THE EFFECTIVENESS OF FOREST CARBON SEQUESTRATION STRATEGIES WITH SYSTEM-WIDE ADJUSTMENTS

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ABSTRACT

This paper addresses the effectiveness of tree planting and forest conservation strategies to increase the sink of carbon in global forests. Because forests are expected to sequester additional carbon without explicit human intervention, a baseline case is presented. The baseline predicts that forests will sequester an additional 17.9 Pg (10^{15} grams) of carbon over the next 150 years, with nearly 95% of this accruing to storage in marketed forest products. The paper then compares strategies which assume markets adjust to changes in future timber supply to an optimistic regional planner case in which no market adjustment occurs. The resulting predictions show that system wide market interactions may lead to substantial leakage of carbon from the forest system.

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INTRODUCTION

In recent years, policy makers have focused on the role of forests to mitigate the potential impacts of climate change. Because forests convert atmospheric carbon into vegetation, increasing the quantity of carbon stored in forests has the potential to offset carbon released from other activities, such as fossil fuel burning. While the possibility of using forests to mitigate carbon has long been discussed, the issue is particularly timely now. Article 3 of the recent Kyoto Protocol includes language that may allow forests to serve as carbon "sinks" to offset other emissions.

Forests already serve as a substantial warehouse for carbon. Dixon et al. (1994), for example, estimate that approximately 1146 Petagrams (a Petagram is 10^{15} grams or a billion metric tons) of carbon are stored in the world's forested ecosystems. Increasing this sink by even modest amounts could provide additional protection from future climate change.

Changing the size of the forest sink requires policy makers to consider activities that will increase the annual uptake of carbon in forests. The Intergovernmental Panel on Climate Change (1996) has suggested several different options, including reducing the conversion of forests to farmland and other uses (i.e. reducing deforestation), setting aside existing forests from harvest, converting marginal agricultural land to carbon plantations, and intensifying forest management. In addition, society must weigh the costs of these different options against the costs of mitigating carbon dioxide emissions in other sectors of the economy.

Over the years, several authors have estimated the costs of establishing plantations in agricultural zones (see, Richards and Stokes, 1995, for a review). Sedjo (1989) examined both tree planting and tree managing schemes. Using the estimate that forests in the temperate zone can sequester approximately 6.24 tons of carbon per hectare per year, Sedjo predicts that it would take 465 million hectares of temperate forest plantations to offset 2.9 Pg (1 Pg = 10^{15} grams) of carbon emissions per year for 30-50 years. The cost of such a program would be approximately $500 billion, amounting to an average of $3.50 per ton of carbon stored. One implication of this study is that forest carbon sequestration programs must use a large area of additional land in order to offset a large quantity of carbon releases. It is likely that a program of this size would have market impacts well beyond the plantations that are established.

Moulton and Richards (1990) examine a set of smaller programs in the US alone. They estimate the costs of a tree planting program that enrolls between 36.9 and more than 300 million hectares of land in forest plantations on marginal agricultural land. Using land rental payments from the Conservation Reserve Program, they estimate the costs of these tree planting strategies to range between $700 million to $19.5 billion per year. The marginal cost of carbon sequestration is estimated to range from $17 to $43 per ton.

Similarly, Parks and Hardie (1995) assess the subsidy that would be required to entice landowners to convert marginal agricultural land in the US to carbon plantations.

Their results suggest that 8.9 million hectares of land could be planted in trees for $3.7 billion to sequester 1.9 tons per acre per year. This would amount to a cost of approximately $9 to $10 per ton of carbon stored. As this program considers a smaller plantation scheme than Moulton and Richards, it is reasonable to expect that marginal costs will be smaller.

Unlike the previous two studies, Stavins (1995) uses a revealed preference approach based on empirical data from 36 southern US counties to estimate costs. The resulting marginal cost function is relatively linear up to 9 million tons of carbon storage per year. For this program, marginal costs are less than $66 per ton. Hoen and Solberg (1994) estimate the cost of carbon sequestration in different management strategies in Norwegian forests. They predict that carbon storage would cost approximately $79 per ton through increased management of existing forests. The overall range of most existing studies suggests that the marginal costs of planting trees range from less than $1 per metric ton (1000 Kg) of carbon to $187 per ton, depending on the region, growing factors, and other conditions (Richards and Stokes, 1995).

While most of these studies examine smaller programs than that proposed by Sedjo (1989), they all ignore the potential market impacts of planting trees. Even if the forests are protected for a short time, markets will adjust now to increased future supply. This may be particularly true if the cumulative effects of many small regional programs are large. Increased supply will lead to lower prices, reduced management intensity, and potentially lower carbon storage. On the positive side, however, lower prices may also reduce the incentive to harvest inaccessible boreal forests. Since these regions have the highest density of carbon per hectare in the globe, this may increase carbon storage.

Models must capture these system wide effects to develop accurate predictions of the costs of carbon sequestration.

By ignoring these effects, the existing studies may over-estimate the effectiveness of carbon sequestration strategies. Landowners have many potential responses to the effects of establishing carbon plantations or setting aside large areas of timberland. They can harvest early, reduce management intensity, reduce the quantity of forests harvested in inaccessible regions, and reduce the area of land established in timber plantations. Without carefully addressing the market response to either regional or global programs, it is difficult to assess either their effectiveness or their costs. This paper begins to address how system-wide impacts will affect carbon storage in forests over time. By using a recently developed dynamic timber market model of the world (see Sohngen et al., 1998a) which optimizes harvests, regeneration intensity, inaccessible forest use, and plantation establishment in 46 timber producing regions of the world, we begin to capture the system-wide, dynamic impacts of alternative carbon sequestration strategies.

Because the effectiveness of different programs must be measured relative to the baseline, the paper begins by presenting a predicted baseline path of carbon sequestration in forests in the absence of both climate change and carbon mitigation policies. Even in the absence of sequestration strategies, some authors (see Plantinga and Birdsey, 1993, for example) predict that timber markets will increase carbon storage in forests in the future in the United States. The results in this paper suggest that timber markets will likewise increase carbon storage in future years, but these increases occur mainly in subtropical regions as the area of plantations expands. As discussed below, these baseline results have important implications for the effectiveness of alternative carbon sequestration strategies.

The paper then examines how four different strategies for increasing carbon storage in forests will affect this system. We begin with an "optimistic regional planner" scenario, which assumes that timber plantations are never harvested, and that there is no leakage. While this strategy is unlikely in reality, several other strategies are contrasted with to show how markets may respond. Carbon storage relative to the baseline case is reported to show how the strategies will increase or decrease storage relative to what might otherwise occur. Carbon storage is measured with the methods used by Sohngen et al. (1998b) and Sohngen and Sedjo (1998).

BASELINE CARBON FLUX

Without human intervention to increase the storage of carbon in forests, the flux of carbon to and from forests will be affected both by natural and by human factors. While natural disturbances are important (see for example Kurz et al., 1995 and Dixon and Krankina, 1993), this paper focuses on fluxes generated by timberland managers in response to changing market conditions. Timber markets will influence forest carbon flux in several ways. First, harvests in regularly accessible forests will remove carbon from the ecosystem, and store some of it in the pool of marketed products. Second, harvests in remaining inaccessible regions, such as the boreal forests of Canada and the Former Soviet Union, may convert old growth forests into younger forests. Third, if demand is increasing and prices are rising, timberland owners may adjust by increasing management. Finally, market incentives alone are likely to lead to increased establishment of timber plantations.

With predictions of optimal harvest, regeneration, and management pathways based on the global timber market model, carbon flux in forested ecosystems and marketed product systems is calculated and reported. A description of these results for the baseline case, as well as two alternative demand scenarios is given in a companion paper by Sohngen and Sedjo (1998). The model predicts not only global carbon flux and storage, but also regional effects, and effects by component (i.e. vegetation vs. marketed product storage and flux).

The baseline case assumes that the demand for industrial wood products rises at 1.0% per year initially, but declines slowly to 0.0% per year by the year 2140. The 1.0% demand increase is consistent with recent studies of global timber demand (Sedjo and Lyon, 1990). The decline in growth represents an assumed slow down in population and economic growth over the next 150 years, as well as a change in technology, both of which reduce the growth in demand for harvests of virgin timber.

Under this scenario, industrial wood prices rise from $76 per cubic meter to $142 per cubic meter in the year 2135. This represents an increase of approximately 0.4% per year, with the most rapid price growth occurring in early periods, and prices stabilizing in later periods. These rising prices indicate increasing global scarcity for timber products. Although higher harvests occur at the same time, higher prices have important consequences for carbon flux. They induce more management, and therefore greater carbon storage in forests that are harvested and subsequently regenerated. The model carefully accounts for how these adjustments in management intensity over time affect carbon flux and storage.

While harvests remove carbon from the terrestrial ecosystem, this carbon is not necessarily emitted into the atmosphere. Some carbon will be stored in short- or long-lived wood products. Many previous studies of the costs of forest carbon sequestration consider forests only as a short term warehouse for carbon, and they have not addressed this component. This is an important omission: If carbon sequestration programs alter the future price of timber, they can be expected to alter the amount of carbon that enters market storage. As shown below, the effectiveness of carbon storage programs may depend heavily on whether carbon stored in forest products is counted.

Figure 1 presents the flux of carbon in four general regions of the globe during climate change. In early periods, carbon is accumulating in temperate forests and wood products as these forests age, and harvests rise. Temperate forests, however, are predicted to emit carbon between the periods 2040 and 2080, as forests in North America are converted to younger stands and stocks decline in the Former Soviet Union.

Most carbon sequestered in forests in the future arises from the establishment of new emerging region plantations. The area of these plantations is predicted to increase from 41 million hectares to 83 million hectares. This rate of establishment is lower than recent establishment rates given by FAO (1995). Those estimates, however, include plantations used for non-industrial wood market purposes, such as fuelwood. Lower future rates of establishment also result from prices that stabilize in the distant future. New plantations are assumed to be established on agricultural land that converts back to forests, not existing natural forests that are converted to plantations. This assumption is consistent with current evidence (Sedjo, 1995).

Over the next 150 years, timber market activity is predicted to store an additional 17.9 Pg of carbon in forest vegetation, soils, and marketed products. While 95% of the long term (150 year) gain results from additional storage in forest products, 30% of the short term (50 year) carbon gain occurs as vegetation carbon. Carbon sequestration strategies, depending on whether or not the forests are available for consumption, can be expected to alter both the total additional storage of carbon, as well as the timing of carbon sequestration.

The result that forests and forest products sequester significant quantities of additional carbon depends heavily on the predicted increase in the area of land in subtropical emerging plantations. It is important to recognize that these plantations are profitable for landowners, and therefore make a good economic investment. They do not result from subsidies for timber or carbon plantations. Global strategies that reduce future prices (by allowing harvests in carbon plantations, for example), can reduce the economic incentive to establish economic plantations, and potentially reduce the quantity of carbon stored in these plantations.

CARBON SEQUESTRATION STRATEGIES

Strategies

Several different policies have been suggested to increase the size of the forest carbon sink. We explore four of them, as shown in table 1, in this paper to see how markets may adjust and adapt in response. Each strategy is implemented over 14 million and 28 million hectares respectively. While these strategies are within the range used by previous studies, they show that markets adjust even when the scope of the project is relatively small. Future extensions of this research will address larger policies that have more dramatic impacts.

The first strategy is dubbed the "optimistic regional planner." This strategy represents the maximum potential for carbon that could be sequestered in forests without market effects. The optimistic planner strategy establishes plantations in Europe and North America, and then keeps markets from using them over time. The plantations are assumed to be established over a 20 year time period, with equal areas of land being planted in each year. For the optimistic regional planner strategy, we assume that tree plantings do not alter the relative value of land in agriculture and forestry so that there are no other market interactions. This strategy is expected to represent an upper bound (even if unattainable) estimate of the potential for forests to sequester carbon over the long term.

The second strategy is a European and North American carbon plantation strategy, where harvests are allowed when the trees have matured. This strategy may be adopted if policy makers are considering lower cost options which would allow landowners to obtain some return from their land in addition to cash rental payments. As with the previous strategy, timber plantations are established over a 20 year time period. This strategy posits that these two regions attempt to increase the area of their accessible forests on marginal agricultural lands, as suggested by Moulton and Richards (1990) and Parks and Hardie (1995).

The third strategy is a timber conservation strategy, which assumes that mature forests in North America and Europe are removed from access and set aside. The rationale for this strategy is that it would lock the carbon in these forests from future harvests or land use changes. This strategy may be attractive to policy makers if they interpret the language of the Kyoto Protocol to suggest that forestry activities are limited to "reforestation, deforestation, and afforestation since 1990." While these regions are likely to undergo natural carbon cycles as suggested by Kurz et al. (1995), we assume that these natural cycles are in long term balance so that there is no net loss of carbon from forests that are set aside.

The final strategy is a subtropical emerging region carbon plantation strategy. These forests are allowed to be harvested when they have matured economically. Given the high timber yields possible from forests in these regions, they potentially have greater storage capacity than longer lived species in North America and Europe. Subtropical emerging regions include South and Central America, Africa, the Asia-Pacific region, and Iberia.

Results

The optimistic regional planner strategy sequesters the largest quantity of carbon relative to the baseline case (table 2). While the other strategies generally predict increased storage, their effectiveness declines dramatically relative to the optimistic planner case. Figure 2 presents the time profile for three of the 28 million hectare strategies that focus on Europe and North America. The additional timber supply caused by tree planting programs in Europe and North America has fairly small long term price implications (prices decrease less than 1% from than the baseline case in any given year), but markets adjust nonetheless. One area where leakage occurs in the system is with the establishment of subtropical emerging region plantations. Overall plantation establishment is reduced by nearly 1 million hectares, leading to less storage of carbon in that region relative to the baseline.

In contrast to these losses, the area of northern inaccessible forests accessed by markets declines by 2 million hectares, suggesting that additional carbon will be stored there. These gains, however, are modest compared to the loss of timber and market storage in subtropical emerging region plantations. Each hectare of northern inaccessible forest that is not accessed retains 9.5 thousand Kg of carbon relative to the baseline, compared to a loss of 194 thousand Kg for each hectare of subtropical plantation that is not established. While it may be important to conserve northern inaccessible forests for reasons other than carbon sequestration, strategies that save them at the expense of more productive plantations in other regions of the world may lose more carbon than they save.

The North American and European set-aside, or forest conservation, strategy actually reduces the quantity of carbon stored by global forests (figure 2). Although this strategy effectively protects the carbon in regions that are conserved, it places additional harvest pressure on remaining forests in the timberland base. Comparing vegetation only storage (in parenthesis in table 2) to market plus vegetation storage in table 2 shows that all of the losses in the set aside strategy result from higher prices and lower market storage. Nevertheless, table 2 also shows that the increase in vegetation storage resulting from this adjustment is small, in part because higher prices place additional pressure on inaccessible forests that might otherwise remain wilderness.

The results suggest that establishing carbon plantations in the subtropical emerging region harbor the most hope for increasing the size of the carbon sink in forests (figure 2). These results, however, depend heavily on lower timber prices and increased storage in marketed products. When only the carbon stored on the landscape is considered, as shown in figure 3, subtropical emerging region carbon plantations are less effective in the long run than plantation establishment in temperate forests.

The most dramatic impact of establishing carbon plantations in the subtropics arises from increased storage in forest products. The large predicted carbon gains depend heavily on prices. Because prices rise to only \$130 per m^3 in the 28 million hectare plantation case, rather than \$142 per m^3 in the baseline case, large quantities of additional timber are purchased, and the carbon is subsequently stored in products. There are two reasons for the large price impacts. First, subtropical plantations can supply more timber to markets on a yearly basis due to quicker rotations and higher yields than their counterparts in temperate forests. Second, subtropical plantations are expected to be an increasing source of future timber supply. Raising output in the region that is already predicted to enjoy the largest growth in output has a large impact on prices. Policy makers must carefully consider how to incorporate carbon storage in forest products into their carbon accounting framework, because these pools may represent a large source of carbon benefits that arise from sequestration programs.

To some extent, establishing plantations for carbon purposes substitutes for plantations that would be established regardless. The baseline case predicts that 42 million new hectares of plantations will be established due to economic reasons alone, while under the 28 million hectare carbon plantation strategy, this number is reduced to 36 million additional hectares.

Another important issue to consider in designing carbon sequestration programs is the effect of a program in one region on carbon sequestration elsewhere. Establishing plantations in the subtropical emerging region has consequences for carbon across the globe. Long term carbon storage in North American forests declines by 1.0 Pg carbon relative to the baseline case as those forests are managed less intensively due to lower future prices. Similarly, carbon storage in European forests decline 0.6 Pg, and storage in Former Soviet Union forests decline 0.4 Pg. These losses occur despite lower harvests in inaccessible regions. Joint implementation projects, where developed countries in the temperate regions purchase carbon plantations in developing subtropical or tropical regions, may inadvertently reduce their own carbon storage capacity as markets adjust.

DISCUSSION AND CONCLUSION

This paper presents a baseline case of carbon sequestration in timber markets without considering human intervention to increase the sink of carbon in forests. Over the next several decades, forests are expected to continue sequestering additional carbon without direct investments in carbon plantations. These gains, amounting to an additional 0.3 Pg of carbon per year for the next 50 years, result from efficient timber market investments alone. Although these gains in forest carbon represent less than 5% of human emissions from other sources, they result from efficient market activity. Importantly, much of the long term gain in carbon results from increased storage of carbon in marketed products.

Several different scenarios of carbon sequestration strategies were then presented to show how markets respond to human intervention. An "optimistic regional planner" scenario is first examined which posits that plantations can be established and protected from harvests in Europe and North America without affecting market activity. A second scenario allows these timber plantations to become part of the future timber supply base. Although the new plantations are fairly marginal in terms of the area of land in global forests -- they range from 5 to 10% of the area of European and North American accessible timberlands-- markets adjust by altering the area of land in forests, altering the area of inaccessible forests that are harvested, and altering timberland management intensity. Despite gains in carbon storage in boreal inaccessible forests due to lower prices, lower management throughout the globe reduces effectiveness relative to the optimistic regional planner case.

A third scenario is then examined which takes existing mature forests and sets it aside from use in timber markets. This adjustment has a negative influence on the stock of carbon due mainly to higher prices and lower market storage. If market storage were ignored, these strategies would have a positive carbon effect, albeit small.

The final scenario establishes plantations in the subtropical emerging region. Although the area of land established in emerging subtropical plantation scenarios is equal to the area of land established in the European/North American scenarios, their impact on global timber markets is greater. This results from shorter rotations and higher timber yields. If storage in timber markets is not considered, establishing plantations in these regions has an even smaller effect on the size of the forest carbon sink than establishing plantations in temperate regions.

These results suggest that policy makers must carefully consider the system wide impacts of different strategies as they assess the costs. The relatively small programs examined in this paper were shown to have effects beyond the scope of the projects considered. Carbon may leak from the system, particularly if timber plantations are eventually allowed to enter timber markets and increase supply.

This leakage occurs over long time periods and from region to region. For example, while additional subtropical emerging region plantations increase carbon storage, they reduce the incentive to manage other plantations as well as natural forests. Thus, future storage will decline in many regions, even as storage increases in regions with the plantations. In the examples above, subtropical emerging carbon plantation establishment reduces the storage of carbon in temperate forests as timberland management declines in these regions.

Many existing studies of the costs of carbon sequestration have taken a short term focus by considering the ability of forests to sequester carbon for the next several decades. However, the results in this paper suggest that earlier studies may present an overly optimistic view of carbon sequestration even in the short term. If markets adjust by reducing management today, the benefits of these short term gains will be reduced.

While this research takes a step towards assessing the potential system wide implications of carbon sequestration in forests, the paper does not fully account for all adjustments markets may undergo. The model does not fully account for adjustments in the relative price between forests and agricultural land. If these adjustments are large, which may be true if plantation strategies involve large land areas, markets may adjust by converting additional existing forests to agricultural land. A recent paper by Alig et al. (1997) suggests that there is nearly a 1 to 1 shift between agricultural and forest land in the US when plantations are established, suggesting that there may be no net gain in carbon.

It is not clear that the same relationship will hold globally. For example, the supply of high quality agricultural and forestry land in the United States and other regions is likely to differ dramatically. Future extensions of this research will develop supply functions for agricultural land in different regions in order to determine how markets might shift land between the two uses across different forest and agricultural zones of the world. Leakage of this sort may have further implications for the effectiveness of carbon sequestration strategies.

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Table 1: Selected strategies examined in this paper for increasing the size of the carbon sink in forests.

	Harvests Allowed	Size of Change
Strategy 1: Optimistic Regional Planner (Plantations established on marginal agriculture land in Europe and North America)	NONE	Low = 14 Million Hectares High = 28 Million Hectares
Strategy 2: European/North American Plantations (Plantations established on marginal agriculture land)	YES	Low = 14 Million Hectares High = 28 Million Hectares
Strategy 3: Forest Conservation/Setaside (Accessible and inaccessible temperate forests setaside)	NONE	Low = 14 Million Hectares High = 28 Million Hectares
Strategy 4: Emerging Subtropical Plantations (Plantations established on marginal agriculture land)	YES	Low = 14 Million Hectares High = 28 Million Hectares

Table 2: Cumulative gain in forest carbon storage relative to the baseline case in the short term (50 years) and long term (150 years). Numbers in parentheses indicate storage in tree carbon components only. The difference between the two values is the storage of carbon in marketed products.

	14 Million Hectares		28 Million Hectares	
	2040	2140	2040	2140
	Petagrams Carbon (10^{15} grams)			
Optimistic Regional Planner	0.56	3.89	1.13	7.82
European/North American Plantations	0.64 (0.64)	1.41 (1.29)	1.24 (1.18)	2.63 (2.32)
Forest Conservation/Setaside	-0.13 (0.05)	-0.11 (0.04)	-0.49 (-0.16)	-0.15 (0.17)
Emerging Subtropical Plantation	1.85 (0.90)	2.85 (0.69)	3.58 (1.75)	5.70 (1.43)

Figure 1: Carbon flux to and from forests in four global regions in the baseline. Positive quantities indicate that forests are sequestering additional carbon, while negative quantities indicate that forests are emitting carbon.

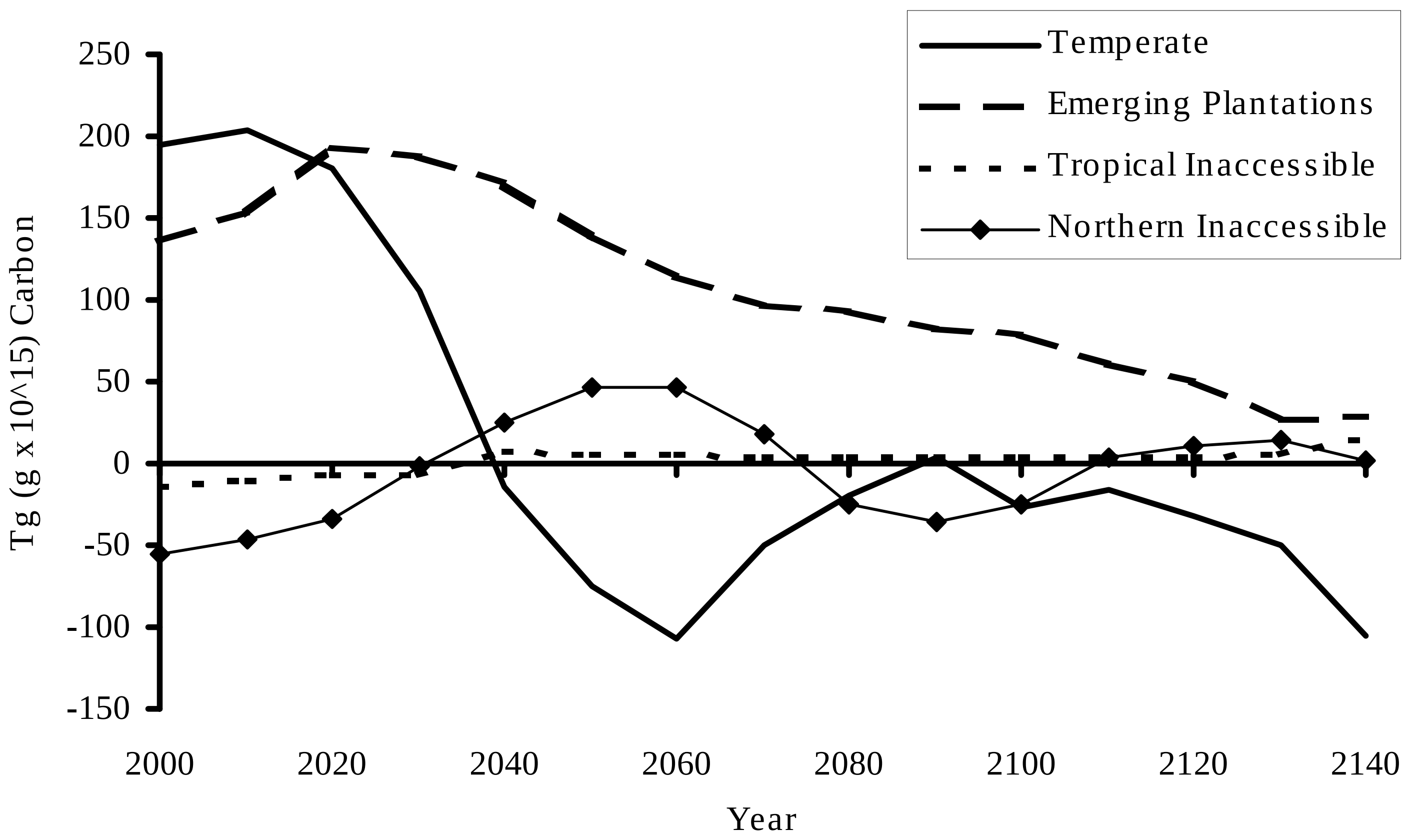

Figure 2: Comparison of three 28 million hectare strategies for increasing the sink of carbon in forests. The results show the gain or loss in the pool of carbon dioxide in forests relative to the baseline case.

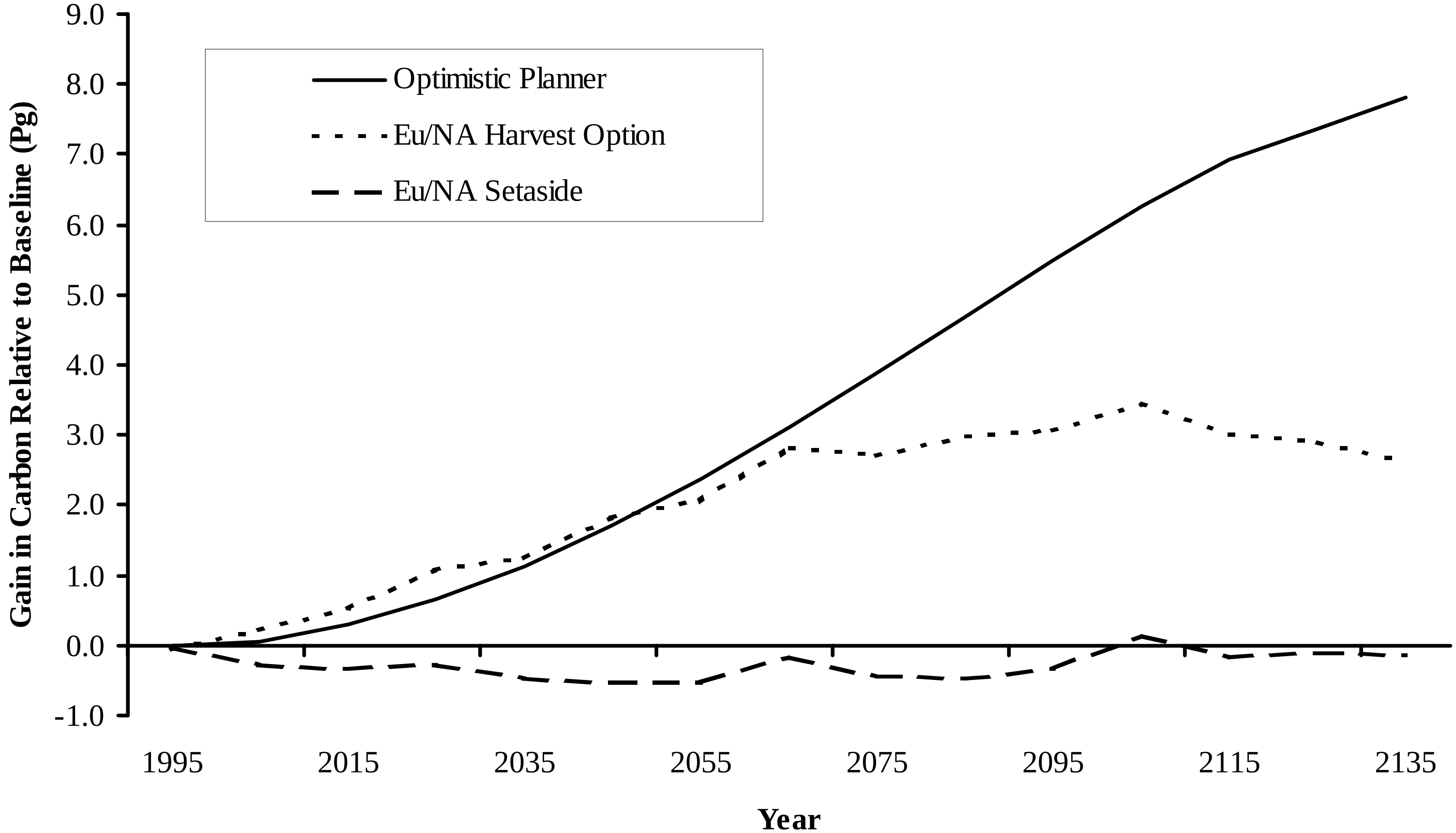

Figure 3: The gain or loss in the pool of carbon dioxide in forests relative to the baseline case for the 28 million hectare emerging plantation and European/North American plantation strategies, with and without carbon storage in forest products..