adding sequestration forests.

Results and Discussion

Base Case

The model predicts how regional timber harvests and overall prices will increase over the next hundred years, as shown in figures 1 and 2.

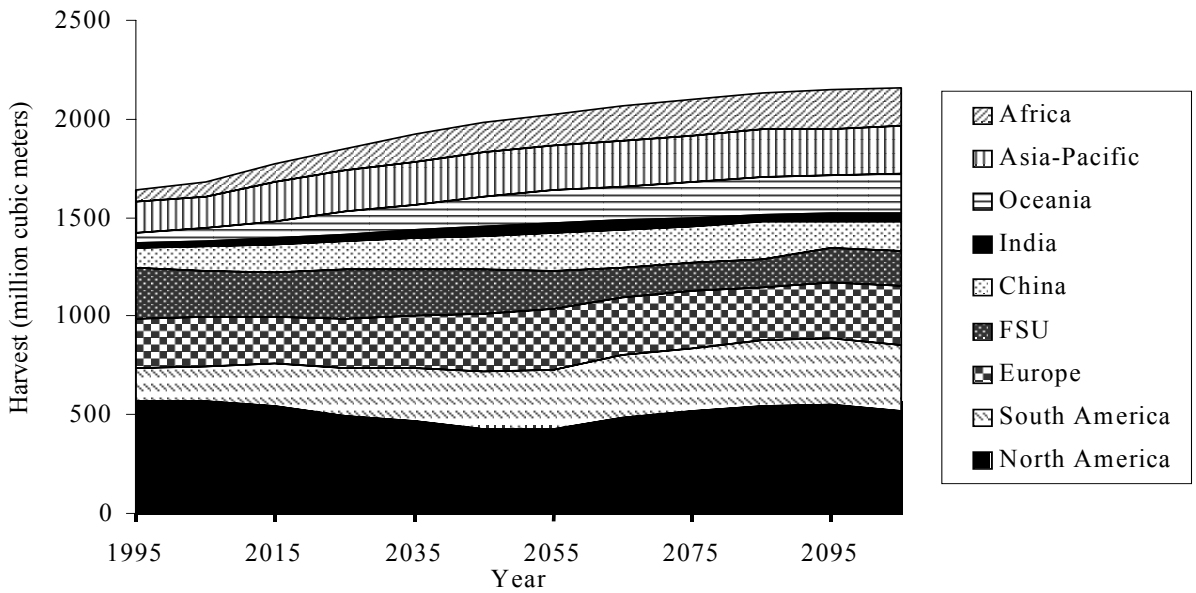

Figure 1 Baseline regional timber harvests

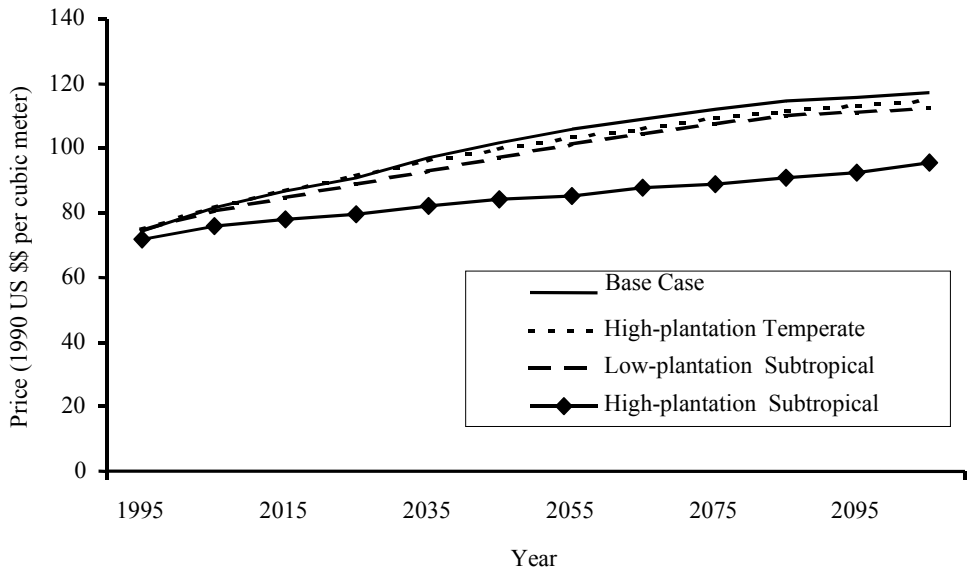

Figure 2 Timber price predictions

Harvests in traditional timber producing regions such as North America, the Former Soviet Union and Europe are expected to stagnate but harvests in most other regions are expected to increase. The predicted increase in timber price is expected to result in an increase in management intensity in emerging region plantations, resulting in an increase in production from 8.9 m^3 per ha per year to 12.8 m^3 per ha per year on average. The increase in forest area and carbon sequestration is therefore predicted to be significantly less than the increase in harvests. The increase in commercial forestry and timber production is expected to result in about 10 Gt of additional carbon sequestration in vegetation, soil and market products within the next hundred years. 10 Gt of carbon is equivalent to slightly less than 2 years of current emissions from use of fossil fuels.

Sequestration scenarios

Introducing carbon sequestration forests with sustainable harvesting is predicted to result in greater timber supply and lower prices. However, in all of the scenarios considered in this report the price of timber in future is still expected to be higher than at present, in real terms, as shown in figure 2. The largest impact is predicted to be for *high-plantation* (50 million ha) of sequestration forests in the sub-tropics, where growth rates are relatively high. In this scenario, timber harvests are predicted to rise from 1712 million m^3 in 2000 to 2717 million m^3 in 2110, i.e. a 59% increase. This is well above the 31% harvest increase in the base case. 50 million ha of sequestration plantation in temperate regions (Europe and North America) has much less impact on the market and price of timber because of the lower growth rates in temperate forests. In this scenario, the timber harvest is predicted to increase by 36% between 2000 and 2110.

Some of the extra timber harvested from the sequestration forests will displace timber from commercial forests. The extra production from the sequestration forests is predicted to reduce the area of commercial forests ("crowding out") by 7.8 Mha in the *subtropical high-plantation* scenario and 1.1 Mha in the *temperate high-plantation* scenario, within a hundred years. The crowding out is inter-regional: for example, the depressed price caused by sequestration plantations in the sub-tropics reduces commercial plantations in the temperate regions as well as in the sub-tropics.

All of the carbon sequestration forestry scenarios result in increased carbon sequestration in the long term, as shown in figure 3. In both of the *high-plantation* scenarios, the extra carbon sequestered in

the long term, compared to the base case, is predicted to be about 5.5 GtC. In the short term, the *sub-tropical high-plantation* scenario results in less carbon sequestered than in the base case. This is because forests in temperate regions would be harvested more heavily in the early periods, because of the lower future prices expected to result from the additional sequestration plantations. The amount of extra carbon sequestered in the *low-plantation* scenarios in the long term is less than in the *high-plantation* scenarios, broadly in proportion to the plantation area.

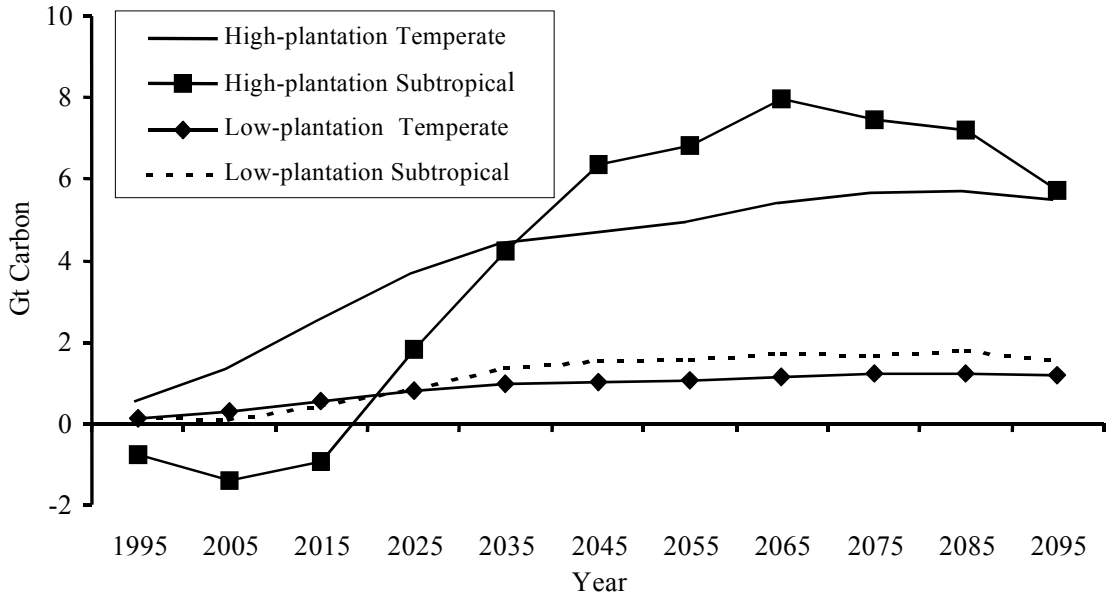

Figure 3 Increase in carbon sequestration compared to the base case

Effects of rotation time

In the scenarios described above, the rotation times, i.e. the times between planting and harvesting, were assumed to be the same in the sequestration forests and the commercial forests. Commercially optimum rotation times for sub-tropical forests are about 20-30 years for softwood species and 10 years for hardwood species. The optimum rotation time depends on costs, timber prices, growth rates and the economic discount rate. A discount rate of 5% (real terms) was assumed for this study. This is in line with the relatively low discount rates normally used for long term forestry activities.

The owners of sequestration forests are likely to receive income based on the amount of carbon sequestered, as well as from the sale of timber. Increasing the rotation time would increase the average amount of carbon in a given area of forest. The economically optimum rotation time may therefore be longer in sequestration forests than in normal commercial forests. The optimum rotation time would depend on the level of carbon sequestration credits, which is highly uncertain over the next hundred years. It would also depend on whether the credit systems include products or just carbon in forests. To cover the range of possible rotation times for sequestration forests, scenarios with *longer rotation times* and with *no-timber harvesting*, equivalent to infinitely long rotation, were both assessed. Both of these scenarios involve 50 million ha of sub-tropical carbon sequestration plantation. In the long rotation scenario, the rotation times are 50 years for softwood species and 30 years for hardwood species.

In the scenario with *no-harvesting*, forests are allowed to grow to maturity, at which point growth is balanced by decomposition and the amount of carbon sequestered is at an upper limit as shown in

figure 4. Figure 4 shows the quantity of carbon sequestered compared to the base case without sequestration forests. In the *no-harvesting* scenario there are no effects on the timber market and therefore no "crowding out". The amount of carbon sequestered in the *no-harvest* scenario is greater than in the scenarios with harvesting.

The amount of carbon sequestered in the *long-rotation* scenario is generally in between that of the *short-rotation* and *no-harves*t scenarios, as expected. Increasing the rotation time increases the average amount of living biomass and reduces the losses of soil carbon which tend to occur due to harvesting, but reduces the amount of carbon stored in long-life-market products.

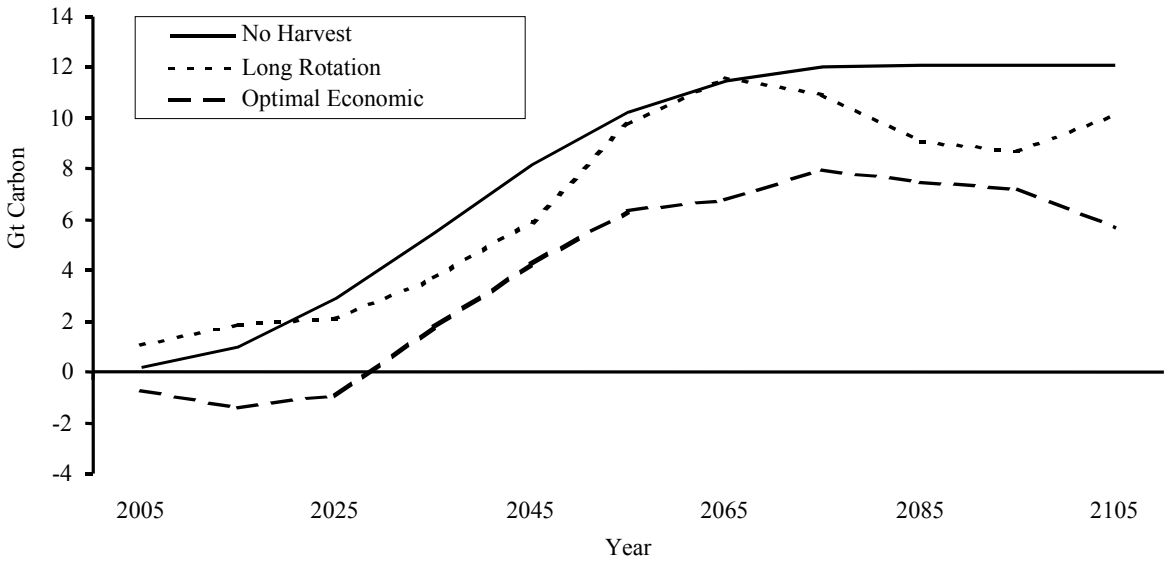

Figure 4 Effect of different rotation periods on a sub-tropical plantation scenario

Timber demand elasticity scenarios

Over time it is expected that, to some extent, wood can substitute for or replace non-wood materials, and vice versa. For example, in many construction uses, wood could be substituted by cement, or steel. On the pulp side, processes that are highly intensive in power[2] could increase their utilisation of wood fibre, but at the cost of higher power usage. In a market model, this anticipated substitution between wood and other materials is captured in the price elasticity of the demand curve. As prices rise, consumers shift away from the higher price commodity and substitute a relatively lower-priced commodity. Thus, the price of wood compared to other goods has a mechanism for including the substitution of other goods. A 'price-inelastic 'demand curve indicates there is little potential for substitution in use, while a 'price-elastic 'demand curve indicates greater substitution possibilities. In general, short-run curves tend to be more inelastic than long-run curves, since greater adaptation can be made over the longer period.

The basic timber supply model used in this study includes a demand curve with a price elasticity of 1.0, a fairly responsive elasticity. The price elasticity of timber is uncertain, particularly over the long time-scales considered in this study. Alternative scenarios were therefore modelled to assess the

[2] e.g. the groundwood process

sensitivity of the results to price elasticity. The FAO[3] has recently estimated the global price elasticity of industrial wood to be 0.686. This elasticity was derived using cross-section samples from 97 countries that account for more than 80 percent of the world's population and 81 percent of industrial round wood consumption. This alternative elasticity was applied to the base case and to the scenario that generates the largest timber output, i.e. the *subtropical-high-plantation* scenario. The results are shown in figure 5. It can be seen that the change in price elasticity has very little effect on the quantity of additional carbon sequestered.

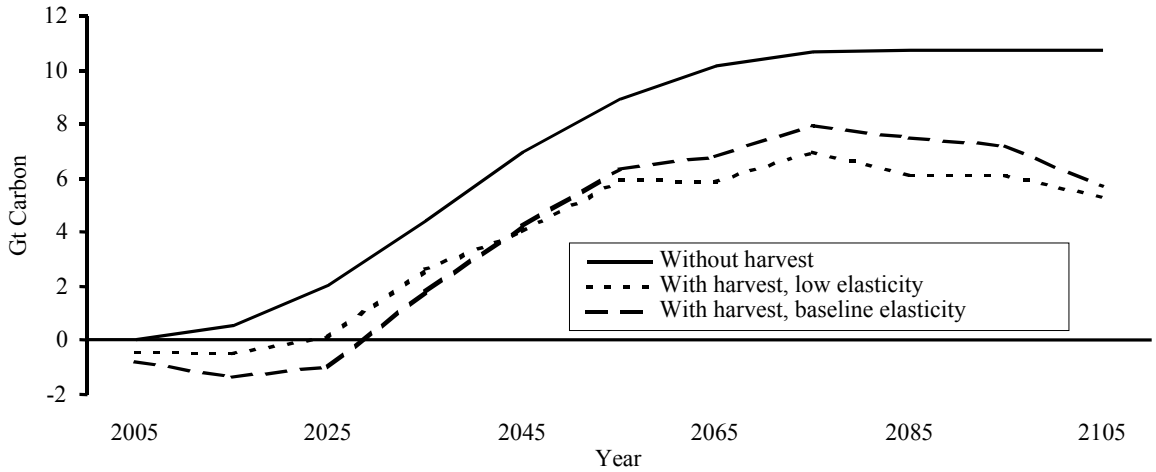

Figure 5 Sensitivity of carbon sequestered to demand elasticity (sub tropical plantation scenarios)

Alternative scenarios

This study evaluated a range of scenarios for introduction of carbon sequestration forests, considering harvesting of timber for premium markets, such as construction and pulp. However, it is recognised that there are a number of other ways in which forests could be used to aid climate change mitigation. For example, harvested timber could also be used as fuel, in which case there would be no effects on the timber market. As the world market for fuel is much greater than the potential market for high value wood products, there would be greater potential for the use of forestry for greenhouse gas abatement. however, fuel wood normally has significantly lower value than timber produced for premium markets and the local demand for fuel wood may be small in the relatively remote and undeveloped locations where sequestration forests are most likely to be established. IEA GHG has carried out a separate assessment of purpose-grown trees for power generation in a European location[4].

The sequestration forests in this study would produce by-products, such as bark, clippings and sawmill wastes, that could be used for heat and power production. IEA GHG is carrying out another study to assess the costs and potential GHG emissions avoidance from using forestry and wood industry by-

[3] UN's Food and Agriculture Organisation
[4] The Use of Biomass to generate Electricity on a Large Scale, IEA Greenhouse Gas R&D Programme, report number PH2/10, July 1997.

products. The potential to avoid GHG emissions by utilising wastes from sequestration forests could be estimated from that study.

Some of the extra timber produced by sequestration forests would displace other materials such as steel and concrete used in construction. The extra supply and lower price of timber may also reduce the amount of wood and paper recycling. Identifying which materials would be substituted by wood was beyond the scope of this study and would be subject to a high degree of uncertainty. Some of the materials that would be substituted by wood, for example steel and concrete, involve large emissions of greenhouse gases during their production. Cutting production of these materials is a potentially significant method of reducing greenhouse gas emissions. Reduction of greenhouse emissions by materials substitution is a broad subject, not necessarily linked to carbon sequestration forestry, which could be assessed in a separate study. The full fuel cycle energy consumptions of forestry and timber production, harvesting and processing would need to be included in such a study.

Expert Group Comments

Comments on the report were received from eight expert reviewers, including experts involved in the IEA Bioenergy Agreement and others working on forestry for sequestration. The comments were mainly editorial or requests for more information, particularly about the model.

Some of the reviewers pointed out the uncertainties associated with long term economic predictions in general, although one of the reviewers commented that the forest industries are remarkably stable in a long-term statistical sense. It was necessary to consider a long time scale in this study because forest growth is slow but the uncertainties of long-term predictions are recognised.

Some reviewers thought the study should have included harvesting of wood for use as fuel - this is discussed above.

Some reviewers thought that more emphasis should have been given to longer rotations and alternative forest management practices to find compromises between extraction of fuel, sequestering carbon and producing timber. This was beyond the scope of this study but could be addressed in future studies.

In this study it was assumed that existing commercial forestry activities would not receive carbon sequestration credits. This is a reasonable aim as, in general, only activities that would not otherwise take place should receive credits. However, in practise it may be difficult to distinguish between plantations established mainly for carbon sequestration and normal commercial plantations. Some reviewers thought that this should have been taken into account in the study. The effects of having to pay carbon sequestration credits to all forest owners could be investigated in a follow-on study.

Several comments were made about potential drawbacks of sequestration forestry in general, in particular that carbon stored in forests is not secure and could be released into the atmosphere quickly, for example as a result of natural disasters. These comments are recognised but they apply to sequestration forestry in general, and are not specific to this study.

Major Conclusions

1. The addition of 50 million hectares of carbon sequestration forests, with sustainable harvesting of timber, offers the potential to sequester up to 5.7 Gtonnes of carbon. This is equivalent to about 1 year of current anthropogenic emissions.

2. The amount of crowding-out and carbon “leakages” resulting from establishment of carbon sequestration forests is predicted to be modest. 50 million ha of carbon sequestration forests is predicted to reduce land areas in industrial plantations (i.e. crowd-out) by only 1.1 to 7.8 million

ha within 100 years. This is equivalent to 1.5-10.7% of the projected baseline industrial forest plantation area.

3. If carbon sequestration plantations are not harvested, the potential carbon sequestration almost doubles, from 5.7 Gt to about 11 Gt after 100 years. This is because the carbon plantations are allowed to approach maturity, which involves higher biomass and soil carbon, and there is no crowding out of commercial plantations. However, if no timber is harvested, the financial costs per tonne of carbon sequestered may rise since there is no financial income from the sale of timber.

4. If carbon sequestration plantations are harvested, but with a longer rotation time, an intermediate amount of additional carbon would be sequestered, about 8-10 Gt.

5. The elasticity of timber demand has little effect on the amount of additional carbon sequestered by sequestration forests.

Recommendations

Further work could be carried out to:

1. Assess the sensitivities to a greater range of input assumptions, using the timber supply model.

2. Assess the effects of having to make carbon sequestration payments for all forestry activities, including forestry that is already commercially viable.

3. Assess the implications for tropical deforestation of changes in timber supply and prices.

4. Assess the greenhouse gas emissions benefits from substituting wood for other materials, such as steel or concrete. This could be part of a broader study of the emissions benefits possible from materials substitution, including timber, aluminium, plastics, etc.

CARBON SEQUESTRATION BY FORESTRY - EFFECTS OF TIMBER MARKETS

Final Report produced for the IEA Greenhouse Gas R&D Programme

Roger Sedjo[1] and Brent Sohngen[2]

1. c/o RFF, 1616 P St NW, Washington, DC 20036, USA
2. c/o Ohio State University, Department of Agricultural Economics, 2120 Fyffe Road, Columbus, OH 43210-1067, USA

CONTENTS

		Page no.
1.	INTRODUCTION	3
2.	PROJECT APPROACH	4
3.	THE MODEL	6
4.	BASE CASE SCENARIO	7
5.	MODEL RUN DESCRIPTION	9
6.	SUMMARY OF SCENARIO RESULTS	10
7.	DISCUSSION AND DETAILS	12
8.	SOME ISSUES	25
9.	SUMMARY AND CONCLUSIONS	26
10.	REFERENCES	27
	APPENDIX 1 – DETAILED RESULTS TABLES	
	APPENDIX 2 – MODEL DESCRIPTION	
	APPENDIX 3 – MODEL INPUT DATA	

1. INTRODUCTION

Forestry has been considered to have potential in reducing the atmospheric concentration of carbon dioxide by sequestrating carbon in above ground timber and below ground roots and soil and some forestry efforts have been undertaken. This potential has been noted in the Kyoto climate protocol, which identified forestry activities for which carbon sequestration credits could be obtained. However, most forestry efforts to date have been undertaken on a small scale. (For a discussion of some of the project scale issues facing forestry and carbon sequestration see Sedjo et.al. 1997). Proposals have been considered that would result in large areas of new forests, which it is believed could offset some of the additional carbon that is being released into the atmosphere. Concerns are expressed, however, that large-scale sequestration operations might have impacts on the world timber market affecting traditional suppliers of timber, and reducing their incentive to invest in forest management and new production. Such a "crowding out" or "leakage" effect, as it is called in the literature, could negate all or a portion of the sequestered carbon generated by the newly created sequestration forest. Accordingly, the purpose of this study is to examine and assess the interactions between carbon sequestration forestry and the markets for timber.

Figure 1, Wood Flows and Uses, describes the flows from the raw wood resource. Some of the wood succumbs to various forms of natural mortality such as fire and infestation. Humans harvest wood for use both for fuel and for industrial wood, i.e. wood that is processed into wood materials and woodpulp for paper. This study is concerned with the approximately 50 percent of raw wood that is harvested worldwide for use as industrial wood.

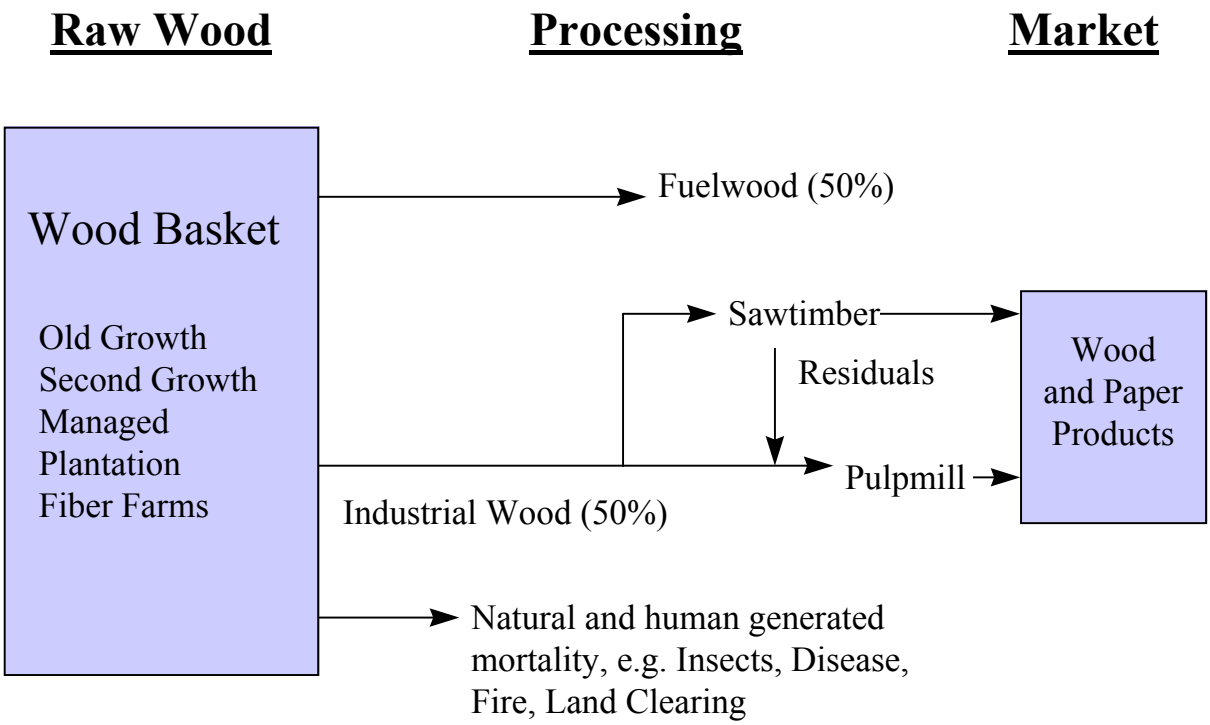

Figure 1: Wood flows and uses.

2. PROJECT APPROACH

Overview: The approach of this study involves utilizing an existing Dynamic Timber Supply Model (DTSM) to examine the interactions between newly created sequestration forests and the markets for timber. There are two other large regional models of which we are aware that can examine carbon sequestration and forests. These are the Forest and Agricultural Sector Optimization Model (FOSUM), (Adams et al. 1994), and the Cintrafor Global Trade Model (CGTM), (see Perez-Garcia et al 1997). However, since the FOSUM covers only the US, it cannot deal comprehensively with global issues. The CGTM is similar in some respects to our DTSM, but, not being a control model, it lacks the ability of the DTSM to carefully monitor timber inventories. It also is limited in its ability to endogenously add or subtract forest land areas from the timber base. Both of these factors are important for assessing the impact of markets on the timber base and thus on the amount of carbon sequestered.

The DTSM has been used to examine global timber markets, industrial wood markets, including both solidwood, e.g., sawtimber, and also pulpwood. The model is "forward-looking" in that it assumes that economic actors anticipate the future effects of current actions. Thus, the establishment of large areas of carbon sequestration forests that are not precluded from harvesting, will be anticipated to depress future timber prices, compared to what they would be in the absence of the carbon forest, and thus will influence current investment actions. The original dynamic DTSM has been modified to allow it to examine the issue of carbon stocks and changes as well as traditional timber markets. The focus of the projections and scenarios is on the carbon sequestered (or released). The model uses a 5 percent real discount rate throughout. Of course, other discount rates could also be used. The approach involves developing a base case scenario with an analysis of that base case, focusing especially on deviations from that base as provided by alternative scenarios. The base case assesses the interactions between forest sequestration and the markets for timber based on a "business as usual" assumption. This involves projections of future industrial wood demand and supply over a 100 year period. Projected supply comes from natural, managed and plantation forests on the basis of maximizing the present value of the industrial wood using a five percent discount rate. Future supply sources include growth and regeneration of natural forests as well as new supplies generated from projected newly created artificial planted forests. These new industrial commercial forests are assumed to be created in response to market forces on the basis of economic calculations. The model is discussed in greater technical detail in Appendix 2.

Problem Statement: The basic problem addressed in this study is that of assessing the effects on the industrial timber market of the imposition of the addition of a large number of carbon tree plantations. These plantations are assumed to be established without regard for their financial returns from industrial wood production. Although these carbon plantations are established primarily to sequester carbon, they may at some future time be used as industrial timber. Hence, if timber producers recognize the carbon plantations as potential future competitors in the industrial wood market, their establishment would have impacts on future industrial wood prices and hence on investment decisions regarding the establishment of industrial commercial plantations. The various scenarios largely focus on the impacts on the total forest and the

associated sequestered carbon of alternative ways of viewing the carbon plantations. Carbon plantations would probably be established either by direct government forest planting activities, on the basis of some type of forest subsidy paid to the landowner/grower to establish trees, or by credits earned on the basis of the carbon sequestered by the forest. All three approaches have the potential to dramatically alter the current market situation of growing forests. Direct tree planting by governments will surely effect private tree planting investment decisions, especially of the government planting is done at locations where harvests are economic. Forest subsidies would also effect industrial forest planting decisions. The direction of the effect would depend on whether industrial firms were eligible for the subsidies and under what conditions. Payment for the carbon sequestration services of planted trees would also influence investment and forest management decisions, again based on eligibility and other details of the program. Large forest companies are already speculating about the repercussions of various forest carbon policies in terms of its likely effects on land prices, extended rotation lengths, or even abandoning harvesting of plantations due to their increased value on the ground in the event of carbon credit payments.

This study, however, does not examine the entire variety of ways that additional forest can be created. Rather, it is assumed that the carbon forests are established independently of their financial potential as industrial wood enterprises, e.g., as if governments simply undertook public sector projects using tax monies either to directly plant additional forests or to subsidize private entities to establish carbon forests, in either case on lands not suitable under anticipated prices for commercial operations due to their inability to meet the financial criteria. Furthermore, the study does not examine the implications of a situation where carbon offsets receive explicit financial credits, either by the government or in a market for sequestration offsets. (Elements of this issue are explicitly examined in Sedjo 1999). Thus, no explicit value has been attributed to carbon in the model nor in this report.

The Major Elements: The approach is first to outline the model. Next, the base case is developed and run. Some of the important base case information is reported. Then, various scenarios are developed on the assumption that carbon sequestration plantation wood is harvested and sold into the global timber market. Next scenarios are developed under the assumption that the wood from the carbon sequestration plantations is not harvested on a financially optimal rotation. Either it is assumed to never be harvested or it is assumed to be harvested on a longer, non-financial rotation. These runs are only applied to one of the earlier scenarios, i.e. that which appears to have the most interesting carbon implications. The carbon implications of the changed harvesting rules are then examined and compared to the results of that same scenario in with economically optimum harvesting. Next the results and the details of the various scenarios and sub scenarios are presented, discussed and analyzed. A number of important issues are then raised and discussed. Finally, a summary of the important findings and conclusions of the study are presented.

The Scenarios: The scenarios developed consist of a base case (Scenario 1) and four other scenarios with a number of variations. In each of the sequestration scenarios, the sequestration plantations were assumed to be established at a constant rate over the next 30 years. The scenarios and variations are:

Scenario 2: Creation of Carbon Sequestration Plantations: High Establishment

a. High sequestration plantation establishment: Establishment of 50 million ha of sequestration plantations in North American and Europe.
b. High sequestration plantation establishment: Establishment of 50 million ha of sequestration plantations in the subtropics.

Scenario 3: Creation of Carbon Sequestration Plantations: Low Establishment

a. Low sequestration plantation establishment: Establishment of 10 million ha of sequestration plantations in North American and Europe.
b. Low sequestration plantation establishment: Establishment of 10 million ha of sequestration plantations in the subtropics.

Scenario 4: Ultimate fate of sequestrated forests

a. Add 50 million ha of sequestration forests to the base case without harvesting.
c. Add 50 million ha of sequestration forests in subtropical regions, with long- rotation harvesting and replanting.

Scenario 5: Substitution Effects

a. Low demand elasticity with no carbon plantations
b. Low demand elasticity with high carbon plantations in subtropical regions (plantations established as in Scenario 2b)

3. THE MODEL

To assess the potential future supply of global timber and its implications on forest carbon stocks, we adapted a recent modeling effort by Sohngen et al (1999) to also account for carbon stocks and changes in those stocks (see Sohngen and Sedjo, in press). The 1999 effort built a dynamic timber market model of the world (DTMW) follows the work of Sedjo and Lyon (1990 and 1996), but expands their earlier model in three important ways. First, the dynamic model incorporates a broader diversity of forests and of geographic regions, including 46 timber types in 9 geographic regions across the globe. Second, unlike the earlier models where the level of commercial timber plantations is determined outside the model, in this model commercial plantation establishment is determined endogenously, within the model, based upon generating an acceptable financial return. Third, the model predicts the area of marginal economic forest that will be accessed for industrial wood market needs. In this way, the model efficiently trades off harvests today from existing multiple types of forest management and species across the globe, with investments in future forests. Finally, the dynamic timber market is modified to include a carbon inventory system with estimates of forest ecosystem carbon and market carbon, i.e., carbon captured in long-lived wood products (adjusted for decomposition and destruction) and changes in that carbon. The figures provided build on and extend the 1990 estimates for carbon in market products with pulp products having fairly short lives while solidwood products have much longer average lives. Although some variants of this model are exploring ways to introduce the ecological changes on forests and forest growth, e.g. the fertilization effects, that would accompany global warming, the model variant used in this project does not consider changes in growth or yields or

changes in forest areas that might occur in a warming world. The model used in this paper is more fully developed in Appendix 2 and in the cited literature.

Furthermore, it should be noted that the model does not have a component to adjust global forests for the anticipated continuation of tropical deforestation. That is, tropical forestland conversion to other uses, e.g., croplands or grazing areas, that are not driven by timber markets. Thus, the projections focus on the changes in timber and carbon sequestration that occur due to the interactions between sequestration forestry and the markets for timber. Most analysts believe that tropical deforestation is driven primarily by desired for land use conversion, primarily to agriculture. Often, in these cases the timber is ignored or burned as part of the clearing operation and thus has little effect on global timber markets. This model assumes that the stock of tropical forests remain unchanged except to the extent that commercial logging changes the age and thus biomass of the forest. Thus the results reflect interactions between the global timber market and sequestration forests and do not consider changes in carbon stocks driven by forestland conversion to nontimber uses. The influence of land use changes could be added to the model by incorporating existing deforestation forecasts. However, we have left this non timber market influence external to our market model and its explorations.

The model presents results by nine regions, each of which have different growing conditions. The timber production of each region contributes to the global total, as do the carbon changes. It should be noted that the timber price, which represents the delivered price of raw wood at the mill gate, is treated as identical throughout the global market. Although clearly a simplification, wood quality often differs and is reflected in prices, this treatment is consistent with viewing the global market as a single market in which the "law of one price" applies. This treatment can also be interpreted as viewing the price as an index of global log prices, recognizing the prices vary with species, quality, etc. A single global price also treats trade restrictions of industrial wood as nonexistent. This simplifying assumption has become less accurate as new restrictions have been coming into effect in recent years. However, it should not distort our global results substantially since, although some of the regional projections could be distorted, such distortions would be greatest at the disaggregate level and smallest when dealing with global averages as we are throughout this report.

4. THE BASE CASE SCENARIO

We begin the base case projections with the initial 1995 situation including the timber inventories for and growth conditions appropriate to the timber types and conditions associated with the different regions. Harvest levels are determined by intertemporal profitability. Harvests occur when financially optimal and investments in replanting occur if financially warranted. Similarly, the level of plantation establishment is determined endogenously within the model by financial considerations. Although human planting does not take place after harvest in many situations, for most timber types natural regeneration is expected in the absence of artificial regeneration. Harvesting costs, including transport costs, are estimated using the best available data, which may vary by region and timber type. As prices rise, a summation of the underlying costs of production of the various regions provides the estimate of

aggregate global supply. Global timber demand is projected beginning with the actual 1990 level and is assumed to increase at 0.75% per year initially, declining exponentially to 0.0% per year by 2190. Any assumption about growth rates of periods of centuries is highly problematical. Other assumptions about growth rates could be used. The growth rate used is roughly consistent with that experienced globally for industrial wood over the past 25 years. Furthermore, the actual growth rate has been declining. For example, total industrial wood production and consumption was roughly the same in 1997 as in 1984. Although some of this stagnation can be attributed to the dramatic decline in industrial wood production and consumption in the former states of the Soviet Union after its dissolution, global long-term wood production and consumption were recognized as increasing only very slowly even earlier (e.g.,see Sedjo and Lyon 1990). The usual explanation for the very slow growth is the substitution of nonwood materials for wood in both the solidwood and fiber uses, including paper. For example, various materials can be substituted in construction, including bricks, concrete, and steel. In packaging there has been a shift from paper and paperboard to the use of plastics, containers and other materials. In communications, newspaper production is stagnate in many parts of the world and there are concerns that electric information flows have or will impact negatively on paper use generally. The results are given for the years 1995-2105. If demand were to continue increasing indefinitely, this would have little effect on our projections of the next several decades and constitute the "base" with which the various scenarios are compared and contrasted.

Some Base Case Information:

- Average carbon density per hectare of forest is given in the following table. These results are consistent with the published literature.

	Vegetation	Soil (one meter)	Total
Region	Mg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}
Temperate			
North America	63	146	209
Europe	70	127	197
Former Soviet Union	73	198	271
China	81	157	238
Emerging and Tropical			
Oceania	50	95	145
South America	130	117	247
India	14	112	126
Asia-Pacific	166	126	292
Africa	107	116	223

- Growth in forests generates the following average carbon yields per hectare per year during between 1995 and 2105:

Temperate forests: 1.94 tonnes carbon per year with soil carbon
1.62 tonnes carbon per year without soil carbon

Subtropical Plantations: 2.4 tonnes carbon per year with soil carbon.
2.1 tonnes carbon per year without soil carbon.

Note that we distinguish between numbers with soil carbon and without (see below)

- Soil carbon is a difficult issue to address. The additional soil carbon in new plantations is calculated here net of the soil carbon that is presumed to exist on the land previously. While the previous use affects the level of carbon initially found in the soil it does not affect the rate of new accumulation. Note that soil carbon on previous land can be low if intensive agriculture is used. If, however, the lands are marginal grazing lands, soil carbon may be quite large. We have used conservative estimates of the additional soil generated by forests throughout this analysis.

- Industrial plantation establishment. The base case begins with 41 million ha already in industrial plantations. This figure climbs to 65.4 million ha by 2045 and 73 million ha by 2105, for increases of 24.4 million ha by 2045 and a total increase of 32.0 million ha by 2105.

5. MODEL RUN DESCRIPTION

- Baseline Scenario: No Carbon Plantations

- Scenario 2a: High Carbon Plantations in Temperate Region (50 million ha total)
  Pacific North West plantations: 1 million ha
  Southern soft and hardwood plantations: 30 million ha
  Temperate deciduous plantations: 5 million ha
  Nordic: 2 million ha
  Central European soft and hardwood: 6 million ha
  Southern European soft and hardwood: 6 million ha

- Scenario 2b: High Carbon Plantations in Subtropical Regions (50 million ha total)
  South America softwood: 15 million ha
  South America hardwood (Eucalyptus): 10 million ha
  Oceania softwood (Douglas Fir): 2.5 million ha
  Oceania hardwood (Eucalypts):2.5 million ha
  Asia-Pacific mixed plantations: 10 million ha
  Africa softwood: 5 million ha
  Africa hardwood: 5 million ha

- Scenario 3a: Low Carbon Plantations in Temperate Regions (10 million ha total)
  Pacific North West plantations: 0.2 million ha
  Southern soft and hardwood plantations: 6 million ha
  Temperate deciduous plantations: 1 million ha
  Nordic: 0.4 million ha
  Central European soft and hardwood: 1.2 million ha
  Southern European soft and hardwood: 1.2 million ha

- Scenario 3b: Low Carbon Plantations in Subtropical Regions (10 million ha total)
  South America softwood: 3 million ha

South America hardwood (Eucalyptus): 2 million ha
Oceania softwood (Douglas Fir): 0.5 million ha
Oceania hardwood (Eucalypts): 0.5 million ha
Asia-Pacific mixed plantations: 2 million ha
Africa softwod: 1 million ha
Africa hardwood: 1 million ha

- Scenario 4: Long Rotation or No Timber Harvesting (plantations established as in scenario 2b above)

- Scenario 5a: Low Demand Elasticity with No Carbon Plantations

- Scenario 5b: Low Demand Elasticity with High Carbon Plantations in Subtropical Regions (plantations established as in scenario 2b above)

6. SUMMARY OF SCENARIO RESULTS

Some General Results

- These results are total carbon storage by the year given.

- Each column represents a different scenario.

- Timber plantations are established endogenously within the model and are dependent upon future prices.

- Plantation establishment discussed below generally refers to carbon sequestration plantations, which are established by a decision external to the model, e.g., exogenously. These must be distinguished from industrial commercial plantations, which are endogenously determined within the model based on profitability criteria.

• Total Carbon in Sequestration Plantation Establishment Scenarios WITH timber harvest:

		High Plantation		Low Plantation		Low Elasticity	
Year	Base	Temperate	Subtropical	Temperate	Subtropical	Base	Plantation
	Petagrams						
2045	7.14	11.48	11.38	8.09	8.50	7.69	11.71
2105	9.40	14.81	15.10	10.59	10.91	12.32	17.62

• Carbon gain relative to baseline in the plantation establishment scenarios WITH timber harvest (NOTE: the low elasticity case carbon gain is calculated relative to the low elasticity baseline):

	High Plantation		Low Plantation		Low Elasticity
Year	Temperate	Subtropical	Temperate	Subtropical	Plantation
	Petagrams				
2045	4.34	4.24	0.95	1.36	4.01
2105	5.41	5.70	1.19	1.51	5.31

• Total Area of Industrial Plantations WITH timber harvest:

	Area of Industrial Plantations (million ha)				
Year	Base	High Plantation		Low Plantation	
		Temperate	Subtropical	Temperate	Subtropical
2045	65.4	64.7	59.7	65.3	63.9
2105	73.0	71.9	65.1	72.8	71.2

	Difference in total plantation area from baseline (million ha)			
Year	High Plantation		Low Plantation	
	Temperate	Subtropical	Temperate	Subtropical
2045	-0.7	-5.6	-0.1	-1.4
2105	-1.1	-7.8	-0.2	-1.7

• Total Incremental Carbon Above that of the Base Case in Carbon Plantation Establishment Scenarios with NO timber harvest:

	High Plantation		Low Plantation	
Year	Temperate	Subtropical	Temperate	Subtropical
	Petagrams			
2045	3.72	8.14	0.74	1.62
2105	8.92	12.06	1.78	2.41

• Total gain in carbon storage between 1995 and the year given in Plantation Establishment Scenarios WITH timber harvest for Three Scenarios:

		High Plantation			Low Plantation	
Year	Base	Temperate	Subtropical	Subtropical long rotation	Temperate	Subtropical
	Petagrams					
2045	7.14	11.48	11.38	13.05	8.09	8.50
2105	9.40	14.81	15.10	19.54	10.59	10.91

• Total carbon gain relative to baseline in the plantation establishment scenarios WITH timber harvest (NOTE: the low elasticity case carbon gain is calculated relative to the low elasticity baseline):

	High Plantation			Low Plantation	
Year	Temperate	Subtropical	Subtropical long rotation	Temperate	Subtropical
	Petagrams				
2045	4.34	4.24	5.90	0.95	1.36
2105	5.41	5.70	10.14	1.19	1.51

• Crowding Out: Comparison of the area of land in industrial subtropical plantations in the year given. These figures do not include the land planted for carbon sequestration purposes. All scenarios begin with 41 million hectares in plantations in 1995.

		High Plantation			Low Plantation	
Year	Base	Temperate	Subtropical	Subtropical long rotation	Temperate	Subtropical
	Million Hectares					
2045	65.4	64.7	59.7	60.3	65.3	63.9
2105	73.0	71.9	65.1	66.0	72.8	71.2

7. DISCUSSION AND DETAILS

These projections provide estimates of annual changes in timber production and in timber prices. Figure 2 presents the baseline regional timber harvest projections.

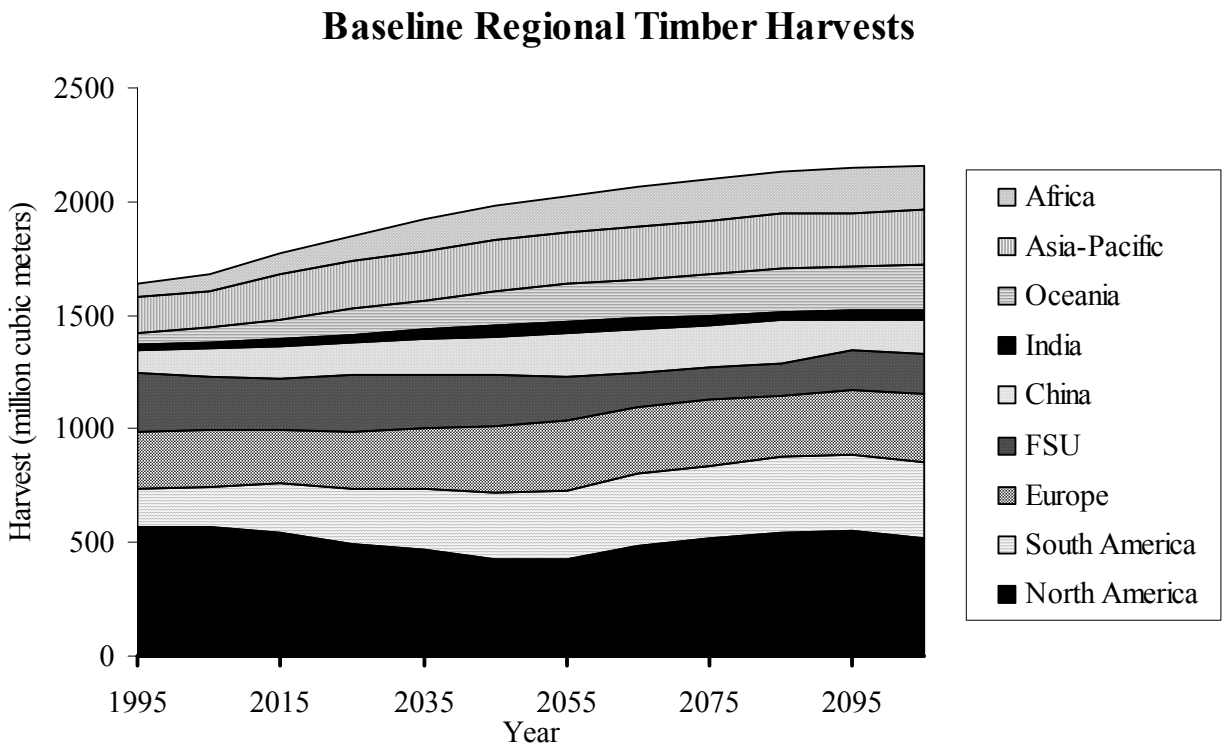

Figure 2: Baseline regional timber harvests.

In addition, seven tables are generated in the base case and are found in Appendix 1. These are:

Table 1: Global price, regional and global timber harvest volumes for approximately a 100 year period.
Table 2: Total carbon pool
Table 3: Tree carbon
Table 4: Forest floor carbon
Table 5: Soil carbon
Table 6: Market carbon, i.e., carbon tied in market products since 1990
Table 7: Regional carbon fluxes

Discussion

Figure 2 shows global harvests rising, but only gradually throughout the over 100 year period. Traditional producing regions such as North America, Europe and the Former Soviet Union (FSU) show stagnate or declining harvest levels. By contrast, increased harvests are found in most of the other regions, especially South America. These increases are driven by commercial planted forests and harvests are projected to increase from 1641 million cubic meters in 2000 to 2157 million cubic meters after 2100, or about 31 percent. Most of the increased volume comes from South America, Oceania, the Asia-Pacific and Africa. Additionally, to meet this demand, a total of 32 million ha of new industrial plantations are established. When combined with the existing 41 million ha of industrial plantations in the initial period, this generates a total of 73 million ha worldwide of intensively managed industrial plantations.

Figure 3 presents the price projections for the various high sequestration plantation scenarios. Projections from low sequestration temperate plantation establishment are not shown but they are not very different from the baseline scenario prices or harvests. Prices are somewhat lower and harvests slightly higher. In the case of temperate sequestration forests, some of the higher cost commercial plantations are crowded-out by the somewhat lower prices anticipated by the harvests of the sequestration plantations. By contrast, the establishment of a “high” number of sequestration plantation starts in the subtropical region crowds out some commercial plantations. However, due to their high productivity they still generate a fairly large increase in total harvest and a significant decrease in price.

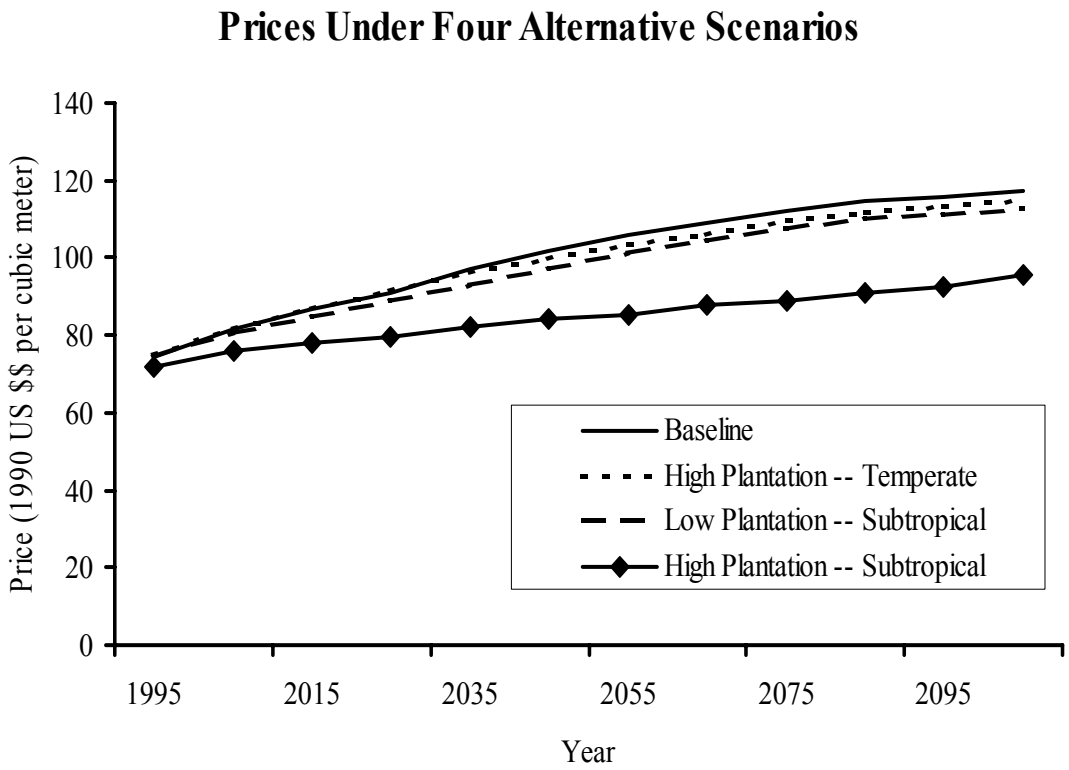

Figure 3: Prices under four alternative scenarios

Figure 3 compares annual carbon fluxes in North America and Europe with those of the rest of the world and the global total for the base case. Forest carbon consists of carbon in the forest biomass, both above and below ground; carbon in forest soils; carbon in the forest understory and forest litter; and carbon in the addition to the stock of long-lived forest products. Soil carbon increases depend on the stock of carbon in the soil initially, and its gradual (logistic) build-up as the carbon approaches the soil's carrying capacity. The carrying capacity is dependent, in part, on the land's previous use.

Total carbon in the forest ecosystem increases only modestly, by about 9.4 Gt. Much of this increase comes from the storage in long-lived wood products. Soils are a source of carbon in early decades because harvests from older northern and boreal forests, which release more carbon, are a little heavier then. Vegetation carbon rises as plantations are established and temperate forests are managed more heavily.

The base case results also comport reasonably well with a priori evidence from the initial period (Figure 4 and appropriate appendix tables). In the first part of the 21st century in North America, Europe, and the Former Soviet Union (FSU), carbon increases only modestly, at about 0.25 Gt annually, or about one-half of the 0.5 Gt per year increase in forest carbon sequestration estimated currently by the by the IPCC. Our results reflect our expectation about that the US South wood basket, and more generally North America, will function like a silo. For the past 75-100 years forest stocks have been rising as former agricultural lands have reverted to forest and young forest matures to older forest. Our projections anticipate that, for a period of 3-4

decades, the financially mature timber will be drawn down as it matures and is intensively harvested. Thus, the first part of the 21st century should see increased harvests and decreased forest and carbon inventories for the US South and elsewhere in North America. Subsequently, toward the middle of the 21st century, inventory rebuilding will again proceed and then decline again toward the end of the century.

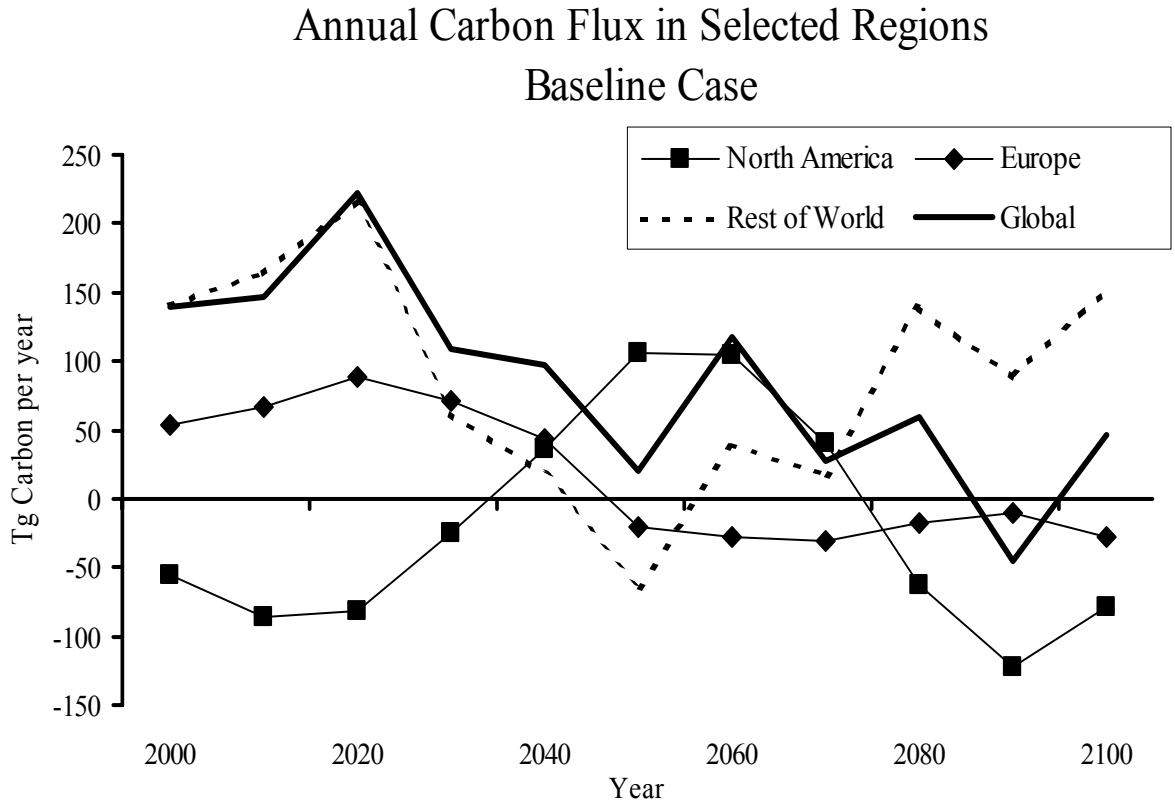

Figure 4: Annual Carbon Flux in selected regions for the baseline case

Figure 5 shows how additional carbon storage is allocated among components, including market carbon. Markets capture most of the additional carbon sequestered. Soils are a source of carbon release in early decades because harvests draw heavily from northern and boreal forests, where soil carbon losses associated with harvests are larger. Vegetative carbon rises as plantations are established and temperate forests are managed more heavily.

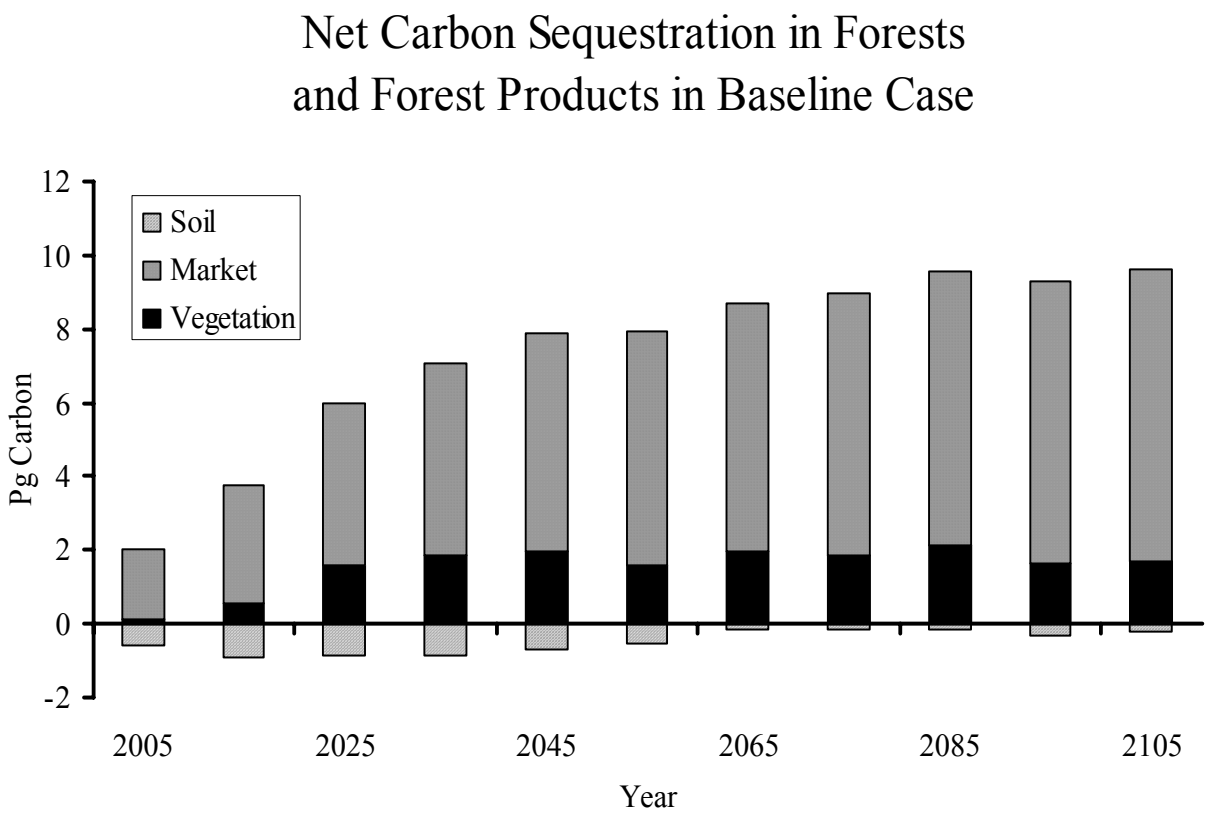

Figure 5: Net carbon sequestration in the baseline case.

One finding of our model is that for the short rotation intensively managed industrial forest plantations used in our model, the relationship between harvests and carbon stocks in the remaining stands is generally much weaker than for second growth forests, natural forests that have regenerated after a harvest of the old-growth forest, with longer rotations. For example, for a regulated forest with equal proportions of the various age classes, the sustainable harvest of a one-hundred year old forest, e.g., one-hundredth of the total stand, the ratio of remaining forest biomass to harvest is in the order of 99:1.

By contrast, for a 10 year short-rotation industrial plantation the remaining stand has only 90 percent of the biomass of the 10 percent area harvested, the ration is about 9:1. Thus, for example, where most of the increased harvests come from short rotation plantations, the increase in carbon stocks in the biomass would be modest. The base case predicts that industrial forest plantations will expand from 41 million hectares to 73 million hectares in emerging regions by 2105 as the result of market forces. Over the long run (approximately 150 years), each new hectare of emerging region plantations provides approximately 400 Mg carbon per hectare of total additional carbon storage in the forest ecosystem and in marketed products (note that this number includes the storage of carbon in market products for some existing plantations. However, eliminating the market-stored products would not reduce the total carbon storage substantially). Carbon sequestration associated with the base case alone generates approximately 9.4 additional Gt. of carbon storage, a number that is consistent with the changes shown in the table below for South America, India,

Oceania, Asia-Pacific, and Africa. This amounts to a 1.3 percent increase gain in the global atmospheric carbon pool.

Alternatively, harvests (production) on emerging region plantations rise from 8.9 cubic meters per hectare per year to 12.8 cubic meters per hectare per year on average as management intensity rises to meet higher prices. The 32 million new hectares in plantations therefore provide approximately 410 million cubic meters per year of additional wood products in the long run. This is an increase in future harvests of 25 percent over harvests in 1995. Plantations have a much greater impact on markets than on carbon stocks, however, although their effect on carbon stocks is helpful because it is growth that is anticipated to be a byproduct of economically efficient, not subsidized, plantations.

Finally, it should be noted that our projections do not include estimates of the carbon losses due to tropical deforestation. Thus, our projections will not comport with those of, for example, the IPCC who estimate a decrease of 1.6 Gt in carbon sequestrated in the tropical forest. Their estimate depends on assuming some continuing rate of tropical deforestation, which our model does not do. We could do this by simply adding in the estimates of others to our model.

Scenario 2

Scenario 2 involves the creation of large areas of carbon sequestration plantations (high establishment), e.g., the establishment of 50 million ha of sequestration plantations over a 30 year period. One alternative establishes these in the slower growing regions of North American and Europe, while the other alternative assumes that the 50 million ha of sequestration plantations are established in the fast-growing subtropics over a 30 year period. Also, there is a low plantation alternative for both North America/Europe and the subtropics.

The largest impact is projected from the high establishment of carbon sequestration plantations in the subtropics. In this case, despite the crowding-out effect on commercial plantations that reduces the total industrial area in 2105 by 7.8 million ha below the area in the base case, total production expands rapidly and prices rise only 33 percent over the 110 year period from 2000 to 2110, as compared to 57 percent in the base case. Harvest rise from 1712 million m^3 to 2717 million m^3 annually, or 59 percent over this period, well above the 31 percent harvest increase of the base case. Importantly, additional net carbon sequestered increased to15.1 Gt over the period to 2105, or 61 percent more than the base case of 9.4 Gt.

The creation of carbon sequestration plantations in North America and Europe results in a similar amount of carbon being sequestered in the period to 2105, a total of 14.81 Gt, or 57 percent over the base case. However, the time profiles of the additional carbon sequestered are quite different (see figure 5), with the temperate forests adding more carbon in the earlier part of the period, less in the later part of the period due to their different growth cycles combined with harvesting, which is assumed to occur on carbon plantations as well as industrial.

While the addition of carbon plantations adds to total industrial wood harvest over time, the impact of temperate carbon plantation on industrial harvests is only modest,

while that of subtropical carbon harvests is large, due to the higher productivity of subtropical plantations. Thus, the effect of subtropical carbon plantations in depressing timber price is much larger than that of the temperate regions.

While crowding-out or "leakages" do occur, they tend to be relative modest. The higher leakages are associated with the high establishment of carbon plantations in the subtropics. This is because of the substantially higher productivity from subtropical carbon plantations depresses the market price and thus "crowds out" some commercial plantations that would have been established. However, output effect of rapidly growing carbon plantations in the subtropics tends to overwhelm the crowding-out effect thereby resulting in substantial global output increases and prices decline. We should note that much of the "crowding out" is cross-regional. For example, the depressed price caused by carbon plantations in the subtropics causes commercial plantation reductions in the temperate regions as well as in the subtropics. However, total carbon sequestration increases due to the carbon plantation bringing about an addition 5.7 Gts of carbon over the period, or about a 60 percent increase in carbon sequestered above that of the base case.

Scenario 3

Scenario 3: Involves the creation of a much lower level of carbon sequestration plantations (Low Establishment), specifically the establishment of 10 million ha of sequestration plantations over a 30 year period in both North America and Europe and in the Subtropical Region. The effects of the establishment in North America and Europe is barely different for price, total harvest, and additional carbon storage from that of the base case. For low carbon sequestration establishment in the subtropics the price and harvest effects are somewhat larger, but the carbon effect is small.

Figure 6 shows how much additional storage would be expected when carbon sequestration plantations are established in our four cases. This measures additional carbon storage relative to the baseline, which assumes no exogenous plantation establishment. Total carbon storage is considered here, which includes vegetation, markets, and soil storage.

Figure 6 also highlights the distortions caused by the high plantation subtropical region scenario. While forests are still sequestering additional carbon in that scenario, they are sequestering much less carbon than the baseline case, as shown by the negative number for the high plantation subtropical scenario. This occurs because forests in temperate regions are harvested more heavily in early periods because of the lower future prices which are expected to result from these additional plantations.

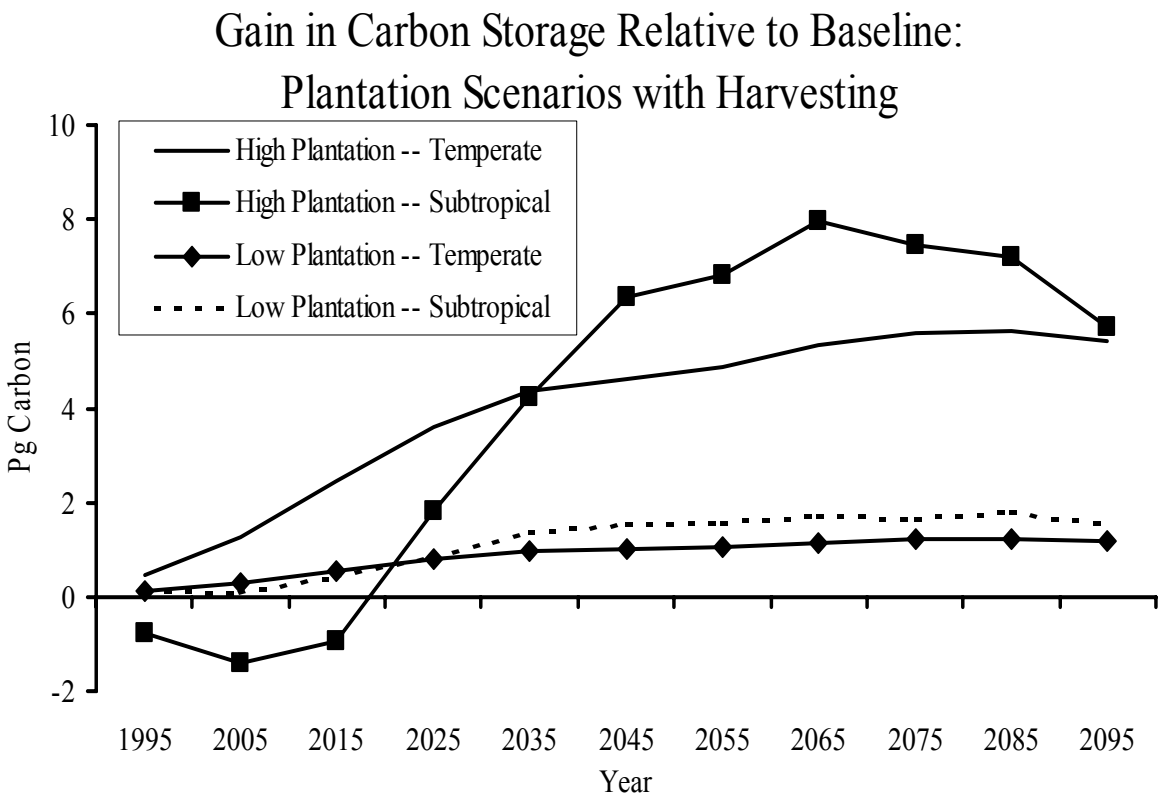

Figure 6: Gain in carbon storage relative to baseline under the plantation scenarios, with harvesting.

Scenario 4: Effects of rotation time.

In scenario 2 we examined the effect of high carbon sequestration plantation establishment in the subtropics on the assumption that the carbon plantations can also be harvested for timber. In this scenario, Scenario 4, we examine the effect on carbon sequestration with no harvest of these forests.

a) Add 50 million ha of sequestration forests to the base case without harvesting.
b) Add 50 million ha of sequestration forests to the base case. Allow harvesting with replanting but use a longer than financial optimum harvest rotation period.

Figure 7 is used to show the effect of harvest restrictions on carbon plantations and on total carbon sequestered over that of the base case when it is anticipated that future harvests from the sequestration plantations will be forbidden. Since under this scenario the carbon sequestration plantations are not expected to produce industrial wood, their creation does not discourage other wood oriented forest management and plantation establishment. By contrast, if it is expected that the wood of carbon plantations is to be harvested, commercial plantations and forest management activities are "crowded out". Thus, less carbon is obtained when these forests enter the market and are harvested at their optimal rotation ages. Additionally, the carbon forests are allowed to add biomass beyond the normal rotation period, thus further contributing to total biomass and related sequestered carbon.

In scenario 4b, carbon plantations are added but the harvest rotation is changed from a financial rotation to a long rotation. As before, it was assumed that 1/3 of the plantations were added each decade, beginning in the first decade. Additionally, it was assumed that softwood species were harvested in 50 years and hardwood species in 30 years. This compares to the typical industrial rotation age of 20-30 years for softwoods and 10 years for hardwoods. This method of harvesting these forests, subtropical long rotation harvests, leads to additional carbon sequestration, but the result is, not surprisingly, between our original harvest and no-harvest scenarios.

In Figure 7 the long rotation harvest carbon is presented together with that of the optimum financial rotation and that of the no harvest scenario. As intuition would suggest, the longer rotation provides for more sequestered carbon than with the financial rotation, but less than in the no harvest situation. The total carbon gain is about 4.44 Gts in year 2105, over what would occur in the shorter rotation case or about twice the incremental carbon sequestered in the optimal rotation case. The components of the difference in the gain in carbon storage for the optimal economic harvest and long rotation scenarios, for 50 million subtropical plantations in year 2005 is given in the table directly below figure 7:

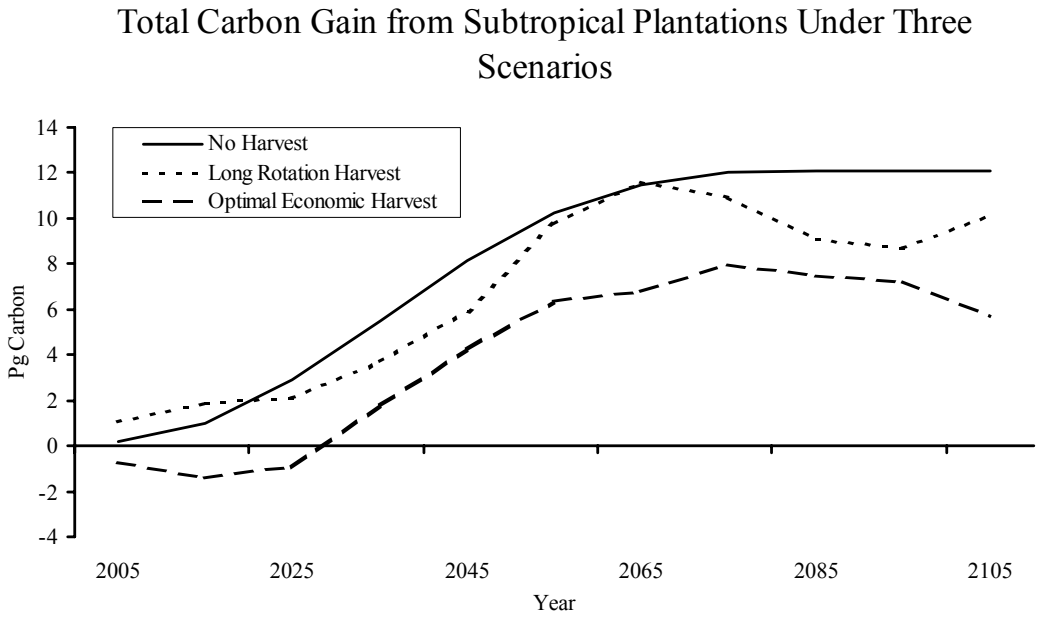

Figure 7 Gain in carbon storage relative to the baseline: effects of harvesting scenario

Gain (loss) in carbon storage in extended rotation case compared to optimal economic harvest case, Pg carbon			
Vegetation	Soil	Market	Total
3.69	1.01	(0.26)	4.44

Scenario 5: Substitution Effects

Over time it is expected that nonwood materials can substitute and replace wood material, at least to some extent. For example, in many uses wood as a material can be replaced by cement, steel, and so forth. On the pulp side, processes that are highly intensive in power, e.g., the groundwood process, increase their utilization of wood fiber, but at the cost of high power usage. Additionally, technology can play a major role. For example, forecasters have predicted the large scale substitution of electronic media for paper for the past several decades. However, thus far, paper production still continues its overall increase in worldwide production and consumption.

In a market model this anticipated substitution from wood to other materials and the reverse is captured in the price elasticity of the demand curve. As price rises, consumers shift away from the higher price commodity and substitute a now relatively lower priced good. Thus, the price of wood vis a vis all other goods has a mechanism for including the substitution of all other goods. A price inelastic demand curve indicates there is little potential for substitution in use, while a price elastic demand curve indicates greater substitution possibilities. In general, short-run curves tend to be more inelastic than long-run curves, since more substitution adaptations can be made over the longer period. Furthermore, the cross price elasticities may be important in some uses, e.g., lumber and steel. If the price of one rises, it can impact the consumption of the other, even if all other prices are unchanged. However, since the commodity of this study is industrial wood, even if steel where highly substitutable for lumber in some market, the overall effect of this one substitute on all industrial wood world-wide would, likely, be very small. Furthermore, most empirical data suggests that these cross elasticities, e.g., steel and concrete are very small (see Spelter 1985).

The basic DTSM uses a demand curve with a unitary price elasticity, i.e., - 1.0, a fairly responsive elasticity. However, if price changes only a small amount, the magnitudes of the substitution will be small.

The substitution scenario involves the introduction of the price elasticity used in a recent FAO study (Brooks, et al. 1996). Using cross-section samples that include 97 countries that account for more than 80 percent of the world's population and 81 percent of industrial round wood consumption, the FAO estimated the global price elasticity of industrial wood to be - 0.686. We build this alternative elasticity into the base case model and applied it to the scenario that generates the largest output forecast.

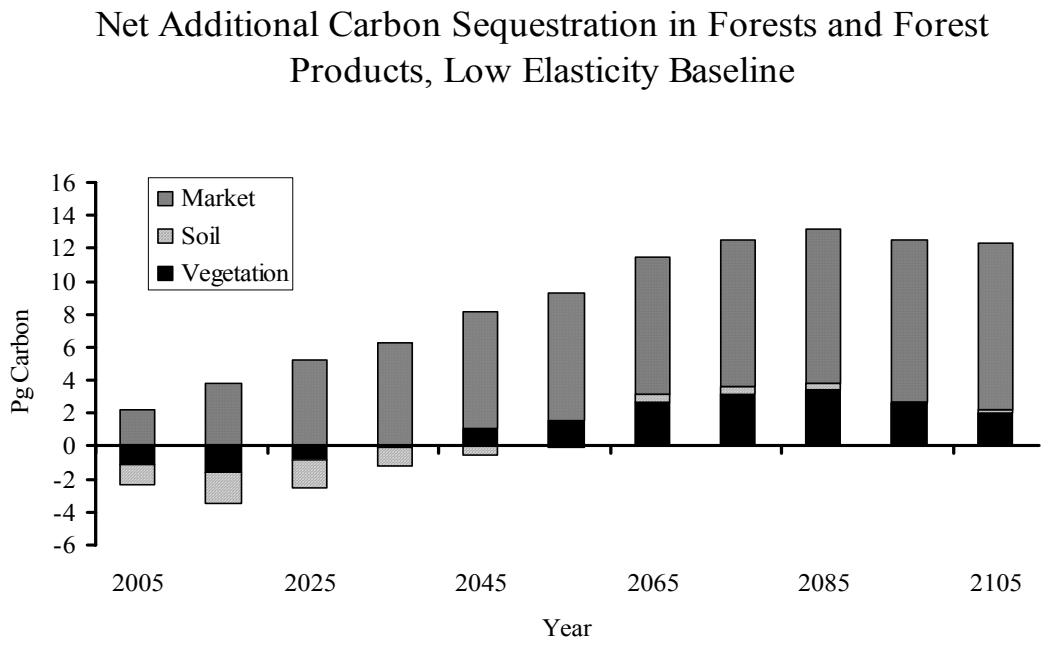

Figure 8: Net additional carbon sequestration in forests and forest products in the low elasticity baseline case.

Using the FAO elasticity this scenario picks up global wood-nonwood substitution that is consistent with recent experience. This can then be compared with a situation where no substitution occurred or where substitution is more fluid, as in the original elasticity used in the DTSM.

Figure 8 shows where the additional carbon from forest management accumulates for the low elasticity case. This case suggests that there are fewer substitution possibilities than the baseline case. This means that harvests rise to higher levels than the baseline, but also that prices rise more rapidly. More harvests imply that product storage increase, which can be seen by comparing this to figure 4 above.

Vegetation storage initially declines, which means that forests themselves are emitting more carbon. This occurs because harvests are heavy in early periods in the northern and boreal forest when we are limited to our initial inventories. Over time, vegetation begins to sequester additional carbon when management intensification can have an effect. This increased management results from the higher prices. Higher prices lead to greater management intensity in temperate forests, and additional plantation establishment.

Higher elasticity means slightly more storage than the baseline, but most of this accrues to storage in market products. It actually means less storage of carbon in vegetation in early periods. Vegetation storage rises above the baseline in later periods because of increased management of forests and increased plantation area.

Figure 9 shows the gain in carbon, relative to the baseline for the high elasticity case, with high plantation establishment in the subtropical regions. Breaking the gains or

losses into categories allows one to see that most of the gains occur in vegetation carbon. This same effect occurs for the baseline case with the addition of plantations.

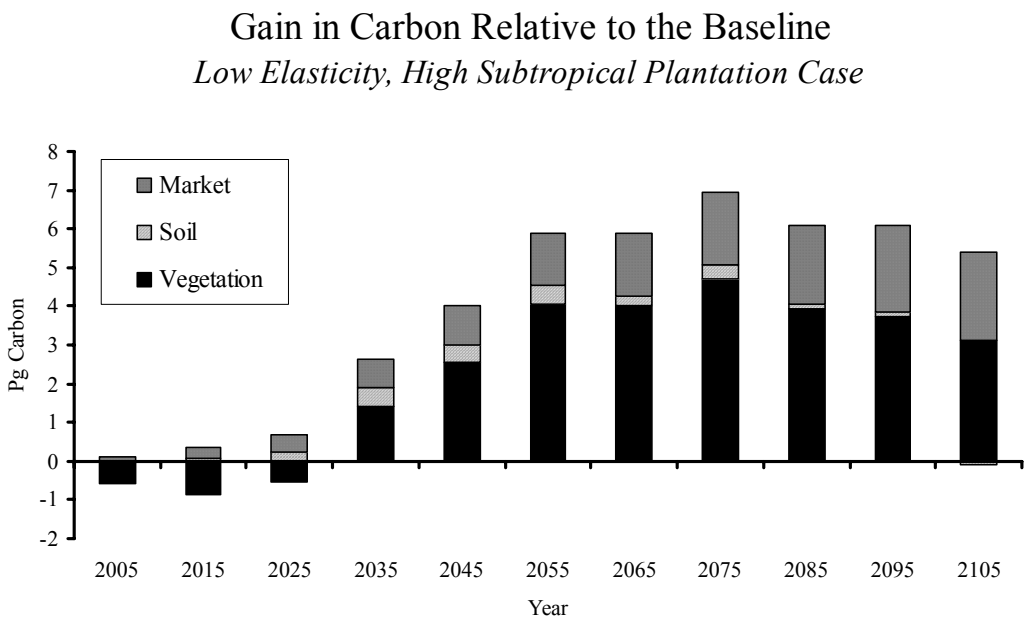

Figure 9: Gain in carbon for low elasticity, high subtropical plantation case.

Compared to the baseline case however, when plantations are added to the low elasticity model, the proportion of total storage that accumulates to market components is higher. This occurs because there is less substitution with other products. In 2105, 47 percent of the additional storage is market storage in the low elasticity case, compared to 43 percent for the baseline case.

For comparative purposes, figure 10 presents the gain in carbon relative to the baseline for the high subtropical plantation case, with the *normal* elasticity.

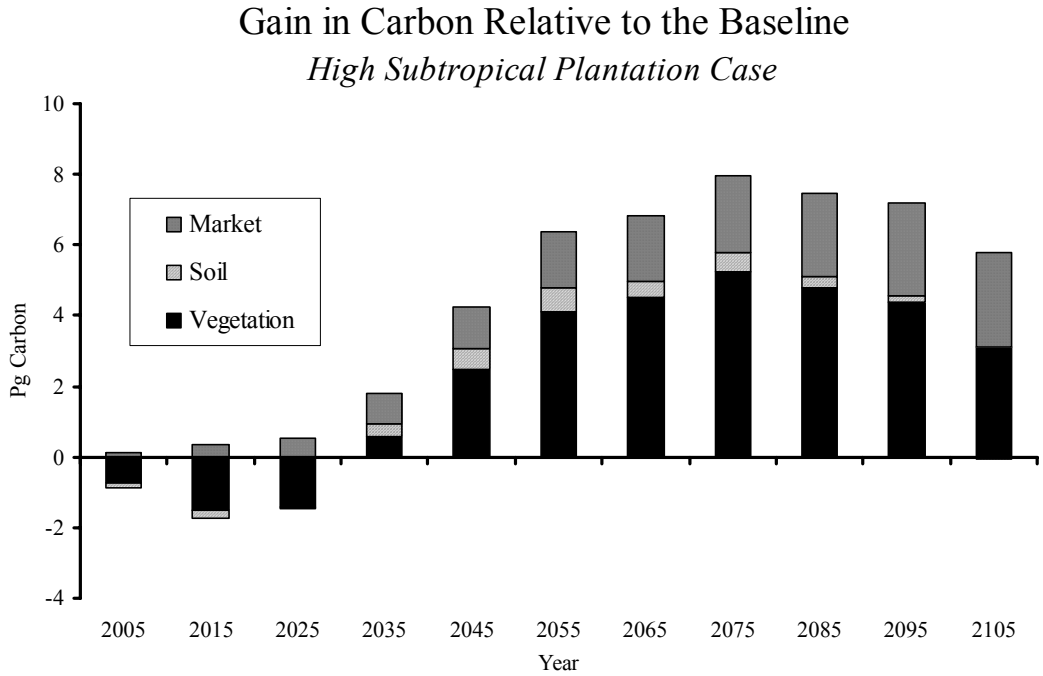

Figure 10: Gain in carbon for normal elasticity, high subtropical plantation case.

Figure 11 examines the extent to which crowding out occurs in the baseline and low elasticity case. The projections show that more crowding out occurs in the early period with the low elasticity case, although these results are reversed over the longer period.

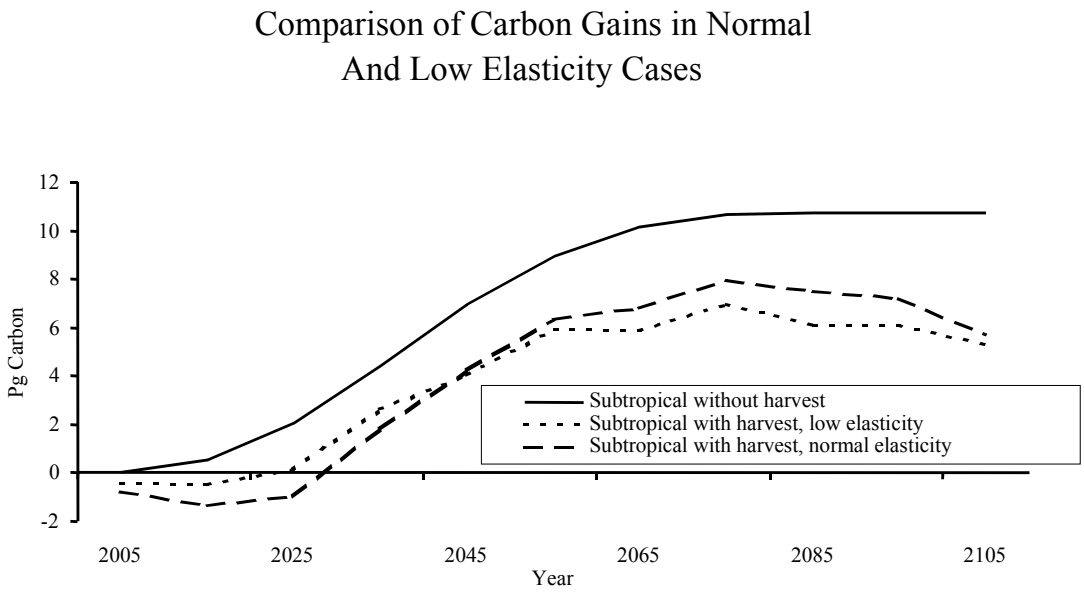

Figure 11: Comparison of carbon gains in normal and low elasticity cases

8. SOME ISSUES

Lands to be Forested: Although one might believe that the lands going into carbon plantations would simply occupy the next best forests lands after those already claimed by the commercial forest industry, this is not what appears to be planned in many developing countries. For example, work in Argentina suggests that the Argentine Government is looking to the establishment of carbon sequestration plantation in Patagonia, clearly not the best forest sites not already claimed by commercial forest interests available in Argentina. The rationale appears to be to use sequestration plantations as a vehicle for the development of some of the more economically backward regions of the country. Similarly in Colombia, the goal appears to be to reforest badly degraded tropical wastelands with carbon sequestration forests as a land rehabilitation scheme. A similar approach may occur in Indonesia. Again, these would be high cost lands that would typically be ignored by the industry. Additionally, there appears to be a strong reluctance by environment groups to agree to provide industry with carbon credit payments for planting trees on lands that they might plant without the carbon sequestration considerations. However, a country could receive credit toward its carbon targets under the Kyoto Protocol. Thus, lands at the commercial land margin might not be eligible for carbon sequestration payments even as the carbon sequestered in these forests is counted toward meeting a country's obligations. Many of these issues remain to be worked out but it seems clear that it is unlikely that carbon sequestration forests will simply be the extension of additional forests onto the best remaining marginal forest lands.

These considerations suggest that growth on the carbon plantations may be less rapid than that assumed in this analysis and the carbon build-up may also be less rapid than estimated in this model.

A Forward Looking Model: The question of the extent to which the industry actually takes account of the activities of others, including government sequestration programs, is an open question. Our DTSM assumes that industry is, on the average, forward looking. Discussions with industry firms and associations, e.g., the American Forest & Paper Association in Washington, DC both reveal the industry is keenly interested in the sources of future timber supplies. Numerous timber forecasting activities are undertaken by firms, consultants and public agencies such as the US Forest Service and the FAO. Industry regularly schedule meetings to discuss future demand and supply of wood resources. There is growing recognition by associations and firms that climate change and carbon sequestration forests may play a major role in future timber supplies. Firms indicate that much of their planting is aimed at meeting very specific future wood requirements. Planting locations and species types are adapted for those anticipated future needs. The industry has followed the climate debate very closely including discussion about forest sinks and sources and these considerations apparently are included in their strategic production plans. Thus, an analysis that assumes forward looking economic agents appears to be very sensible.

9. SUMMARY AND CONCLUSIONS

This study used a global timber market model, the Dynamic Timber Supply Model (DTSM) to examine the effects of introducing noncommercial carbon sequestration forests to the global timber production system with the focus on the effects of the carbon sequestration forests on total forest carbon. A baseline case was constructed and compared against a number of alternative scenarios, which introduced noncommercial carbon sequestration forests. Since the distribution of any likely global approach to carbon sequestration forests is unknown, they were introduced into the northern developed countries and then into the subtropical "southern" countries. Furthermore, the costs of the carbon sequestration plantations are unknown.

A number of conclusions flow from this study:

1. Even without any specific sequestration efforts, commercial forestry offers the potential to sequester substantial quantities of carbon, approaching 10 Gt, in vegetation, soils and market products over the next century. This quantity of carbon sequestration could be increased by 50 to 100 percent with 50 million ha of rapidly growing plantation forests

2. The projections suggest that the amount of crowding-out and carbon "leakages" is likely to be very modest. The 50 million ha of carbon plantations are projected to reduce land areas in industrial plantations, crowd-out, only by 1.1 to 7.8 million ha over the 100 year period.

3. The addition of carbon sequestration forests offers the potential to increase the carbon sequestration of the forest system over 50 percent, up to 5.7 Gts, above that already captured from market activity. This estimate assumes that crowding-out and associated leakages projected **will** occur. At current rates of atmospheric carbon buildup, about 2.8 percent of the expected total buildup in atmospheric carbon over the next century could be offset by 50 million ha of carbon plantations.

4. If the industrial wood from carbon sequestration plantations is kept out of the industrial wood basket, the potential forest carbon sequestration almost doubles for the high plantation scenario, from 5.7 Gts in the base case to about 11 Gts after 100 years. This is because the carbon plantations are allowed to approach maturity, which involves higher biomass and soil carbon. This amount of carbon is over 5 percent of the buildup of atmosphere carbon at current rates over 100 years. However, in this case the financial costs probably rise since financial returns from timber are not realized.

5. If carbon plantations are harvested, but put on a longer rotation, an intermediate amount of carbon would be sequestered, about 8-10 Gts over that of the base case, or about 4 percent of the expected buildup of atmospheric carbon over the next 100 years.

6. To the extent that demand is less elastic, e.g., nonwood materials are limited in their substitutability for wood, the commercial system will increase the amount of

carbon sequestration. In our example, the inelastic demand gave a base case increase of about 40 percent over the initial base case result, from 9.7 to about 12 Gts, in an approximately 100 year period. It should be noted here that this estimate does not consider the comparative fossil fuel carbon releases associated with using wood and nonwood materials.

7. Commercial forest activities plus the high carbon sequestration forest alternative (even allowing for short rotation harvests of sequestration plantations) can capture about 15 to 20 Gts of carbon over the next 100 years or about 5-6 percent of the current net carbon build-up in the atmosphere of about 3.0-3.5 Gts per year.

.

10. REFERENCES

Adams, D., R. Alig, J.M. Callaway, and B. McCarl. 1994. "Forest and Agricultural Sector Optimization Model: Model Description." Final Report to the Environmental Protection Agency, Climate Change Division, Washington, D.C. Variously numbered.

Brooks, David, Heikki Pajulja, Tim Peck, Birger Solberg, Philip Wardle, "Long-term Trends and Prospects in the *Supply and Demand for Timber and Implications for Sustainable Forest*," by FAO 1996, Rome.

Perez-Garcia, J. L.A. Joyce, C.S. Binkley, and A.D. McGuire. 1997. Economic Impacts of Climatic Change on the Global Forest Sector: An Integrated Ecological/Economic Assessment," in *Economics of Carbon Sequestration in Forestry*, R. Sedjo, R.N. Sampson and J. Wisniewski, editors, Lewis Publishers, 363 pps, Boca Raton, 1997.

Sedjo, R.A. R. Neil Sampson and Joe Wisniewski, 1997. *Economics of Carbon Sequestration in Forestry*, editors, Lewis Publishers, 363 pps, Boca Raton, and also in *Critical Reviews in Environmental Science and Technology*, Vol. 27:1-364, Special Issue.

Sedjo, Roger A. 1999. "Potential for Carbon Forest Plantation in marginal Timber Forests: the Case of Patagonia, Argentina," Discussion paper 99-27, Resources for the Future, Washington, D.C*.

Sedjo, Roger. A. and Kenneth. S. Lyon. 1990. *The Long Term Adequacy of the World Timber Supply*. Washington: Resources For the Future. 230 p*.

Sedjo, Roger A. and Kenneth S. Lyon. 1996. "Timber Supply Model 96: A Global Timber Supply Model with a Pulpwood Component." Discussion Paper 96-15. Resources For the Future, Washington, D.C. 60 p*.

Sohngen, Brent; Robert Mendelsohn, and Roger Sedjo. "Forest Management, Conservation, and Global Timber Markets," *American Journal of Agricultural Economics*, February 1999, Vol. 81, p 1-13.

Sohngen, Brent and Roger Sedjo. in press. "Potential Carbon Flux From Timber Harvest and Management in the Context of A Global Timber Market," in *Climatic Change.*

Spelter, Henry. 1985. A Product Diffusion Approach to Modeling Softwood Lumber Demand, *Forest Science*, Vol. 31, No. 3 (1985)

*RFF Discussion Papers are available from RFF, 1616 P Street NW, Washington, DC 20036

APPENDIX 1

DETAILED RESULTS TABLES

Scenario 1:	Baseline case
Scenario 2a:	Temperate high plantation case
Scenario 2b:	Subtropical high plantation case
Scenario 3a:	Temperate low plantation case
Scenario 3b:	Subtropical low plantation case
Scenario 4a:	No timber harvest
Scenario 4b:	Subtropical high plantation case with long rotation harvesting
Scenario 5a:	Low demand elasticity base case
Scenario 5b:	Low demand elasticity subtropical high plantation case

SCENARIO 1: BASELINE CASE

Price and Harvest

	Price	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
						Million m^3 per year					
1980		456	84	280	277	76	21	26	114	52	1386
1992		582	117	279	256	93	25	32	133	59	1575
2000	75	571	161	257	255	101	27	49	161	59	1641
2010	82	568	180	250	231	123	29	62	166	76	1685
2020	87	541	217	234	228	142	31	84	200	94	1771
2030	91	490	247	252	251	138	33	116	209	115	1852
2040	97	470	269	267	232	160	36	132	217	142	1925
2050	102	429	286	297	222	174	47	153	222	153	1983
2060	106	427	300	311	191	192	48	168	228	161	2027
2070	109	489	311	299	143	195	49	172	231	178	2068
2080	112	516	320	295	139	183	48	184	234	181	2100
2090	114	547	328	268	148	188	38	192	236	184	2129
2100	116	556	334	281	173	138	39	192	238	197	2147
2110	117	516	339	298	181	149	41	199	238	196	2157

Baseline Total Carbon

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	164.9	229.5	38.5	212.9	31.7	1.5	22.3	88.8	123.0	913.1
2005	164.3	229.5	39.0	212.4	32.7	1.6	22.9	89.0	123.0	914.5
2015	163.5	229.6	39.7	212.4	33.6	1.6	23.5	88.9	123.1	916.0
2025	162.6	229.9	40.6	212.4	34.3	1.7	24.1	89.2	123.3	918.2
2035	162.4	230.2	41.3	211.3	34.9	1.9	24.5	89.3	123.5	919.3
2045	162.8	230.4	41.7	209.8	35.4	2.0	24.9	89.7	123.6	920.2
2055	163.8	230.6	41.5	208.8	35.3	1.9	25.1	89.7	123.8	920.5
2065	164.9	230.7	41.3	209.4	34.2	1.8	25.2	90.3	123.9	921.6
2075	165.3	230.8	40.9	210.2	33.4	1.8	25.3	90.3	124.0	921.9
2085	164.7	230.9	40.8	210.8	33.6	1.8	25.4	90.5	124.0	922.5
2095	163.4	231.0	40.7	211.3	33.8	1.9	25.4	90.5	124.1	922.0
2105	162.7	231.0	40.4	211.3	34.5	2.0	25.5	91.0	124.1	922.5

Baseline Tree Carbon

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	29.6	74.4	9.4	29.8	7.5	0.1	7.0	46.4	36.8	241.0
2005	29.1	74.5	9.7	29.3	8.2	0.1	7.5	46.3	36.9	241.5
2015	28.3	74.6	10.1	29.3	8.7	0.2	7.9	46.2	37.0	242.2
2025	27.6	74.7	10.7	29.3	9.2	0.2	8.2	46.2	37.1	243.3
2035	27.4	74.7	11.3	28.5	9.7	0.3	8.5	46.2	37.2	243.8
2045	27.7	74.8	11.6	27.5	10.1	0.4	8.7	46.2	37.2	244.1
2055	28.5	74.8	11.5	26.7	10.0	0.3	8.7	46.1	37.2	243.9
2065	29.4	74.8	11.3	27.2	9.1	0.2	8.7	46.3	37.3	244.2
2075	29.8	74.9	11.1	27.7	8.4	0.2	8.7	46.2	37.3	244.2
2085	29.4	74.9	11.0	28.2	8.5	0.2	8.8	46.3	37.3	244.5
2095	28.6	74.9	10.9	28.6	8.7	0.3	8.7	46.2	37.3	244.1
2105	27.9	74.9	10.6	28.7	9.3	0.3	8.8	46.3	37.3	244.2

Baseline Floor and Understory Carbon

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	19.6	46.5	4.0	27.1	3.2	0.1	0.6	3.9	22.1	127.1
2005	19.3	46.4	4.0	27.1	3.3	0.1	0.6	3.9	22.0	126.7
2015	19.1	46.3	4.1	27.0	3.3	0.1	0.7	3.8	22.0	126.4
2025	19.0	46.3	4.2	27.0	3.4	0.1	0.7	3.8	22.0	126.4
2035	18.9	46.3	4.2	26.8	3.4	0.1	0.7	3.8	22.0	126.2
2045	18.9	46.3	4.2	26.6	3.4	0.1	0.7	3.8	22.0	126.0
2055	19.0	46.2	4.2	26.4	3.4	0.1	0.7	3.8	22.0	125.8
2065	19.1	46.2	4.1	26.5	3.3	0.1	0.7	3.8	22.0	125.8
2075	19.0	46.2	4.1	26.6	3.2	0.1	0.7	3.8	22.0	125.7
2085	18.9	46.2	4.1	26.7	3.2	0.1	0.7	3.8	22.0	125.7
2095	18.7	46.2	4.0	26.7	3.2	0.1	0.7	3.8	22.0	125.6
2105	18.7	46.2	4.0	26.8	3.3	0.1	0.7	3.8	22.0	125.6

Baseline Soil Storage

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	114.2	108.2	24.4	155.4	20.7	1.3	14.6	38.1	64.0	540.9
2005	113.8	108.1	24.5	155.3	21.0	1.3	14.6	37.9	63.9	540.3
2015	113.5	108.0	24.6	155.3	21.1	1.3	14.7	37.9	63.8	540.0
2025	113.3	108.0	24.7	155.2	21.1	1.3	14.8	37.9	63.8	540.0
2035	113.3	108.1	24.7	154.9	21.1	1.3	14.8	37.9	63.9	540.0
2045	113.4	108.1	24.7	154.7	21.2	1.3	14.9	37.9	63.9	540.2
2055	113.6	108.2	24.6	154.7	21.1	1.3	14.9	37.9	64.0	540.3
2065	113.7	108.2	24.6	154.9	21.0	1.3	15.0	38.0	64.0	540.7
2075	113.6	108.2	24.5	155.1	21.0	1.3	15.0	38.0	64.0	540.8
2085	113.4	108.2	24.5	155.2	21.1	1.4	15.0	38.0	64.1	540.8
2095	113.1	108.2	24.5	155.2	21.1	1.4	15.0	37.9	64.1	540.6
2105	113.1	108.3	24.5	155.1	21.1	1.4	15.0	38.1	64.1	540.7

Baseline Market Storage

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	1.5	0.3	0.7	0.6	0.3	0.1	0.1	0.4	0.2	4.1
2005	2.1	0.6	0.8	0.8	0.4	0.1	0.2	0.9	0.2	6.0
2015	2.5	0.8	1.0	0.9	0.5	0.1	0.3	1.0	0.3	7.3
2025	2.7	0.9	1.1	1.0	0.6	0.1	0.4	1.3	0.4	8.5
2035	2.8	1.1	1.1	1.0	0.6	0.1	0.5	1.5	0.4	9.3
2045	2.8	1.2	1.2	1.0	0.7	0.2	0.6	1.7	0.5	10.0
2055	2.7	1.3	1.3	0.9	0.8	0.2	0.7	1.9	0.6	10.4
2065	2.7	1.4	1.3	0.8	0.8	0.2	0.8	2.1	0.6	10.8
2075	2.8	1.5	1.3	0.8	0.8	0.2	0.9	2.3	0.6	11.2
2085	3.0	1.6	1.3	0.7	0.8	0.2	0.9	2.5	0.7	11.5
2095	3.0	1.6	1.3	0.7	0.8	0.2	1.0	2.6	0.7	11.8
2105	3.0	1.6	1.3	0.7	0.7	0.2	1.0	2.7	0.7	12.0

Baseline Average Annual Carbon Flux by Decade

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
	Petagrams carbon									
1995-2005	-56	0	54	-47	106	5	59	17	1	140
2005-2015	-85	15	67	2	84	8	59	-10	8	147
2015-2025	-81	27	88	-3	71	10	58	34	19	223
2025-2035	-24	27	71	-111	57	13	45	12	19	109
2035-2045	36	21	43	-153	52	12	34	35	16	97
2045-2055	106	18	-21	-99	-10	-5	18	2	12	20
2055-2065	105	12	-27	64	-111	-8	15	58	10	118
2065-2075	41	12	-31	76	-78	-9	8	1	8	27
2075-2085	-62	7	-18	67	16	7	10	26	7	60
2085-2095	-123	8	-10	45	24	9	4	-6	5	-45
2095-2105	-78	4	-28	5	70	11	7	51	4	46

SCENARIO 2a: TEMPERATE HIGH PLANTATION

Price and Harvest

	Price	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
						Million m^3 per year					
1980		456	84	280	277	76	21	26	114	52	1386
1992		582	117	279	256	93	25	32	133	59	1575
2000	75	571	161	256	256	101	27	47	161	58	1638
2010	82	569	180	249	233	123	29	60	165	74	1681
2020	87	541	217	234	226	143	31	85	200	91	1767
2030	91	492	247	259	249	143	33	112	209	112	1855
2040	96	492	268	274	229	157	36	131	216	138	1942
2050	100	488	284	286	218	170	47	154	222	148	2016
2060	103	511	296	300	190	188	48	162	227	155	2078
2070	106	586	307	289	142	186	48	169	230	171	2129
2080	109	594	315	292	138	192	47	182	233	174	2167
2090	112	614	322	301	147	179	38	185	234	176	2197
2100	113	626	328	305	173	132	39	187	236	189	2215
2110	115	593	333	303	182	153	41	197	237	188	2228

Temperate High Plantation Total Carbon

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	164.8	229.5	38.5	212.9	31.7	1.5	22.4	88.8	123.0	913.0
2005	164.8	229.5	39.0	212.4	32.7	1.6	22.9	89.0	123.1	914.9
2015	164.7	229.7	39.7	212.3	33.6	1.6	23.5	88.9	123.2	917.1
2025	165.0	229.9	40.7	212.3	34.3	1.7	24.1	89.2	123.4	920.6
2035	166.0	230.2	41.5	211.2	34.6	1.9	24.5	89.3	123.5	922.8
2045	167.0	230.4	41.9	209.8	35.2	2.0	24.9	89.7	123.7	924.5
2055	168.1	230.6	42.0	208.8	35.1	1.9	25.0	89.7	123.8	925.0
2065	168.7	230.7	42.1	209.4	34.2	1.9	25.2	90.2	123.9	926.4
2075	169.0	230.8	42.3	210.2	33.5	1.8	25.3	90.3	124.0	927.1
2085	168.8	230.9	42.3	210.9	33.4	1.8	25.4	90.5	124.1	928.0
2095	167.8	230.9	42.0	211.3	33.6	1.9	25.4	90.5	124.1	927.6
2105	166.9	231.0	41.8	211.4	34.2	2.0	25.5	91.0	124.1	927.8

Temperate High Plantation Tree Carbon

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	29.6	74.4	9.4	29.8	7.5	0.1	7.0	46.4	36.8	241.0
2005	29.3	74.5	9.6	29.3	8.1	0.1	7.5	46.3	36.9	241.7
2015	29.1	74.6	10.1	29.2	8.7	0.2	7.9	46.2	37.0	242.8
2025	29.0	74.7	10.7	29.2	9.2	0.2	8.2	46.2	37.1	244.6
2035	29.6	74.7	11.3	28.5	9.5	0.3	8.5	46.2	37.2	245.7
2045	30.3	74.8	11.5	27.5	9.9	0.4	8.6	46.2	37.2	246.4
2055	31.0	74.8	11.6	26.7	9.8	0.3	8.7	46.1	37.2	246.4
2065	31.6	74.8	11.7	27.2	9.1	0.2	8.7	46.3	37.3	247.0
2075	31.9	74.9	12.0	27.7	8.5	0.2	8.7	46.2	37.3	247.3
2085	31.8	74.9	12.0	28.3	8.4	0.2	8.7	46.3	37.3	247.8
2095	31.1	74.9	11.8	28.6	8.6	0.3	8.7	46.1	37.3	247.5
2105	30.3	74.9	11.6	28.7	9.1	0.3	8.8	46.3	37.3	247.4

Temperate High Plantation Floor and Understory Carbon

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	19.6	46.5	4.0	27.1	3.2	0.1	0.6	3.9	22.1	127.1
2005	19.5	46.4	4.1	27.0	3.3	0.1	0.6	3.9	22.1	126.9
2015	19.5	46.3	4.2	27.0	3.3	0.1	0.7	3.8	22.0	126.9
2025	19.5	46.3	4.3	27.0	3.4	0.1	0.7	3.8	22.0	127.0
2035	19.5	46.3	4.3	26.8	3.4	0.1	0.7	3.8	22.0	127.0
2045	19.6	46.3	4.4	26.6	3.4	0.1	0.7	3.8	22.0	126.9
2055	19.7	46.2	4.4	26.4	3.4	0.1	0.7	3.8	22.0	126.7
2065	19.7	46.2	4.4	26.5	3.3	0.1	0.7	3.8	22.0	126.7
2075	19.7	46.2	4.4	26.6	3.2	0.1	0.7	3.8	22.0	126.7
2085	19.6	46.2	4.3	26.7	3.2	0.1	0.7	3.8	22.0	126.7
2095	19.4	46.2	4.3	26.8	3.2	0.1	0.7	3.8	22.0	126.6
2105	19.3	46.2	4.3	26.8	3.3	0.1	0.7	3.8	22.0	126.6

Temperate High Plantation Soil Storage

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	114.2	108.2	24.4	155.4	20.7	1.3	14.6	38.1	64.0	540.9
2005	113.9	108.1	24.5	155.3	21.0	1.3	14.6	37.9	63.9	540.3
2015	113.7	108.0	24.5	155.2	21.1	1.3	14.7	37.9	63.8	540.2
2025	113.7	108.0	24.7	155.2	21.1	1.3	14.8	37.9	63.9	540.5
2035	114.0	108.1	24.7	154.9	21.1	1.3	14.8	37.9	63.9	540.8
2045	114.2	108.1	24.8	154.7	21.1	1.4	14.9	37.9	64.0	541.1
2055	114.4	108.2	24.8	154.7	21.1	1.3	14.9	37.9	64.0	541.3
2065	114.3	108.2	24.8	155.0	21.0	1.3	15.0	38.0	64.1	541.6
2075	114.2	108.2	24.7	155.1	21.0	1.3	15.0	38.0	64.1	541.6
2085	114.0	108.2	24.7	155.2	21.0	1.4	15.0	38.0	64.1	541.6
2095	113.9	108.3	24.6	155.2	21.0	1.4	15.0	37.9	64.1	541.4
2105	113.8	108.3	24.6	155.1	21.1	1.4	15.0	38.1	64.1	541.5

Temperate High Plantation Market Storage

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	1.5	0.3	0.7	0.6	0.3	0.1	0.1	0.4	0.2	4.1
2005	2.1	0.6	0.8	0.8	0.4	0.1	0.2	0.9	0.2	6.0
2015	2.5	0.8	1.0	0.9	0.5	0.1	0.3	1.0	0.3	7.3
2025	2.7	0.9	1.1	1.0	0.6	0.1	0.4	1.3	0.4	8.5
2035	2.8	1.1	1.1	1.0	0.6	0.1	0.5	1.5	0.4	9.3
2045	2.9	1.2	1.2	1.0	0.7	0.2	0.6	1.7	0.5	10.1
2055	3.0	1.3	1.2	0.9	0.8	0.2	0.7	1.9	0.5	10.6
2065	3.1	1.4	1.3	0.8	0.8	0.2	0.8	2.1	0.6	11.1
2075	3.2	1.5	1.3	0.8	0.8	0.2	0.8	2.3	0.6	11.5
2085	3.4	1.5	1.3	0.7	0.8	0.2	0.9	2.5	0.6	11.8
2095	3.4	1.6	1.3	0.7	0.7	0.2	0.9	2.6	0.6	12.1
2105	3.4	1.6	1.3	0.7	0.7	0.2	1.0	2.7	0.7	12.4

Temperate High Plantation Average Annual Carbon Flux by Decade

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
	Petagrams carbon									
1995-2005	-6	0	54	-50	106	5	56	17	4	186
2005-2015	-6	15	72	-6	84	8	59	-10	10	226
2015-2025	28	27	100	-3	71	11	58	34	19	344
2025-2035	99	27	78	-107	36	13	44	12	19	221
2035-2045	107	21	40	-144	52	12	34	34	16	171
2045-2055	106	17	5	-98	-8	-5	18	1	12	49
2055-2065	63	11	16	66	-86	-8	14	58	10	144
2065-2075	30	11	19	77	-73	-9	8	0	8	71
2075-2085	-24	7	3	67	-13	6	10	26	6	88
2085-2095	-98	8	-33	45	26	8	4	-6	5	-42
2095-2105	-92	4	-20	1	58	10	7	51	4	24

SCENARIO 2b: SUBTROPICAL HIGH PLANTATION

Price and Harvest

	Price	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
						Million m^3 per year					
1980		456	84	280	277	76	21	26	114	52	1386
1992		582	117	279	256	93	25	32	133	59	1575
2000	72	577	179	287	274	103	27	46	154	65	1712
2010	76	547	250	253	243	140	28	65	179	90	1794
2020	78	509	359	230	226	123	30	105	233	139	1952
2030	80	434	487	217	193	119	31	154	282	192	2109
2040	82	424	563	195	163	136	34	189	311	242	2259
2050	84	374	619	222	156	142	44	225	336	270	2389
2060	85	419	628	240	137	175	45	232	341	276	2493
2070	88	456	635	275	139	164	45	235	343	289	2581
2080	89	494	642	276	141	174	44	245	345	288	2649
2090	91	528	648	274	166	159	35	248	347	291	2695
2100	93	514	653	275	200	141	35	249	348	303	2719
2110	96	481	660	264	189	177	37	258	350	301	2717

Subtropical Region High Plantation Total Carbon

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	164.7	229.5	38.4	212.8	31.7	1.5	22.4	88.8	123.0	912.7
2005	163.5	230.2	38.5	211.4	32.6	1.6	23.1	89.3	123.3	913.4
2015	162.5	231.0	38.8	210.5	32.8	1.7	23.8	89.4	123.7	914.2
2025	161.9	232.1	39.2	209.8	33.6	1.8	24.6	89.8	124.1	916.9
2035	162.1	232.8	40.1	209.5	34.2	1.9	25.2	90.4	124.5	920.7
2045	162.5	233.3	40.7	209.1	35.3	2.0	25.6	90.8	124.7	924.1
2055	164.0	233.5	41.0	209.5	34.9	1.9	25.8	91.0	124.8	926.4
2065	164.6	233.9	41.1	210.3	33.9	1.8	26.0	91.5	125.0	928.1
2075	165.3	233.9	40.9	211.2	33.5	1.8	26.1	91.9	125.0	929.5
2085	164.1	234.1	40.6	211.8	33.9	1.8	26.2	92.0	125.1	929.6
2095	163.5	234.1	40.2	211.5	34.2	1.9	26.2	92.1	125.1	928.8
2105	162.5	234.3	40.1	210.5	34.5	2.0	26.3	92.5	125.2	927.8

Subtropical Region High Plantation Tree Carbon

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	29.4	74.4	9.3	29.6	7.5	0.1	7.0	46.4	36.8	240.4
2005	28.4	74.9	9.2	28.6	8.0	0.1	7.5	46.5	37.0	240.2
2015	27.6	75.4	9.3	27.8	8.1	0.2	8.1	46.5	37.3	240.2
2025	27.0	75.8	9.5	27.2	8.7	0.2	8.6	46.6	37.5	241.3
2035	27.1	76.0	10.3	27.1	9.3	0.3	8.8	46.8	37.7	243.3
2045	27.5	76.1	10.7	26.9	10.1	0.4	9.0	46.8	37.7	245.3
2055	28.6	76.0	11.1	27.1	9.8	0.3	9.0	46.7	37.8	246.5
2065	29.2	76.2	11.2	27.8	9.0	0.2	9.1	46.8	37.8	247.2
2075	29.7	76.1	11.1	28.5	8.6	0.1	9.1	46.9	37.8	247.8
2085	28.9	76.2	10.8	29.0	8.8	0.2	9.1	46.8	37.8	247.7
2095	28.4	76.1	10.5	28.9	9.1	0.2	9.1	46.8	37.8	247.0
2105	27.7	76.2	10.4	28.1	9.4	0.3	9.1	46.9	37.8	246.0

Subtropical Region High Plantation Floor and Understory Carbon

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	19.6	46.5	4.0	27.1	3.2	0.1	0.6	3.9	22.1	127.1
2005	19.3	46.5	4.0	26.9	3.2	0.1	0.7	3.9	22.1	126.6
2015	19.1	46.5	4.0	26.8	3.3	0.1	0.7	3.9	22.1	126.4
2025	18.9	46.5	4.1	26.7	3.3	0.1	0.7	3.9	22.1	126.4
2035	18.9	46.5	4.2	26.7	3.4	0.1	0.8	3.9	22.1	126.6
2045	19.0	46.5	4.2	26.6	3.4	0.1	0.8	3.9	22.1	126.7
2055	19.1	46.5	4.2	26.6	3.4	0.1	0.8	3.9	22.1	126.7
2065	19.2	46.5	4.2	26.7	3.3	0.1	0.8	3.9	22.1	126.8
2075	19.2	46.5	4.1	26.8	3.2	0.1	0.8	3.9	22.1	126.8
2085	19.0	46.5	4.1	26.9	3.3	0.1	0.8	3.9	22.1	126.7
2095	18.9	46.5	4.0	26.8	3.3	0.1	0.8	3.9	22.1	126.5
2105	18.8	46.5	4.0	26.7	3.3	0.1	0.8	3.9	22.1	126.3

Subtropical Region High Plantation Soil Storage

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	114.2	108.3	24.4	155.4	20.7	1.3	14.6	38.1	64.0	541.0
2005	113.7	108.1	24.5	155.1	20.9	1.3	14.7	37.9	63.9	540.3
2015	113.4	108.1	24.6	155.0	20.9	1.3	14.8	37.9	63.9	539.9
2025	113.3	108.2	24.6	154.9	21.0	1.3	14.9	37.9	64.0	540.1
2035	113.4	108.2	24.7	154.9	21.0	1.4	14.9	37.9	64.0	540.5
2045	113.6	108.3	24.7	154.9	21.1	1.4	15.0	37.9	64.1	540.9
2055	113.8	108.3	24.7	155.0	21.0	1.4	15.0	37.9	64.1	541.1
2065	113.8	108.4	24.6	155.1	20.9	1.4	15.0	38.0	64.1	541.3
2075	113.7	108.4	24.6	155.3	21.0	1.4	15.0	38.0	64.2	541.4
2085	113.4	108.4	24.5	155.2	21.0	1.4	15.0	38.0	64.2	541.2
2095	113.3	108.4	24.5	155.1	21.1	1.4	15.0	37.9	64.2	540.9
2105	113.2	108.4	24.5	154.9	21.1	1.4	15.1	38.0	64.2	540.8

Subtropical Region High Plantation Market Storage

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	1.5	0.3	0.7	0.6	0.3	0.1	0.1	0.4	0.2	4.2
2005	2.0	0.7	0.9	0.8	0.4	0.1	0.2	0.9	0.2	6.2
2015	2.4	1.1	1.0	0.9	0.5	0.1	0.3	1.1	0.3	7.7
2025	2.5	1.5	1.0	0.9	0.5	0.1	0.5	1.5	0.5	9.1
2035	2.6	2.0	1.0	0.9	0.5	0.1	0.7	1.8	0.6	10.2
2045	2.5	2.3	1.0	0.8	0.6	0.2	0.9	2.2	0.7	11.2
2055	2.5	2.6	1.0	0.7	0.7	0.2	1.0	2.5	0.8	12.1
2065	2.5	2.8	1.1	0.7	0.7	0.2	1.1	2.8	0.9	12.8
2075	2.7	2.9	1.1	0.7	0.7	0.2	1.2	3.0	0.9	13.4
2085	2.8	3.0	1.2	0.7	0.7	0.2	1.2	3.3	1.0	14.0
2095	2.8	3.1	1.2	0.7	0.7	0.2	1.3	3.5	1.0	14.5
2105	2.8	3.1	1.2	0.8	0.7	0.2	1.3	3.7	1.0	14.8

Subtropical Region High Plantation Average Annual Carbon Flux by Decade

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
	Petagrams carbon									
1995-2005	-119	64	17	-139	96	6	68	49	23	64
2005-2015	-103	85	33	-86	21	8	78	9	39	84
2015-2025	-58	108	37	-75	75	10	80	43	45	267
2025-2035	22	66	87	-24	63	12	58	62	38	384
2035-2045	43	59	56	-39	112	12	41	37	20	340
2045-2055	145	17	34	33	-46	-6	18	20	15	232
2055-2065	66	37	10	82	-101	-9	18	48	11	163
2065-2075	69	1	-22	92	-40	-10	6	37	8	141
2075-2085	-119	25	-32	57	40	5	12	16	6	10
2085-2095	-63	-7	-35	-26	37	7	1	9	4	-72
2095-2105	-99	21	-12	-103	28	9	9	39	4	-103

SCENARIO 3a: TEMPERATE LOW PLANTATION

Price and Harvest

	Price	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
						Million m^3 per year					
1980		456	84	280	277	76	21	26	114	52	1386
1992		582	117	279	256	93	25	32	133	59	1575
2000	75	570	161	257	255	101	27	49	161	58	1639
2010	82	568	180	250	231	123	29	62	165	74	1683
2020	87	541	217	234	228	142	31	84	200	91	1768
2030	91	490	247	255	251	138	33	116	209	113	1851
2040	97	475	269	267	232	160	36	132	217	139	1926
2050	102	441	286	295	222	173	47	153	222	150	1988
2060	106	445	299	308	191	192	48	167	228	158	2036
2070	108	508	310	296	143	195	49	172	231	175	2078
2080	111	532	319	296	139	183	48	183	234	177	2111
2090	114	562	327	272	148	188	38	191	236	179	2141
2100	115	570	333	291	173	135	39	190	237	192	2161
2110	117	534	338	297	180	152	41	198	238	192	2170

Temperate Low Plantation Total Carbon

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	164.9	229.5	38.5	212.9	31.7	1.5	22.3	88.8	123.0	913.1
2005	164.4	229.5	39.0	212.4	32.7	1.6	22.9	89.0	123.1	914.6
2015	163.7	229.6	39.7	212.4	33.6	1.6	23.5	88.9	123.2	916.3
2025	163.1	229.9	40.6	212.4	34.3	1.7	24.1	89.2	123.3	918.7
2035	163.1	230.2	41.3	211.3	34.9	1.9	24.5	89.3	123.5	920.1
2045	163.6	230.4	41.8	209.8	35.4	2.0	24.9	89.7	123.7	921.2
2055	164.7	230.6	41.6	208.8	35.3	1.9	25.1	89.7	123.8	921.4
2065	165.6	230.7	41.5	209.4	34.2	1.8	25.2	90.3	123.9	922.6
2075	166.0	230.8	41.2	210.2	33.4	1.8	25.3	90.3	124.0	923.0
2085	165.5	230.9	41.1	210.8	33.5	1.8	25.4	90.5	124.1	923.7
2095	164.3	231.0	41.0	211.3	33.7	1.9	25.4	90.5	124.1	923.2
2105	163.5	231.0	40.7	211.3	34.5	2.0	25.5	91.0	124.2	923.7

Temperate Low Plantation Tree Carbon

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	29.6	74.4	9.4	29.8	7.5	0.1	7.0	46.4	36.8	241.0
2005	29.1	74.5	9.7	29.3	8.2	0.1	7.5	46.3	36.9	241.6
2015	28.5	74.6	10.1	29.3	8.7	0.2	7.9	46.2	37.0	242.4
2025	27.9	74.7	10.7	29.3	9.2	0.2	8.2	46.2	37.1	243.6
2035	27.8	74.7	11.3	28.5	9.7	0.3	8.5	46.2	37.2	244.2
2045	28.2	74.8	11.6	27.5	10.1	0.4	8.7	46.2	37.2	244.6
2055	29.0	74.8	11.5	26.7	10.0	0.3	8.7	46.1	37.2	244.4
2065	29.8	74.8	11.4	27.1	9.1	0.2	8.7	46.3	37.3	244.8
2075	30.2	74.9	11.3	27.7	8.4	0.2	8.7	46.2	37.3	244.9
2085	29.9	74.9	11.2	28.2	8.5	0.2	8.8	46.3	37.3	245.2
2095	29.1	74.9	11.1	28.6	8.7	0.3	8.7	46.2	37.3	244.9
2105	28.4	74.9	10.8	28.7	9.3	0.3	8.8	46.3	37.3	244.9

Temperate Low Plantation Floor and Understory Carbon

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	19.6	46.5	4.0	27.1	3.2	0.1	0.6	3.9	22.1	127.1
2005	19.4	46.4	4.0	27.1	3.3	0.1	0.6	3.9	22.1	126.7
2015	19.2	46.3	4.1	27.0	3.3	0.1	0.7	3.8	22.0	126.6
2025	19.1	46.3	4.2	27.0	3.4	0.1	0.7	3.8	22.0	126.5
2035	19.0	46.3	4.2	26.8	3.4	0.1	0.7	3.8	22.0	126.4
2045	19.0	46.3	4.3	26.6	3.4	0.1	0.7	3.8	22.0	126.2
2055	19.1	46.2	4.2	26.4	3.4	0.1	0.7	3.8	22.0	126.0
2065	19.2	46.2	4.2	26.5	3.3	0.1	0.7	3.8	22.0	126.0
2075	19.2	46.2	4.1	26.6	3.2	0.1	0.7	3.8	22.0	126.0
2085	19.0	46.2	4.1	26.7	3.2	0.1	0.7	3.8	22.0	125.9
2095	18.9	46.2	4.1	26.8	3.2	0.1	0.7	3.8	22.0	125.8
2105	18.8	46.2	4.1	26.8	3.3	0.1	0.7	3.8	22.0	125.8

Temperate Low Plantation Soil Storage

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	114.2	108.2	24.4	155.4	20.7	1.3	14.6	38.1	64.0	540.9
2005	113.8	108.1	24.5	155.3	21.0	1.3	14.6	37.9	63.9	540.3
2015	113.5	108.0	24.6	155.2	21.1	1.3	14.7	37.9	63.8	540.1
2025	113.4	108.0	24.7	155.2	21.1	1.3	14.8	37.9	63.9	540.1
2035	113.5	108.1	24.7	154.9	21.1	1.3	14.8	37.9	63.9	540.2
2045	113.6	108.1	24.7	154.7	21.2	1.3	14.9	37.9	64.0	540.4
2055	113.8	108.2	24.7	154.7	21.1	1.3	14.9	37.9	64.0	540.6
2065	113.8	108.2	24.6	154.9	21.0	1.3	15.0	38.0	64.0	540.9
2075	113.7	108.2	24.6	155.1	21.0	1.3	15.0	38.0	64.1	541.0
2085	113.5	108.2	24.5	155.2	21.1	1.4	15.0	38.0	64.1	541.0
2095	113.3	108.2	24.5	155.2	21.1	1.4	15.0	37.9	64.1	540.8
2105	113.2	108.3	24.5	155.1	21.1	1.4	15.0	38.1	64.1	540.9

Temperate Low Plantation Market Storage

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	1.5	0.3	0.7	0.6	0.3	0.1	0.1	0.4	0.2	4.1
2005	2.1	0.6	0.8	0.8	0.4	0.1	0.2	0.9	0.2	6.0
2015	2.5	0.8	1.0	0.9	0.5	0.1	0.3	1.0	0.3	7.3
2025	2.7	0.9	1.1	1.0	0.6	0.1	0.4	1.3	0.4	8.4
2035	2.8	1.1	1.1	1.0	0.6	0.1	0.5	1.5	0.4	9.3
2045	2.8	1.2	1.2	1.0	0.7	0.2	0.6	1.7	0.5	10.0
2055	2.8	1.3	1.3	0.9	0.8	0.2	0.7	1.9	0.5	10.4
2065	2.8	1.4	1.3	0.8	0.8	0.2	0.8	2.1	0.6	10.9
2075	2.9	1.5	1.3	0.8	0.8	0.2	0.9	2.3	0.6	11.2
2085	3.0	1.6	1.3	0.7	0.8	0.2	0.9	2.5	0.6	11.6
2095	3.1	1.6	1.3	0.7	0.8	0.2	0.9	2.6	0.7	11.8
2105	3.1	1.6	1.3	0.7	0.7	0.2	1.0	2.7	0.7	12.1

Temperate Low Plantation Average Annual Carbon Flux by Decade

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
	Petagrams carbon									
1995-2005	-47	0	54	-47	106	5	59	17	4	152
2005-2015	-69	15	68	2	84	8	59	-10	10	165
2015-2025	-58	27	90	-3	71	10	58	34	19	248
2025-2035	0	27	71	-111	57	13	45	12	19	133
2035-2045	49	21	45	-153	51	12	34	35	16	111
2045-2055	107	18	-16	-99	-10	-5	18	2	12	26
2055-2065	96	12	-15	65	-111	-8	15	58	10	121
2065-2075	41	12	-23	76	-76	-9	8	1	8	36
2075-2085	-55	7	-14	67	13	7	10	26	6	67
2085-2095	-118	8	-9	45	20	9	4	-6	5	-44
2095-2105	-81	4	-30	4	72	11	7	51	4	43

SCENARIO 3b: SUBTROPICAL LOW PLANTATION

Price and Harvest

	Price	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
						Million m^3 per year					
1980		456	84	280	277	76	21	26	114	52	1386
1992		582	117	279	256	93	25	32	133	59	1575
2000	75	569	165	260	258	101	27	49	160	59	1648
2010	81	566	194	244	241	123	28	63	169	77	1704
2020	85	537	246	234	220	142	31	88	207	101	1806
2030	89	484	295	247	242	136	32	124	224	128	1913
2040	93	466	328	265	220	156	35	143	236	159	2009
2050	97	420	353	303	203	172	46	166	245	174	2082
2060	101	425	365	308	190	191	47	180	251	181	2139
2070	104	477	376	307	142	194	48	184	254	198	2181
2080	107	519	385	289	138	184	47	195	257	200	2214
2090	110	556	393	267	147	176	38	203	259	203	2242
2100	111	555	399	277	175	140	38	203	260	215	2263
2110	113	518	404	286	192	147	40	210	261	215	2273

Subtropical Regions Low Plantation Total Carbon

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	164.8	229.5	38.5	212.9	31.7	1.5	22.3	88.8	123.0	913.0
2005	164.2	229.6	39.0	212.3	32.7	1.6	23.0	89.0	123.1	914.5
2015	163.4	229.9	39.7	211.9	33.6	1.6	23.6	89.0	123.3	916.0
2025	162.6	230.4	40.6	211.9	34.3	1.7	24.2	89.4	123.5	918.5
2035	162.4	230.7	41.4	210.9	34.8	1.9	24.7	89.5	123.7	920.0
2045	162.7	231.0	41.8	209.8	35.4	2.0	25.0	89.9	123.9	921.5
2055	163.9	231.2	41.5	208.9	35.3	1.9	25.2	90.0	124.0	921.9
2065	164.9	231.3	41.2	209.6	34.2	1.9	25.4	90.5	124.1	923.1
2075	165.6	231.4	40.9	210.3	33.3	1.8	25.4	90.6	124.2	923.5
2085	164.8	231.5	40.7	211.0	33.5	1.8	25.5	90.8	124.3	924.1
2095	163.6	231.6	40.6	211.5	33.9	1.9	25.6	90.8	124.3	923.7
2105	162.5	231.7	40.4	211.4	34.6	2.0	25.7	91.3	124.4	923.9

Subtropical Regions Low Plantation Tree Carbon

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	29.6	74.4	9.4	29.8	7.5	0.1	7.0	46.4	36.8	240.9
2005	29.0	74.6	9.6	29.2	8.1	0.1	7.5	46.3	36.9	241.5
2015	28.3	74.8	10.1	28.9	8.7	0.2	7.9	46.2	37.1	242.1
2025	27.6	74.9	10.7	28.9	9.2	0.2	8.3	46.3	37.2	243.3
2035	27.4	75.0	11.3	28.2	9.7	0.3	8.6	46.3	37.3	244.0
2045	27.6	75.1	11.6	27.5	10.1	0.4	8.7	46.3	37.3	244.7
2055	28.5	75.1	11.5	26.8	10.0	0.3	8.8	46.2	37.3	244.5
2065	29.4	75.1	11.2	27.2	9.1	0.2	8.8	46.4	37.4	244.9
2075	30.0	75.1	11.0	27.8	8.4	0.2	8.8	46.3	37.4	244.9
2085	29.5	75.2	10.9	28.4	8.4	0.2	8.8	46.4	37.4	245.2
2095	28.6	75.2	10.8	28.8	8.8	0.3	8.8	46.3	37.4	244.9
2105	27.8	75.2	10.6	28.8	9.4	0.3	8.8	46.5	37.4	244.8

Subtropical Regions Low Plantation Floor and Understory Carbon

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	19.6	46.5	4.0	27.1	3.2	0.1	0.6	3.9	22.1	127.1
2005	19.3	46.4	4.0	27.0	3.3	0.1	0.6	3.9	22.1	126.7
2015	19.1	46.3	4.1	27.0	3.3	0.1	0.7	3.9	22.1	126.5
2025	19.0	46.3	4.2	26.9	3.4	0.1	0.7	3.9	22.1	126.4
2035	18.9	46.3	4.2	26.8	3.4	0.1	0.7	3.8	22.1	126.3
2045	18.9	46.3	4.2	26.6	3.4	0.1	0.7	3.8	22.1	126.2
2055	19.0	46.3	4.2	26.5	3.4	0.1	0.7	3.8	22.1	126.0
2065	19.1	46.3	4.1	26.5	3.3	0.1	0.7	3.9	22.1	126.0
2075	19.1	46.3	4.1	26.6	3.2	0.1	0.7	3.8	22.1	126.0
2085	18.9	46.3	4.1	26.7	3.2	0.1	0.7	3.8	22.1	125.9
2095	18.8	46.3	4.0	26.8	3.3	0.1	0.7	3.8	22.1	125.8
2105	18.7	46.3	4.0	26.8	3.3	0.1	0.7	3.9	22.1	125.8

Subtropical Regions Low Plantation Soil Storage

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	114.2	108.2	24.4	155.4	20.7	1.3	14.6	38.1	64.0	540.9
2005	113.8	108.1	24.5	155.2	20.9	1.3	14.7	37.9	63.9	540.3
2015	113.5	108.0	24.6	155.2	21.1	1.3	14.7	37.9	63.8	540.0
2025	113.3	108.0	24.7	155.1	21.1	1.3	14.8	37.9	63.9	540.1
2035	113.3	108.1	24.7	154.9	21.1	1.3	14.8	37.9	63.9	540.2
2045	113.5	108.2	24.7	154.7	21.2	1.4	14.9	37.9	64.0	540.4
2055	113.7	108.2	24.6	154.7	21.1	1.3	14.9	37.9	64.0	540.5
2065	113.7	108.2	24.6	155.0	21.0	1.3	15.0	38.0	64.1	540.9
2075	113.7	108.2	24.5	155.1	21.0	1.3	15.0	38.0	64.1	540.9
2085	113.4	108.3	24.5	155.2	21.0	1.4	15.0	38.0	64.1	540.9
2095	113.2	108.3	24.5	155.2	21.1	1.4	15.0	37.9	64.1	540.7
2105	113.1	108.3	24.5	155.1	21.1	1.4	15.0	38.1	64.1	540.7

Subtropical Regions Low Plantation Market Storage

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	1.5	0.3	0.7	0.6	0.3	0.1	0.1	0.4	0.2	4.1
2005	2.1	0.6	0.8	0.8	0.4	0.1	0.2	0.9	0.2	6.0
2015	2.5	0.8	1.0	0.9	0.5	0.1	0.3	1.0	0.3	7.4
2025	2.7	1.1	1.0	1.0	0.6	0.1	0.4	1.3	0.4	8.6
2035	2.8	1.3	1.1	1.0	0.6	0.1	0.5	1.6	0.5	9.5
2045	2.7	1.5	1.2	1.0	0.7	0.2	0.7	1.8	0.5	10.3
2055	2.7	1.6	1.3	0.9	0.8	0.2	0.8	2.0	0.6	10.8
2065	2.7	1.7	1.3	0.8	0.8	0.2	0.9	2.2	0.6	11.3
2075	2.8	1.8	1.3	0.7	0.8	0.2	0.9	2.4	0.7	11.7
2085	3.0	1.9	1.3	0.7	0.8	0.2	1.0	2.6	0.7	12.1
2095	3.0	1.9	1.2	0.7	0.7	0.2	1.0	2.8	0.7	12.3
2105	3.0	1.9	1.2	0.7	0.7	0.2	1.1	2.9	0.7	12.6

Subtropical Regions Low Plantation Average Annual Carbon Flux by Decade

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
	Petagrams carbon									
1995-2005	-59	13	50	-57	105	6	61	24	8	151
2005-2015	-84	29	73	-37	84	8	62	-7	16	144
2015-2025	-78	43	86	-1	71	10	62	38	24	255
2025-2035	-22	35	82	-98	57	12	47	18	23	154
2035-2045	34	28	37	-110	56	12	35	37	17	147
2045-2055	114	18	-21	-96	-10	-5	18	5	13	37
2055-2065	103	17	-31	68	-113	-8	16	59	10	120
2065-2075	65	9	-38	79	-84	-9	8	4	8	42
2075-2085	-73	11	-13	69	13	6	10	26	6	56
2085-2095	-128	5	-16	46	47	8	4	-3	5	-34
2095-2105	-105	8	-18	-5	67	10	7	51	4	19

SCENARIO 4a: NO TIMBER HARVESTING ALLOWED:

i) 50 million hectares in temperate forests

	Carbon Storage with Soil Carbon	Carbon Storage without Soil Carbon
2005	0.22	0.00
2015	0.70	0.14
2025	1.60	0.63
2035	2.64	1.42
2045	3.72	2.35
2055	4.67	3.20
2065	5.55	4.03
2075	6.41	4.86
2085	7.27	5.69
2095	8.11	6.52
2105	8.92	7.33

ii) 50 million hectares in subtropical plantation forests

	Carbon Storage with Soil Carbon	Carbon Storage without Soil Carbon
2005	0.19	0.01
2015	1.00	0.52
2025	2.89	2.04
2035	5.49	4.42
2045	8.14	6.94
2055	10.22	8.94
2065	11.46	10.14
2075	12.03	10.70
2085	12.06	10.73
2095	12.06	10.73
2105	12.06	10.73

iii) 10 million hectares in temperate forests

	Carbon Storage with Soil Carbon	Carbon Storage without Soil Carbon
2005	0.04	0.00
2015	0.14	0.03
2025	0.32	0.13
2035	0.53	0.28
2045	0.74	0.47
2055	0.93	0.64
2065	1.11	0.81
2075	1.28	0.97
2085	1.45	1.14
2095	1.62	1.30
2105	1.78	1.47

iv) 10 million hectares in subtropical plantation forests

	Carbon Storage with Soil Carbon	Carbon Storage without Soil Carbon
2005	0.04	0.00
2015	0.20	0.10
2025	0.57	0.40
2035	1.09	0.88
2045	1.62	1.38
2055	2.04	1.78
2065	2.28	2.02
2075	2.40	2.13
2085	2.41	2.14
2095	2.41	2.14
2105	2.41	2.14

SCENARIO 4b: HIGH PLANTATION SUBTROPICAL CASE -- LONG ROTATION HARVESTS
Price and Harvest

	Price	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
						Million m^3 per year					
1980		456	84	280	277	76	21	26	114	52	1386
1992		582	117	279	256	93	25	32	133	59	1575
2000	73	557	159	284	280	103	27	47	159	58	1674
2010	79	562	207	256	247	122	28	68	163	88	1742
2020	82	535	271	242	231	151	30	101	197	118	1875
2030	84	462	402	223	204	133	32	153	245	182	2033
2040	83	432	524	183	164	126	34	197	291	249	2200
2050	84	369	610	179	156	129	45	234	335	286	2342
2060	87	373	618	241	137	169	45	240	340	290	2452
2070	91	478	550	312	139	195	46	225	301	273	2519
2080	94	509	556	312	142	205	45	235	303	272	2578
2090	93	539	561	336	160	178	35	237	305	274	2624
2100	94	556	641	248	146	124	35	258	335	317	2659
2110	97	465	646	256	218	111	38	266	353	315	2666

High Plantation/Subtropical /Long Rotation Total Carbon

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	164.7	229.9	38.4	212.8	31.7	1.5	22.4	88.9	123.2	913.5
2005	163.9	231.0	38.6	211.6	32.6	1.6	23.2	89.7	123.6	915.9
2015	163.0	232.4	39.0	210.8	33.4	1.6	24.1	89.9	124.1	918.2
2025	162.1	233.9	39.1	209.7	33.7	1.8	25.0	90.6	124.8	920.7
2035	161.6	234.9	39.7	209.5	34.1	1.9	25.6	91.0	125.2	923.3
2045	162.1	235.2	40.4	209.1	34.9	2.0	25.9	91.4	125.4	926.5
2055	163.8	235.0	41.7	209.4	36.0	1.9	26.0	91.5	125.3	930.6
2065	165.4	235.1	42.2	210.2	35.1	1.9	26.1	92.2	125.3	933.6
2075	165.5	235.6	41.4	211.1	33.7	1.8	26.3	92.2	125.6	933.2
2085	164.6	236.0	40.4	211.7	32.6	1.8	26.5	92.5	125.8	931.9
2095	163.4	236.1	39.7	211.6	33.3	1.9	26.5	92.7	125.8	931.1
2105	162.8	235.6	40.6	212.5	34.4	2.0	26.4	93.1	125.6	933.0

High Plantation/Subtropical /Long Rotation Tree Carbon

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	29.4	74.7	9.3	29.7	7.5	0.1	7.1	46.4	36.9	241.1
2005	28.7	75.6	9.3	28.7	8.0	0.1	7.7	46.9	37.3	242.4
2015	27.9	76.6	9.4	28.0	8.5	0.2	8.3	47.0	37.7	243.7
2025	27.2	77.6	9.4	27.2	8.8	0.2	8.9	47.3	38.2	244.9
2035	26.8	78.0	9.9	27.1	9.1	0.3	9.2	47.4	38.4	246.2
2045	27.2	77.9	10.6	26.8	9.8	0.4	9.3	47.4	38.4	247.8
2055	28.5	77.3	11.7	27.1	10.7	0.3	9.2	47.3	38.2	250.3
2065	29.7	77.3	12.1	27.7	10.0	0.2	9.2	47.5	38.1	252.0
2075	29.9	77.8	11.5	28.5	8.8	0.1	9.3	47.4	38.3	251.6
2085	29.3	78.1	10.6	28.9	7.8	0.2	9.4	47.5	38.5	250.3
2095	28.4	78.0	10.1	29.0	8.4	0.2	9.4	47.5	38.5	249.3
2105	27.9	77.4	10.7	29.6	9.3	0.3	9.3	47.5	38.2	250.3

High Plantation/Subtropical /Long Rotation Floor and Understory Carbon

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	19.6	46.5	4.0	27.1	3.2	0.1	0.6	3.9	22.1	127.1
2005	19.3	46.4	4.0	27.0	3.2	0.1	0.6	3.9	22.1	126.6
2015	19.1	46.4	4.0	26.9	3.3	0.1	0.7	3.9	22.0	126.4
2025	18.9	46.5	4.0	26.7	3.3	0.1	0.7	3.9	22.0	126.2
2035	18.9	46.5	4.1	26.7	3.4	0.1	0.7	3.8	22.0	126.1
2045	18.9	46.5	4.2	26.6	3.4	0.1	0.7	3.8	22.0	126.2
2055	19.1	46.4	4.3	26.6	3.5	0.1	0.7	3.8	22.0	126.5
2065	19.2	46.4	4.3	26.7	3.4	0.1	0.7	3.9	22.0	126.7
2075	19.2	46.4	4.2	26.8	3.2	0.1	0.7	3.8	22.0	126.5
2085	19.0	46.4	4.0	26.8	3.2	0.1	0.7	3.8	22.0	126.2
2095	18.9	46.4	4.0	26.9	3.2	0.1	0.7	3.9	22.0	126.1
2105	18.8	46.4	4.1	26.9	3.3	0.1	0.7	3.9	22.0	126.3

High Plantation/Subtropical /Long Rotation Soil Storage

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	114.2	108.3	24.4	155.4	20.7	1.3	14.7	38.1	64.0	541.2
2005	113.8	108.4	24.5	155.1	20.9	1.3	14.7	38.0	64.0	540.8
2015	113.5	108.4	24.6	155.0	21.0	1.3	14.8	38.0	64.0	540.6
2025	113.3	108.6	24.6	154.8	21.0	1.3	14.9	38.0	64.1	540.7
2035	113.3	108.7	24.6	154.8	21.0	1.4	15.0	38.0	64.2	541.0
2045	113.5	108.7	24.7	154.8	21.1	1.4	15.0	38.1	64.2	541.5
2055	113.8	108.7	24.8	155.0	21.2	1.4	15.1	38.0	64.2	542.1
2065	113.9	108.7	24.7	155.1	21.0	1.4	15.1	38.1	64.3	542.4
2075	113.7	108.8	24.6	155.3	20.9	1.4	15.1	38.1	64.3	542.0
2085	113.4	108.8	24.5	155.2	20.9	1.4	15.1	38.1	64.3	541.7
2095	113.3	108.8	24.5	155.1	21.0	1.4	15.1	38.1	64.3	541.6
2105	113.3	108.7	24.6	155.2	21.1	1.4	15.1	38.2	64.3	541.9

High Plantation/Subtropical /Long Rotation Market Storage

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	1.5	0.3	0.7	0.6	0.3	0.1	0.1	0.4	0.2	4.1
2005	2.0	0.6	0.9	0.8	0.4	0.1	0.2	0.9	0.2	6.1
2015	2.5	0.9	1.0	0.9	0.5	0.1	0.3	1.0	0.3	7.5
2025	2.7	1.3	1.0	0.9	0.6	0.1	0.5	1.4	0.5	8.9
2035	2.7	1.7	1.0	0.9	0.6	0.1	0.7	1.7	0.6	10.0
2045	2.5	2.2	0.9	0.8	0.6	0.2	0.9	2.1	0.8	11.0
2055	2.4	2.5	1.0	0.8	0.6	0.2	1.0	2.3	0.9	11.8
2065	2.5	2.6	1.1	0.7	0.7	0.2	1.1	2.6	0.9	12.5
2075	2.7	2.6	1.2	0.7	0.8	0.2	1.1	2.9	0.9	13.1
2085	2.9	2.7	1.3	0.7	0.8	0.2	1.2	3.1	1.0	13.7
2095	2.9	2.9	1.2	0.7	0.7	0.2	1.3	3.3	1.0	14.1
2105	2.8	3.0	1.2	0.7	0.6	0.2	1.3	3.5	1.1	14.4

High Plantation/Subtropical /Long Rotation Average Annual Carbon Flux by Decade

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995-2005	-83	114	23	-112	93	6	82	84	42	248
2005-2015	-94	134	34	-88	78	8	85	16	52	224
2015-2025	-83	155	14	-107	33	11	86	69	68	247
2025-2035	-52	94	59	-24	36	12	60	37	44	266
2035-2045	51	39	71	-39	82	12	39	44	20	319
2045-2055	164	-25	127	33	107	-6	9	10	-11	408
2055-2065	165	7	57	82	-83	-9	11	65	3	299
2065-2075	10	50	-80	91	-142	-10	14	7	22	-38
2075-2085	-90	46	-103	56	-114	6	17	29	24	-130
2085-2095	-122	5	-71	-6	76	7	4	20	4	-83
2095-2105	-56	-53	88	89	105	9	-6	37	-21	193

SCENARIO 5a: LOW DEMAND ELASTICITY BASE CASE

Price and Harvest

	Price	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
						Million m^3 per year					
1980		456	84	280	277	76	21	26	114	52	1386
1992		582	117	279	256	93	25	32	133	59	1575
2000	116	615	180	267	290	118	29	54	166	70	1788
2010	126	614	212	259	264	140	31	75	175	93	1863
2020	133	596	269	254	238	162	35	118	215	131	2019
2030	140	530	320	283	229	166	39	164	229	169	2129
2040	147	522	357	301	191	177	43	195	241	207	2234
2050	153	460	383	316	175	212	55	237	249	234	2323
2060	157	484	404	335	169	193	61	250	257	245	2399
2070	162	544	420	305	149	206	65	258	261	264	2473
2080	164	565	432	296	151	205	66	283	265	276	2538
2090	166	621	441	298	174	172	58	284	267	277	2593
2100	168	614	449	303	213	162	56	283	268	289	2636
2110	170	582	456	319	204	171	56	303	269	296	2656

Low Elasticity Base Case Total Storage

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	165.4	229.3	38.8	213.2	31.8	1.3	22.2	88.8	122.9	913.7
2005	164.3	229.3	39.3	212.0	32.7	1.3	22.8	89.1	122.8	913.6
2015	163.1	229.4	40.0	210.9	33.6	1.4	23.5	89.1	123.0	914.0
2025	162.3	229.9	41.0	210.2	34.5	1.6	24.2	89.5	123.3	916.4
2035	162.2	230.3	41.7	209.8	34.9	1.8	24.8	89.7	123.7	918.7
2045	162.6	230.7	41.8	209.3	35.5	2.1	25.3	90.1	123.9	921.3
2055	164.1	231.0	41.7	209.2	34.9	2.1	25.6	90.2	124.2	922.9
2065	165.1	231.2	41.3	210.0	34.4	2.1	25.8	90.8	124.3	925.1
2075	165.7	231.4	41.3	211.0	33.6	2.1	25.9	90.8	124.5	926.1
2085	164.8	231.5	41.1	211.6	33.9	2.1	26.1	91.1	124.6	926.8
2095	163.7	231.6	41.2	211.6	34.1	2.2	26.1	91.1	124.6	926.1
2105	162.9	231.6	40.9	210.5	35.1	2.3	26.2	91.6	124.7	926.0

Low Elasticity Base Case Tree Carbon

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	30.0	74.4	9.7	30.1	7.6	0.1	7.0	46.4	36.8	242.2
2005	29.2	74.6	10.0	29.1	8.1	0.1	7.5	46.3	37.0	242.0
2015	28.3	74.8	10.5	28.3	8.6	0.2	8.0	46.3	37.2	242.0
2025	27.6	74.9	11.1	27.8	9.2	0.3	8.4	46.3	37.3	243.0
2035	27.5	75.0	11.6	27.5	9.5	0.4	8.7	46.3	37.4	243.9
2045	27.8	75.0	11.7	27.3	10.0	0.5	8.8	46.3	37.5	245.0
2055	29.0	75.1	11.6	27.2	9.6	0.5	8.9	46.3	37.5	245.6
2065	29.9	75.1	11.4	27.8	9.1	0.5	8.9	46.5	37.6	246.8
2075	30.4	75.2	11.4	28.6	8.4	0.4	8.9	46.4	37.6	247.3
2085	29.9	75.2	11.3	29.1	8.7	0.3	9.0	46.4	37.6	247.6
2095	29.1	75.2	11.4	29.1	8.9	0.4	9.0	46.3	37.7	247.0
2105	28.5	75.2	11.1	28.4	9.7	0.5	9.0	46.5	37.7	246.5

Low Elasticity Base Case Floor and Understory Carbon

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	19.6	46.5	4.0	27.1	3.2	0.1	0.6	3.9	22.1	127.1
2005	19.2	46.3	4.0	26.9	3.2	0.1	0.6	3.9	22.0	126.2
2015	18.9	46.1	4.1	26.7	3.3	0.1	0.7	3.8	21.9	125.6
2025	18.6	46.1	4.1	26.6	3.3	0.1	0.7	3.8	21.9	125.4
2035	18.6	46.1	4.2	26.5	3.3	0.1	0.7	3.8	21.9	125.3
2045	18.6	46.1	4.2	26.4	3.4	0.1	0.8	3.8	21.9	125.2
2055	18.7	46.1	4.1	26.3	3.3	0.1	0.8	3.8	21.9	125.1
2065	18.8	46.1	4.1	26.4	3.2	0.1	0.8	3.9	21.9	125.2
2075	18.7	46.1	4.0	26.5	3.1	0.1	0.8	3.8	21.9	125.1
2085	18.5	46.1	4.0	26.6	3.2	0.1	0.8	3.8	21.9	125.0
2095	18.4	46.1	4.0	26.6	3.2	0.1	0.8	3.8	21.9	124.9
2105	18.3	46.0	4.0	26.5	3.3	0.1	0.8	3.9	21.9	124.8

Low Elasticity Base Case Soil Storage

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	114.2	108.0	24.4	155.4	20.7	1.1	14.5	38.1	63.8	540.1
2005	113.6	107.7	24.4	155.1	21.0	1.0	14.4	38.0	63.6	538.8
2015	113.2	107.6	24.5	154.9	21.1	1.0	14.5	37.9	63.5	538.2
2025	113.0	107.7	24.6	154.8	21.2	1.1	14.6	37.9	63.6	538.5
2035	113.0	107.8	24.6	154.8	21.2	1.2	14.7	37.9	63.7	539.0
2045	113.2	107.9	24.6	154.7	21.3	1.3	14.8	38.0	63.8	539.6
2055	113.4	108.0	24.6	154.8	21.2	1.3	14.9	38.0	63.9	540.0
2065	113.4	108.1	24.5	155.0	21.2	1.3	14.9	38.2	63.9	540.5
2075	113.3	108.1	24.5	155.2	21.1	1.3	14.9	38.1	64.0	540.5
2085	113.0	108.1	24.5	155.2	21.2	1.4	15.0	38.1	64.0	540.5
2095	112.8	108.1	24.5	155.0	21.2	1.4	15.0	38.1	64.0	540.2
2105	112.8	108.1	24.5	154.8	21.4	1.4	15.0	38.2	64.0	540.3

Low Elasticity Base Case Market Storage

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	1.6	0.4	0.7	0.6	0.3	0.1	0.1	0.4	0.2	4.3
2005	2.2	0.6	0.9	0.9	0.4	0.1	0.2	0.9	0.3	6.5
2015	2.7	0.9	1.0	1.0	0.6	0.1	0.3	1.1	0.4	8.1
2025	3.0	1.2	1.1	1.0	0.7	0.1	0.5	1.4	0.5	9.5
2035	3.1	1.4	1.2	1.0	0.8	0.2	0.7	1.6	0.6	10.6
2045	3.0	1.6	1.3	1.0	0.8	0.2	0.9	1.9	0.7	11.5
2055	3.0	1.8	1.4	0.9	0.9	0.2	1.0	2.1	0.8	12.1
2065	3.0	1.9	1.4	0.8	0.9	0.3	1.2	2.3	0.9	12.7
2075	3.2	2.0	1.4	0.7	0.9	0.3	1.3	2.5	1.0	13.2
2085	3.3	2.1	1.3	0.8	0.9	0.3	1.4	2.7	1.0	13.7
2095	3.3	2.2	1.4	0.8	0.8	0.3	1.4	2.9	1.0	14.1
2105	3.3	2.2	1.4	0.8	0.8	0.3	1.5	3.0	1.1	14.4

Low Elasticity Base Case Average Annual Carbon Flux by Decade

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
	Petagrams carbon									
1995-2005	-115	-8	52	-120	99	1	57	29	-4	-9
2005-2015	-118	18	75	-106	85	8	69	-6	16	42
2015-2025	-82	45	95	-70	85	18	74	42	34	241
2025-2035	-9	43	68	-46	40	24	57	20	34	232
2035-2045	43	37	16	-43	65	25	49	41	29	263
2045-2055	154	28	-15	-17	-60	7	27	8	22	155
2055-2065	98	21	-35	84	-47	-1	24	62	17	224
2065-2075	56	16	-5	97	-89	-7	12	5	13	98
2075-2085	-90	13	-14	65	40	5	15	29	9	71
2085-2095	-109	9	7	-9	12	10	5	-3	7	-71
2095-2105	-75	8	-28	-104	101	14	11	53	6	-15

SCENARIO 5b: LOW DEMAND ELASTICITY SUBTROPICAL HIGH PLANTATION CASE

Price and Harvest

	Price	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
						Million m^3 per year					
1980		456	84	280	277	76	21	26	114	52	1386
1992		582	117	279	256	93	25	32	133	59	1575
2000	112	630	198	298	285	128	28	52	159	74	1852
2010	117	603	282	267	253	151	30	78	189	106	1960
2020	119	559	412	252	238	135	34	135	248	173	2185
2030	120	471	561	229	197	134	37	199	304	240	2370
2040	122	418	650	207	171	179	40	243	337	300	2545
2050	124	392	713	233	161	149	51	293	365	341	2698
2060	126	431	726	266	142	186	53	301	371	346	2821
2070	129	518	735	290	143	155	54	304	373	361	2932
2080	128	544	743	293	145	177	53	322	375	366	3019
2090	131	582	750	291	180	167	44	323	377	367	3080
2100	134	583	757	277	211	166	44	323	379	378	3119
2110	138	526	765	288	200	192	48	340	381	385	3125

Low Elasticity Subtropical Plantations Total Storage

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	165.2	229.4	38.6	213.1	31.7	1.4	22.3	88.8	122.9	913.4
2005	163.4	230.0	38.7	211.3	32.4	1.5	23.0	89.5	123.1	912.9
2015	161.8	230.9	39.0	210.3	32.7	1.6	23.8	89.6	123.6	913.2
2025	161.0	232.2	39.2	209.6	33.6	1.7	24.8	90.1	124.2	916.3
2035	161.2	233.0	40.2	209.4	34.6	1.8	25.4	90.8	124.7	921.1
2045	162.4	233.7	40.9	209.0	34.9	2.0	26.0	91.2	125.0	925.1
2055	164.3	234.0	41.5	209.4	34.4	2.0	26.2	91.5	125.2	928.5
2065	165.7	234.4	41.3	210.3	33.3	1.9	26.5	92.0	125.4	930.8
2075	165.5	234.4	41.1	211.4	34.2	1.8	26.6	92.4	125.5	932.8
2085	164.6	234.7	40.7	212.1	33.8	1.9	26.7	92.6	125.6	932.7
2095	163.4	234.7	40.8	211.6	34.4	2.0	26.7	92.7	125.6	931.9
2105	163.1	234.9	40.7	210.4	34.2	2.1	26.9	93.1	125.7	931.0

Low Elasticity Subtropical Plantations Tree Carbon

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	29.8	74.4	9.6	29.9	7.5	0.1	7.0	46.4	36.8	241.5
2005	28.5	75.0	9.4	28.6	7.8	0.1	7.6	46.6	37.1	240.8
2015	27.3	75.5	9.5	27.8	7.9	0.2	8.1	46.6	37.5	240.5
2025	26.6	76.1	9.6	27.3	8.6	0.2	8.7	46.7	37.7	241.6
2035	26.7	76.2	10.4	27.1	9.4	0.3	9.0	46.9	37.9	244.0
2045	27.7	76.4	11.0	26.9	9.7	0.4	9.2	46.9	38.0	246.2
2055	29.1	76.3	11.6	27.2	9.3	0.4	9.2	46.9	38.0	248.0
2065	30.2	76.5	11.4	28.0	8.5	0.3	9.3	47.0	38.1	249.1
2075	30.2	76.4	11.3	28.8	9.0	0.2	9.2	47.0	38.1	250.2
2085	29.6	76.5	11.0	29.4	8.7	0.3	9.3	47.0	38.1	249.8
2095	28.7	76.4	11.0	29.1	9.2	0.3	9.3	46.9	38.1	249.1
2105	28.3	76.5	10.9	28.2	9.1	0.4	9.3	47.0	38.1	248.0

Low Elasticity Subtropical Plantations Floor and Understory Carbon

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	19.6	46.5	4.0	27.1	3.2	0.1	0.6	3.9	22.1	127.1
2005	19.1	46.4	4.0	26.8	3.2	0.1	0.7	3.9	22.1	126.2
2015	18.8	46.3	4.0	26.7	3.2	0.1	0.7	3.9	22.1	125.7
2025	18.6	46.4	4.0	26.6	3.3	0.1	0.8	3.9	22.1	125.7
2035	18.6	46.4	4.1	26.5	3.3	0.1	0.8	3.9	22.1	125.9
2045	18.7	46.4	4.2	26.4	3.3	0.1	0.8	3.9	22.1	126.0
2055	18.9	46.4	4.2	26.5	3.3	0.1	0.8	3.9	22.1	126.2
2065	19.0	46.4	4.1	26.6	3.2	0.1	0.8	3.9	22.1	126.2
2075	18.9	46.4	4.1	26.7	3.2	0.1	0.8	4.0	22.1	126.3
2085	18.8	46.4	4.0	26.8	3.2	0.1	0.8	3.9	22.1	126.1
2095	18.6	46.4	4.0	26.7	3.3	0.1	0.8	3.9	22.1	125.9
2105	18.6	46.4	4.0	26.5	3.3	0.1	0.8	3.9	22.1	125.7

Low Elasticity Subtropical Plantations Soil Storage

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	114.2	108.1	24.4	155.4	20.7	1.2	14.5	38.1	63.8	540.4
2005	113.5	107.9	24.4	155.0	20.9	1.2	14.5	38.0	63.7	539.1
2015	113.1	107.8	24.5	154.9	21.0	1.2	14.6	37.9	63.7	538.6
2025	113.0	107.9	24.5	154.8	21.1	1.2	14.7	37.9	63.8	539.0
2035	113.1	108.0	24.6	154.8	21.2	1.3	14.8	38.0	63.9	539.8
2045	113.4	108.2	24.7	154.8	21.1	1.3	14.9	38.0	64.0	540.4
2055	113.6	108.2	24.7	154.9	21.0	1.3	15.0	38.0	64.1	540.8
2065	113.7	108.3	24.6	155.1	21.0	1.3	15.0	38.1	64.1	541.1
2075	113.4	108.3	24.5	155.2	21.2	1.3	15.0	38.1	64.1	541.2
2085	113.2	108.3	24.5	155.2	21.1	1.4	15.0	38.1	64.1	540.9
2095	113.0	108.3	24.5	155.0	21.2	1.4	15.0	38.0	64.1	540.6
2105	113.1	108.3	24.5	154.8	21.2	1.4	15.0	38.1	64.1	540.5

Low Elasticity Subtropical Plantations Market Storage

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
					Petagrams carbon					
1995	1.6	0.4	0.7	0.7	0.3	0.1	0.1	0.4	0.2	4.4
2005	2.2	0.8	0.9	0.8	0.5	0.1	0.2	1.0	0.3	6.7
2015	2.6	1.2	1.0	0.9	0.6	0.1	0.4	1.2	0.4	8.5
2025	2.8	1.8	1.1	1.0	0.6	0.1	0.6	1.6	0.6	10.1
2035	2.7	2.3	1.1	0.9	0.7	0.1	0.9	2.0	0.8	11.4
2045	2.7	2.7	1.1	0.9	0.7	0.2	1.1	2.3	0.9	12.6
2055	2.6	3.0	1.1	0.8	0.8	0.2	1.3	2.7	1.0	13.5
2065	2.8	3.3	1.2	0.7	0.7	0.2	1.4	3.0	1.1	14.4
2075	2.9	3.4	1.2	0.7	0.7	0.2	1.5	3.3	1.2	15.1
2085	3.0	3.5	1.2	0.7	0.7	0.2	1.6	3.6	1.2	15.8
2095	3.1	3.6	1.2	0.8	0.8	0.2	1.6	3.8	1.3	16.4
2105	3.1	3.7	1.2	0.8	0.7	0.2	1.7	4.0	1.3	16.8

Low Elasticity Subtropical Plantations Average Annual Carbon Flux by Decade

	North America	South America	Europe	FSU	China	India	Oceania	Asia-Pacific	Africa	TOTAL
	Petagrams carbon									
1995-2005	-180	59	14	-174	69	6	70	60	22	-55
2005-2015	-161	92	27	-101	24	9	87	13	48	38
2015-2025	-82	128	21	-69	93	13	93	50	59	306
2025-2035	24	81	95	-25	100	15	68	69	52	480
2035-2045	124	73	71	-36	28	15	53	43	30	401
2045-2055	186	25	66	40	-42	-2	25	26	22	344
2055-2065	138	44	-27	91	-111	-6	25	52	15	222
2065-2075	-18	3	-20	103	82	-6	8	41	11	204
2075-2085	-89	29	-35	70	-39	9	16	18	8	-13
2085-2095	-120	-7	8	-48	61	11	3	12	6	-73
2095-2105	-35	23	-9	-121	-19	11	13	41	5	-91

APPENDIX 2

MODEL OF GLOBAL TIMBER MARKETS[1]

The demand for timber logs is derived from a well behaved utility function over industrial wood end-products and all other goods. Any increase in demand for timber logs reflects an increase in demand for end products, net of the effect of technological change in the timber processing sector. In this model, the global demand function is assumed to be the additive sum of many different regional demand functions. While trade could be addressed with a more detailed demand system and bilateral trade flows such a model would distract from the long term, dynamic focus of this paper. The model accounts for trade by assuming that each region has a distinct constant marginal cost of transporting timber to its major demand region. Regional price differences therefore exist, but are assumed to follow the law of one price.

The inverse demand function is:

(1) $$P(t) = D(Q(t), Z(t)),$$

where *Z(t)* is the vector of all other goods purchased. Demand is expected to shift over time due to population growth and changes in per capita income. The benefit of industrial wood harvests is Marshallian consumer surplus, or the area underneath the demand curve.

This model explores how supply adjusts to the anticipated increase in demand for timber products over time. Globally, the forest resource is composed of i different stocks of trees, $X_i(t)$. The ecological characteristics of these stocks vary dramatically, depending on locational factors such as climate and soils. The use of these stocks for industrial wood also varies depending on the quality of the wood and access. For example, large stocks of mature natural forests in Northern Canada, the Former Soviet Union, and the tropics have yet to be exploited. In contrast, landowners in accessible fertile areas in South America, Africa, Iberia, Australia, and New Zealand are spending substantial resources every year establishing approximately 3.2 million hectares of new fast growing plantations each year (United Nations, Food and Agriculture Organization, 1995). This model seeks to explain these choices and predict how they will change over time.

Forests in different regions are assumed to grow according to $V_i(a_i(t);m_i(t_0))$, where $a_i(t)$ is the age of the stand of tree type i at time t, and $m(t_0)$ represents management intensity for a stand planted at time t_0. A single yield function exists for the species in each ecosystem type. Ecosystem types are aggregations of many timber species, which have been classified as one for modeling purposes (see, for example, Kuchler). This yield function is assumed to be typical for the species in each ecosystem type, where $V_{a_i}>0$ and $V_{a_i a_i}<0$. Over all species harvested in a given year, the quantity of

[1] This appendix draws extensively from Sohngen, Mendelsohn and Sedjo (1999) and Sohngen and Sedjo (forthcoming).

timber harvested at time t is the sum of the area harvested, $H_i(t)$, times the yield per hectare:

$$(2) \qquad Q(t) = \sum_i H_i(t) V_i\left(a_i(t); m_i(t_0)\right) .$$

There are many costs of timber management, including the costs associated with accessing, harvesting, and transporting timber. These costs are expressed as

$$(3) \qquad C_H(Q(t)) = \sum_i c_i^A(q_i(t)) + \sum_i c_i^H(q_i(t)) .$$

$c_i^A(q_i(t))$ are the costs of accessing timber stocks and $c_i^H(q_i(t))$ are the costs of harvesting and transporting timber to markets. These costs are expressed as a function of the quantity of timber harvested in each type, $q_i(t)$, in time t. Access costs are important for stocks of natural forests at the economic margin due to the absence of roads and infrastructure. Marginal access costs are assumed to rise as additional land is harvested in this region because the costs of building and maintaining new roads are high in inhospitable regions such as the boreal forests of Canada and the Former Soviet Union. Marginal harvesting and transportation costs are assumed to be constant in terms of the quantity of timber harvested, although they vary by region.

Resources can also be spent regenerating forests after they are harvested. The costs of regenerating timberland, where the annual area regenerated in species i is $G_i(t)$, are

$$(4) \qquad C_G(t) = \sum_i p_{i,m} m_i(t) G_i(t) ,$$

where $m_i(t)$ is a unit of management intensity purchased at price $p_{i,m}$ (Sedjo and Lyon). Management intensity determined at the time of planting has an effect on the future stock of timber, in that greater (lower) management intensity will enhance (decrease) future yields. The returns to additional units of management are assumed to increase at a decreasing rate (they are concave). In this case, the following two conditions hold, $\frac{dV_i(t_{a_i} - t_0; m_i(t_0))}{dm_i(t_0)} \geq 0$, and $\frac{d^2 V_i(t_{a_i} - t_0; m_i(t_0))}{dm_i(t_0)^2} \leq 0$, where t_{a_i} is the time of harvest for species i, and t_0 is the time the land was regenerated.

In some circumstances, such as when future prices are rising rapidly, it may be advantageous to expand the area of forests. Establishing new lands in timber plantations involves additional costs over replanting existing forestlands because the landowner must expend resources finding new lands and preparing it for timber. If new lands in timber plantations are $N_i(t)$, the costs of new land are given as

$$(5) \qquad C_N(t) = \sum_i p_{m,i} m_i(t) N_i(t) + \sum_i f_{N,i}(N_i(t)) ,$$

where $f_{N,i}(N_i(t))$ represents labor and land conversion costs associated with establishing an additional hectare of land for plantations. These costs are assumed to be an increasing function of the total area of plantations established in type i.

The objective of a social planner (economic efficiency under competition) is to maximize the present value of net market benefits:

$$(6) \qquad \underset{H_i(t), G_i(t), N_i(t), m_i(t)}{Max} \quad W = \int_t^{\infty} e^{-rt} \{S(\cdot)\} dt ,$$

where r is the interest rate and annual net benefits, S(·), are defined as:

$$(7) \qquad S(\cdot) = \int_0^{Q^*(t)} \{D(Q(t), Z(t)) - C_H(Q(t))\} dQ(t) - C_G(t) - C_N(t) - \sum_i R_i(X_i(t))$$

Annually, the net benefits are the gross revenues from harvesting timber less the costs involved with managing and holding timber, where $R_i(t)$ is the annual cost of holding land in timber (land rent), and $X_i(t)$ is the total area of land in timber type i. The model tracks both the total area of land in timber, $X_i(t)$, as well as the age of timber. The age of timber is tracked through the yield function associated with each hectare of land in timber. The model solution determines how much to harvest, $H_i(t)$, how many hectares to regenerate, $G_i(t)$, how many new hectares to plant, $N_i(t)$, and how intensively to regenerate, $m_i(t)$.

The problem is constrained by the stock of land maintained in forests,

$$(8) \qquad \dot{X}_i = -H_i(t) + G_i(t) + N_i(t) , \qquad \forall \text{ i}$$

which expresses the change in the size of the total population of each type of organism in each period. Equation (8) is the difference between area harvested and regenerated. In addition, initial stocks must be given (equation 9), and all choice variables are constrained to be greater than or equal to 0 (equation 10):

$$(9) \qquad X_i(0) = X_{i,0} \qquad \forall \text{ i}$$

$$(10) \qquad X_i(t), H_i(t), G_i(t), N_i(t), m_i(t) \geq 0 \qquad \forall \text{ i}$$

Equation (9) defines not only the total quantity harvested, but also the age distribution through a yield function associated with each hectare of land.
The model can be solved using the maximum theorem (Pontryagin, et al.). One set of conditions resulting from this model involves harvesting accessible forests. These forests will be harvested according to

$$(11) \quad \dot{V}_i(a_i(t); m_i(t_0)) + (P(t) - c_i^{H\prime})\dot{V}_i = r(P(t) - c_i^{H\prime})V_i(a_i(t); m_i(t_0)) + R_i(t) .$$

P(t) is the global market clearing price of industrial timber logs, and $c_i^{H\prime}$ is the marginal cost of harvesting an additional unit of timber. Timber will be harvested along a time path where the marginal benefits of waiting an extra moment to harvest are equated with the marginal costs. The marginal benefits of waiting, the left hand side of (11), arise from additional growth in the organism, $\dot{V}_i$, and changes in price,

$\dot{P}$. If prices are declining, the marginal benefits of waiting are reduced. The marginal costs of waiting, the right hand side of (11), include the opportunity costs of delaying harvests and using the land for one more period. For example, if stocks are left intact, $R_i(t)$, is the value of the delay in future rotations.

While condition (11) involves the use of accessible timber stocks, one form of intensifying timberland management is to harvest natural forests at the economic margin more heavily, thereby bringing these forests into the accessible timberland base. In the extensive margin, harvests will occur according to

$$(12) \qquad \dot{P} = r\left(P(t) - c_i^{H\prime} - c_i^{A\prime}\right),$$

where $c_i^{A\prime}$ is the marginal access cost. Equation (12) differs from (11) in two distinct ways. First, annual growth ($\dot{V}$) is 0 because these stocks are considered old growth, and as much timber dies in any year as grows. Second, rental costs, $R_i(t)$, are low or nonexistent in this region because there is little competition for land. From this equation, one can see that if all forest land was old growth, then harvests would occur along a path where the rate of growth in net timber price equals r, a condition described by Hotelling.

Along the economic margin, the key issue is whether forests have a net positive value at all. Access costs are high enough that there is little or no incentive to harvest extensive stocks. This close choice between harvesting or not, however, makes harvests of marginal forests sensitive to world prices. Any public decision which raises these costs, for example, by insisting on planting for regeneration, would reduce the incentive to develop these resources further.

Deciding whether or not to regenerate timberland, $G_i(t)$, once it has been harvested, requires comparing the discounted future marginal benefits with the current marginal costs,

$$(13) \qquad \left(P(t_{a_i}) - c_i^{H\prime}\right)V_i(t_{a_i} - t_0; m_i(t_0))e^{-r(t_{ai}-t_0)} = p_{m,i}m_i(t_0) + \int_{t_0}^{t_{ai}} \left[R_i(z_i)e^{-rz_i}\right]dz_i$$

According to (13), land will be replanted in forests as long as the discounted marginal benefits of the last hectare offset the current marginal costs. The marginal costs include the costs of regeneration, $p_{m,i}m_i(t_0)$, and the discounted stream of rental costs for maintaining these lands in forests. If prices are expected to remain high in the future, land will remain in forests. If, however, prices are declining relative to other goods in society, some land may flow out of forests and into other uses.

In addition to deciding whether or not to maintain lands in forests, managers must decide on investments in regeneration. In many regions, even if land is left alone, it will regenerate in forests naturally. Foresters, however, control the stocking density of forests according to

$$(14) \qquad \left(P(t_{a_i}) - c_i^{H\prime}\right)\left(\frac{dV_i(t_{a_i} - t_0; m_i(t_0))}{dm_i(t_0)}\right)e^{-r(t_{ai}-t_0)} = p_{m,i}\,.$$

At the margin, landowners continue investing in management intensity until the discounted marginal benefits just equal the current marginal costs.

Determining the area of new hectares in plantations requires comparing the discounted marginal benefits of one additional hectare of land with the marginal costs of that additional hectare of land,

(15)

$$\left(P(t_{a_i}) - c_i^H{}'\right)V_i(t_{a_i} - t_0; m_i(t_0))e^{-r(t_{ai}-t_0)} = p_{m,i}m_i(t_0) + f_{N,i}{}'\left(N_i(t_0)\right) + \int_{t_0}^{t_{ai}} \left[R_i(z_i)e^{-rz_i}\right]dz_i$$

If prices are expected to increase in the future, the marginal benefit of establishing additional plantation lands increases, and new lands flow into plantations.

Empirical Model and Baseline Case

The model is programmed and solved using the GAMS programming language and the MINOS solver. Terminal conditions are imposed on the system in order to solve the model. The terminal conditions are defined by a steady state that would evolve if demand were held at a constant level starting in 150 years. It is difficult to know what terminal conditions to choose, but the above are at least reasonable. Further, by choosing a moment sufficiently far in the future, the terminal conditions should have little impact on current decisions.

Global demand for timber logs is assumed to be the linear sum of regional demand functions. The resulting annual global log market demand function is given as

(16) $P(t) = 140*\exp(bt) - 0.04*Q(t)$,

where Q(t) is given in million m^3, b is the rate of growth in demand, and P(t) is the price per m^3. As the demand for forest products increases (with GNP), the demand curve will shift out. Under current global prices and consumption, the initial time elasticity of demand in the baseline case is approximately 0.75. This is consistent with the empirical results of Sohngen, and the price elasticity used by Sedjo and Lyon.

Carbon Flux Model

The carbon flux model keeps track of carbon storage on hectares in the timber inventory described above. Carbon is estimated for four pools: Vegetation, forest floor, soil, and market. Changes in carbon storage between time periods measure flux. Positive fluxes imply that forests or forest products are sequestering additional carbon from the atmosphere, and negative fluxes imply that forests or industrial wood products are emitting carbon to the atmosphere.

The vegetation component of the model consists of carbon stored in live woody material in the forest, including both the tree and understory components. Tree carbon stored on each hectare is calculated as,

(1') $\text{TreeC}_i(a_i(t)) = (\phi_i)(\pi_i)(\omega_i)V_i(a_i(t); m_i(t_h))$,

where ϕ_i is the ratio of total wood biomass to industrial wood biomass, π_i is the proportion of wood biomass that is carbon, ω_i is the wood density, $V_i(a_i(t); m_i(t_h))$ is the yield of industrial wood per hectare of timber at age class $a_i(t)$ in time t, and $m_i(t_h)$ defines the management intensity of the forest at time t_h. Note that management intensity can shift over time, depending on prices. Management intensity can range from 0 when stands regenerate naturally, to large positive numbers in the case of plantations. This calculation allows for carbon storage to increase as timber ages, taking into account the yield function and management intensity.

The second component of vegetation storage is understory carbon. Carbon accumulates in living woody matter that grows below the canopy in forests. Understory carbon storage is assumed to be 2% of the carbon stored in mature forests (Birdsey, 1992). However, the model accounts for the fact that understory vegetation peaks well before trees age because growing conditions are favorable for understory vegetation early in the succession cycle. The model assumes that understory vegetation attains its maximum in year 10 for all species, and is then stable until harvested. At harvest, understory vegetation becomes 0 and begins growing again. Vegetation carbon at time t for timber of age $a_i(t)$ is given as:

(2') $\text{VegC}_i(a_i(t)) = \text{TreeC}_i(a_i(t)) + \text{UnderC}_i(a_i(t))$,

where $\text{UnderC}_i(a_i(t))$ is the storage of carbon in the understory.

Forest floor storage includes detrital matter that accumulates on the forest floor as leaves and branches fall and decay. When a stand is harvested, floor storage is assumed to return to near 0 levels. Carbon begins accumulating on the floor as forests grow in proportion to the yield function for timber. The amount of carbon stored on the forest floor in any year for a hectare of land is:

(3') $$\text{FloorC}_i(a_i(t)) = \frac{V_i(a_i(t); m_i(t_h))}{V_{i,Max}}(\gamma_i)$$

γ_i is the steady state maximum quantity of carbon stored at the forest floor for late successional stands. $V_{i,Max}$ is the yield of late successional forests of type i. Thus, as forests grow, the quantity of carbon stored in detrital matter at the forest floor increases with age to a maximum steady state value for older stands.

Soil storage includes organic matter that accumulates in soil, but does not include storage in roots and other living matter associated with growing trees (these components are included in vegetation as discussed above). Johnson (1992) suggests that harvests do not lead to large quantities of carbon emissions from soils. Some authors, however, include carbon emissions from forests after harvest (see Plantinga and Birdsey, 1993). In order to account for the fact that some carbon may be emitted in the form of soil erosion or other factors, this model assumes that 20% of soil carbon is lost in the first decade after harvest, and that carbon stocks then "regenerate" to steady state levels over time.

For land that is harvested and then regenerates in forests, the initial soil carbon is therefore 20% of the steady state maximum soil quantity, $K_i(T)$. Soil carbon then begins to accumulate according to the following logistic growth function:

$$\text{(4')} \qquad \frac{\mathrm{dSoilC_i}(t)}{dt} = (r_i)\mathrm{SoilC_i}(t)\left[\frac{K_i(t) - \mathrm{SoilC_i}(t)}{\mathrm{SoilC_i}(t)}\right]$$

In equation (4'), $\mathrm{SoilC_i}(t)$ is the soil carbon in the current year t, r_i is the growth rate of soil carbon, $K_i(t)$ is the steady state level of soil carbon for mature forests of type i.

Note that this model allows $K_i(t)$ to be a function of t. The steady state maximum is assumed to be constant on land that has been in forests for many years. Because some land in this model (i.e. new plantations) is converted from old agricultural land, steady state soil carbon is allowed to adjust from lower to higher levels over time. When land converts to forests from agricultural and grazing land, $K_i(t)$ will rise over several rotations from agricultural levels to the steady state maximum forest levels. While $K_i(t)$ changes over rotations, it is constant for any given rotation.

The total soil carbon stored on a hectare of land in forests of type i at time t can therefore be calculated by integrating (4') between t_h and t and adding that to the initial soil carbon level:

$$\text{(5')} \qquad Soil_i C(t) = Soil_i(t_h) + \int_{t_h}^{t}\left(\frac{\mathrm{dSoilC_i}(n)}{dn}\right)dn$$

$\mathrm{Soil_i}(t_h)$ is the initial soil level after regeneration (or afforestation in the case of plantations). $\mathrm{Soil_i}(t_h)$ is $0.8K_i(T)$ for lands that have been forested for many years. It is set at a regional agricultural or grassland value for lands that have just been converted, and it lies between these two levels for lands that have been converted within the time frame of this model.

If land were to convert out of forests, if prices decline for example, the model allows soil carbon to decay at a rate of 5% per year. This is measured as a net flux of carbon from the forests to the atmosphere. Over time, total net loss in forest carbon is the difference between steady state soil carbon in forests and steady state soil carbon in the new land use, such as agriculture. Under the scenarios examined in this paper, forests are not lost due to timber market price effects, so that these changes are not incorporated.

Market storage of carbon is calculated by tracking annual harvests. As trees are harvested, only some of the wood will be removed from the forest. The wood removed is the merchantable biomass, which is measured by the parameter ϕ_i (the ratio of total wood biomass to merchantable wood biomass). Much of the carbon in merchantable biomass is converted immediately to wood products such as pulp, paper, furniture, or houses, and stored for some period of time. Using data from FAO (1997), we estimate the proportion of harvests in each region which end up in sawnwood and pulpwood products, and use these values to determine into which products harvested timber flows.

Only some of the merchantable timber flows into products, however. Heath et al. (1996) and Plantinga and Birdsey (1993), for example, suggest that between 40% and 58% of merchantable timber is used for end products, while the rest is waste material or is used for energy. The percentage used in end products depends in part on whether the merchantable product is sawnwood or pulpwood. The estimates provided by Plantinga and Birdsey (1993) suggest that approximately 50% of sawnwood harvests and 42% of pulpwood harvests flow immediately into end products.

Over time, these end products will decay into atmospheric carbon. Using the estimates provided by Plantinga and Birdsey (1993) and Heath et al. (1996) for industrial wood products, we estimate that pulpwood products decay at a rate of 1.03% per year, and solidwood products decay at a rate of 0.79% per year. The quantity of carbon stored in wood products can then be tracked through time. The following equation presents a representative equation for carbon stored in pulpwood products ($t-t_h$) years after harvest in time t_h:

(6') $$PulpC_i(t-t_h) = (0.42)(\pi_i)(\omega_i)Q_{p,i}(t_h)\exp[-0.0103*(t-t_h)],$$

As in equation (1') above, we must account for wood density and carbon storage to determine the quantity of carbon stored in each unit of timber harvested for pulp, $Q_{p,i}(t_h)$, in period t_h.

Note that equation (6') tracks carbon storage in wood products for each year after harvests in the year t_h. To determine the total quantity of carbon stored in the market in a given year, we integrate equation (6') over t_h from the initial time period in the model, t_0 to the current time period t, and add this to the state of the initial stock of carbon in pulp products at time t, $TPWC_i(t_0)\exp[-0.0103t]$. This is:

(7') $$TPWC_i(t) = TPWC_i(t_0)e^{-0.0103t} + \int_{t_0}^{t} PulpC_i(t-n)dn$$

where $TPWC_i(t)$ is the total storage of carbon in pulp wood products at time t harvested from type i. Similar equations can be used to determine the storage of carbon in solid wood products, $TSWC_i(t)$.

With equations (1') – (7'), the model tracks carbon storage in all components of forests. Summing carbon stored in the i different types of forests, the model determines the total storage. Since the objective of this paper is to determine carbon flux, carbon storage in successive time periods is compared.

References:

Birdsey, R.A.: 1992, "Carbon Storage and Accumulation in United States Forest Ecosystems," U.S. Department of Agriculture, Forest Service, General Technical Report WO-59, Washington, DC.

Birdsey, R.A., Plantinga, A.J., and Heath, L.S.: 1993, "Past and Prospective Carbon Storage in United States Forests," *Forest Ecology and Management*, **58**, 33-40.
FAO: 1995, *Forest Resource Assessment 1990: Global Synthesis,* FAO Forestry Paper 124, The Food and Agriculture Organization of the United Nations, Rome.

Heath, L.A., Birdsey, R.A., Row, C., and Plantinga, A.J.: 1996, "Carbon Pools and Fluxes in U.S. Forest Products." *NATO ASI Series*, I, 40, 271 - 278.

Heath, L.A. and Birdsey, R.A.: 1993, "Carbon Trends of Productive Temperate Forests of the Coterminous United States," *Water, Air, and Soil Pollution*, **70**, 279-293.

Johnson, D.W.: 1992, "Effects of Forest Management on Soil Carbon Storage," *Water, Air, and Soil Pollution*, **64**, 83-120.

Plantinga, A.J. and Birdsey, R.A.: 1993, "Carbon Fluxes Resulting From U.S. Private Timberland Management," *Climatic Change*, **23**, 37-53.

Pontryagin, L.S., V.S. Boltyanskii, R.V. Gamkrelidze, and E.F. Mischenko. *The Mathematical Theory of Optimal Processes*. New York: John Wiley Co., 1962.

Sohngen, B.,; Mendelsohn, R., and Sedjo, R.: 1999, "Forest Management, Conservation, and Global Timber Markets," *American Journal of Agricultural Economics*, **81,** 1-13.

Sohngen, B. and Sedjo, R.: forthcoming, "Potential Carbon Flux From Timber Harvests and Management in the Context of A Global Timber Market," *Climatic Change.*

APPENDIX 3

MODEL INPUT DATA

Timber data and inventory

Inventory data was obtained from the following sources:

US -- John Mills, USDA Forest Service, Portland, Oregon;
Canada -- Lowe et al. (1994);
Europe – Kuusela (1994), Bazett (1993);
Former Soviet Union -- Backman and Waggener (1991);
Oceania -- FAO (1995), and Pandey (1992);
China – Yin (1995), FAO (1993a), Richardson (1990), FAO (1982), and Center for Forest Inventory, "A Working Report on the Forest Inventory in China," Ministry of Forestry, China;
South America -- FAO (1993b) and Pandey (1992);
India -- FAO (1993b) and Pandey (1992);
Asia Pacific -- FAO (1993b), Pandey (1992), Sedjo and Lyon (1990);
Africa -- FAO (1993b) and Pandey (1992).

Yield function data was determined in one of two ways. First, where data was available, yield functions were estimated. In some regions, however, data was not available, yield functions were fitted using information on current stocking density and age distribution. Information was obtained from the following sources: Sohngen (1996); Sedjo and Lyon (1990); Backman and Waggener (1991); Kuusela (1994); and Pandey (1992).

Harvesting costs were generally obtained from Sedjo and Lyon (1990). Where harvesting cost data was not available, costs were determined using costs from similar regions in other parts of the globe. Data from US Forest Service (1996) was used to develop access cost functions for building roads in different regions of the US. This data was used to estimate cost functions for other regions of the world with similar terrain and access characteristics. Plantation establishment and regeneration costs were obtained from Sedjo (1983), and Sedjo and Lyon (1990).

Carbon Model Data

The main source of information on tree carbon storage in temperate forests was Birdsey (1992). These estimates were extrapolated to regions where similar species or ecosystem types exist in the temperate zone. A uniform assumption that the proportion of carbon per unit of biomass of 0.5 was used for all species.

Tree carbon in emerging plantation forests was estimated by assuming that the ratio of total tree to merchantable tree components is 1.6. Many softwood plantations in the subtropical emerging region utilize species similar to southern pines. In Oceania, however, species native to the Pacific Northwestern U.S. are often used, suggesting that parameter values for PNW U.S. forests should be used. Hardwood plantations

are often composed of Eucalyptus, which was assumed to have 470 kg of carbon per m^3 of wood.

Forest floor carbon and soil carbon were estimated from a data base obtained from Kristiina Vogt. Yale School of Forestry. The soil component values were compared to those in Post et al. (1982) and several small adjustments were made. Average carbon storage in forests for our inventories are similar to the estimates made by Dixon et al. (1994).