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PREFACE

ABSTRACT

Terrestrial ecosystems store approximately 1 trillion tons of CO_2 in the biomass of living trees and plants. Current estimates suggest that it would be possible to increase this carbon efficiently in order to reduce the future damages of climate change. The methods that could be used include afforestation (planting old agricultural land in trees), reduced deforestation, and forest management. Current estimates in the literature accounting for opportunity costs and implementation and management costs suggest that an additional 6.8 billion tons CO_2 per year may be sequestered in forests by 2030 for $30 per ton CO_2. Around 42% of this would arise from avoided deforestation, with the rest roughly equally split between afforestation and forest management options.

Analysis indicates that if society follows an "optimal" carbon abatement policy, as defined in Nordhaus (2009), forestry could accomplish roughly 30% of total abatement over the century. If society instead places strict limits on emissions in order to meet a 2°C temperature increase limitation, then the component forestry provides lowers overall abatement costs by as much as 50%. The benefit cost ratio in the optimal scenario is 1.0, while it is 1.8 in the 2°C limiting case. The results of the benefit cost analysis do not substantially change with a lower interest rate, and they also do not substantially change when transactions costs are included. This rather optimistic economic analysis is useful, but it does not account directly for leakage. Given that the literature suggests that leakage could be as large as 90% - 100%, it would have large implications for costs, potentially reducing the benefit cost ratio below 1. Importantly, leakage can only be reduced by including more countries into the control program. The paper also does not account for other potential benefits of adding forestland over time. These benefits are ecological in nature, and they are difficult to measure systematically across the globe. They do, however, represent a potentially large, additional, benefit of a forestry carbon sequestration program.

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The Copenhagen Consensus Center has commissioned 21 papers to examine the costs and benefits of different solutions to global warming. The project's goal is to answer the question:

"If the global community wants to spend up to, say $250 billion per year over the next 10 years to diminish the adverse effects of climate changes, and to do most good for the world, which solutions would yield the greatest net benefits?"

The series of papers is divided into Assessment Papers and Perspective Papers. Each Assessment Paper outlines the costs and benefits of one way to respond to global warming. Each Perspective Paper reviews the assumptions and analyses made within an Assessment Paper.

It is hoped that, as a body of work, this research will provide a foundation for an informed debate about the best way to respond to this threat.

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INTRODUCTION

There is widespread belief now that forests can be used to reduce the costs of slowing climate change. While the role of forests in the global carbon cycle has long been acknowledged, recent discussions within the context of the United Nations Framework Convention on Climate Change, as well as efforts to write climate change legislation in the United States, have emphasized the role forests might play. The most recent policy efforts have focused on near-term actions to reduce deforestation in tropical countries.

The rationale for considering forests at all in the policy mix stems partly from the physical components of the issue. The world's forest estate is exceedingly large: It contains roughly 3.9 billion hectares of forestland and 1 trillion tons[1] of CO_2 (UN Food and Agricultural Organization, 2006). Current estimates indicate that roughly 11 million hectares each year are lost in tropical regions due to deforestation and conversion of land to agriculture (Houghton, 1999, 2003). These losses cause emissions of about 3.6-4.5 billion tons of CO_2, so that deforestation accounts for around 17% of global carbon emissions. Countries like Indonesia and Brazil are near the top of total emissions when estimated by country if deforestation is included in carbon emission calculations. Efforts to slow these emissions, of course, could have enormous benefits for society.

In contrast to the story in the tropics, the area of forests in temperate zones is fairly stable. Carbon stocks are increasing in most temperature regions as forests continue to age (Sohngen et al., 2005; Smith et al., 2003), although perturbations around natural cycles can cause large emissions (Kurz and Apps, 1999). Current estimates from the Intergovernmental Panel on Climate Change suggest that northern forests presently may sequester 3.2 billion tons CO_2 per year currently (IPCC, 2007). Growth in northern forests may offset much of the loss in tropical zones. Efforts to increase these carbon stocks by changing management, increasing forest area, or shifting species, could also help reduce net emissions of green house gases and could benefit society.

Can avoiding deforestation in tropical areas, reforesting old agricultural lands in temperate and tropical regions, or changing management practices increase the total uptake of carbon into the forests? Several studies so far suggest that forest actions can cost effectively provide roughly 30% of the total global effort needed in all sectors to meet climate mitigation strategies (Sohngen and Mendelsohn, 2003; Tavoni et al., 2007). This paper examines these and other results in the literature, and argues that the evidence clearly indicates that forests should be an important part of any national or global strategy aimed at avoiding climate change. If society is both serious about climate mitigation and serious about containing costs, there is little choice but to develop programs that increase the stock of carbon in forests.

Of course, developing a program that fundamentally alters future land use by valuing carbon stored on the landscape will not be easy, or cheap. It will require that countries agree to manage their forest resources in different ways (e.g., to value maintenance of the stock over conversion to agriculture). It will require the development and innovation of new systems for measuring monitoring and verifying carbon gains that are made, whether these systems are accomplished with satellites or the proverbial boots on the ground. It will require new types

1 Tons in this paper are metric tons, or 1000 Kg.

of services that can assemble carbon and deliver it to an emerging carbon market place. None of this will in fact be easy, but if incentives are large enough, then there is no reason to believe that carbon in forests will not become an important, valued commodity across the landscape.

To examine the potential for carbon sequestration in forests, this paper begins with a brief discussion of the categories of costs that are important to include in the analysis of forestry options. Then, several of the forestry options that have been widely discussed in the literature are presented. The technical components of these options are briefly described to provide readers with some general background on them. The paper then presents estimates of the potential costs of a large-scale carbon sequestration program, considering which options appear most cost effective and manageable, and which options may be more difficult. The paper then presents new calculations of the benefits of forest carbon sequestration options derived from integrating a forestry and land use model with a global integrated assessment model. Finally, the paper describes some of the limitations associated with implementing a large scale forest carbon sequestration program.

COST CATEGORIES

It is perhaps useful to begin with a discussion about the categories of costs that should be considered when addressing the economics of forest carbon sequestration. The most important category for land-based activities like forestry is *opportunity cost*. Opportunity costs are the costs of holding land in forests. Opportunity costs arise because land has other potential uses and those uses would also provide value, thus opportunity costs are defined as the value of the next best alternative use of the land. If one converts cropland to forests to sequester carbon, the opportunity costs are the value of the foregone returns to agriculture.

A second cost category is the *implementation and management cost*, which includes all the direct costs of installing or implementing a practice and maintaining and managing that practice over time. Implementation costs include those costs that can be directly attributed to the action. For example, the costs of buying seedlings to plant and the costs of the labor to plant the seedlings are implementation costs. The costs of herbicide or nutrient treatments used to increase the value of the stand over time would also be included in this category. In addition, any costs of thinning or ultimately harvesting a stand would be considered here as well, although one must also be careful to include the benefits of thinning and harvesting operations in the analysis, as discussed below.

A third category is *measurement, monitoring, and verification costs (MMV)*. These costs include the costs of measuring the carbon in areas that have undergone afforestation, or improved management. They also include the costs of monitoring and verifying stands to ensure that the carbon under contract actually is there. While these costs will be very important to consider, in forest carbon cost analyses, they often are assumed to be programmatic in nature, and they are ignored. That is, authors typically measure the opportunity, implementation and management costs, but assume MMV will be undertaken programmatically so that the costs are not borne by the individual actors. The studies on which this paper reports by-and-large do not account for MMV costs, but analysis is conducted below to assess the potential implications of these costs on benefits and costs.

A fourth category is *other transaction costs*. The modifier "other" is used here because some authors include MMV costs in transaction costs. Other transaction costs are any other unaccounted for costs associated with developing and implementing contracts for carbon sequestration on the landscape. These could include the time costs of learning about the biology of carbon sequestration, the costs of hiring lawyers to draft contracts, the costs third parties impose to bring together buyers and sellers, etc. There are many potential categories of these types of costs, some of which may be borne directly by buyers and sellers, and some of which may be more programmatic in nature. Most of the existing literature on carbon sequestration costs does not include these costs, and there is actually very little literature on what the extent of these costs may be. The estimates provided in this study do not include transactions costs, but as with MMV costs, analysis is conducted below to consider them.

A final category of costs is called *system-wide adjustment costs*. These costs arise specifically from the design of the sequestration program. One example of this type of cost is leakage, which occurs when an incomplete program is developed. Such a program may provide incentives only for some forest options or some regions of the world. Subsequent adjustments in timber prices in the market may cause shifts in other regions that offset the sequestered carbon. Another important secondary effect of forest carbon sequestration may occur in land markets and land prices. For instance, if reducing deforestation reduces the area of productive agricultural land, then crop or livestock prices could rise. These rising prices would be expected to increase the opportunity costs of land. These secondary effects could have important implications for estimation of carbon sequestration costs. Some studies do in fact model both forest and agriculture, and thus capture these secondary effects[2], while most studies do not. Neither of these issues is explicitly addressed in the cost estimates provided in this study, although the study does discuss the potential implications of system-wide adjustment costs below.

In summary, the cost estimates discussed in this section and with the forestry model focus on opportunity costs and implementation and management costs. The cost estimates also account for any timber market benefits that may accrue to the activities through timber harvesting. These benefits may be particularly important for afforestation and forest management activities. MMV and other transactions costs, while important, are not considered in this section of the paper, but will be addressed later. In addition, discussions about leakage and secondary market effects are saved to later in the paper.

OPTIONS FOR CARBON SEQUESTRATION IN FORESTS

Afforestation

Afforestation has been the most widely recognized and studied option for mitigation using forests to date. Afforestation refers to taking agricultural land and converting it into forests. Because agricultural land stores very little carbon in aboveground biomass, converting the land to trees, and allowing those trees to grow, will remove carbon from the atmosphere. A forest that is growing can remove 5-11 tons CO_2 per hectare per year, depending on

2 The only model we report on that captures the full range of price effects across markets is the work of Murray et al. (2005).

location and productivity. A large proportion of the world's crop and grazing lands are rain-fed, indicating that they also can support trees. As a result, there are many opportunities to sequester carbon by converting this agricultural land into forests.

Of course, converting land from agriculture to forests comes with a cost. Afforestation requires implementation and management costs, as well opportunity costs. Depending on the region, tree species, labor costs, site quality and other factors, planting and managing trees may cost $700 to more than $3000 per hectare in present value terms. As noted above, opportunity costs associated with converting land from agricultural uses to forest will also be important, and they will depend on the value of the land in agricultural production. The costs are important, but it is also important to recognize that there may be future benefits to planting trees. That is, because afforestation ultimately leads to standing forest stocks with potentially valuable timber, there may be some future benefits that can reduce the costs. When measuring the net costs of afforestation, all of these categories (planting, management, opportunity costs, and benefits) must be included.

The main reason why afforestation is so widely acknowledged as having large potential throughout the world relates to the rather substantial value of the carbon embodied in forests. Consider a southern upland hardwood forest in the United States, which may typically be harvested at age 50. A stand like this may contain 257 tons CO_2 per hectare in aboveground carbon (Sohngen et al., 2009). If there is no value to carbon sequestration, under current timber prices, such a stand would have a typical return of $30-$40 per hectare per year. If, however, carbon prices are $14 per ton CO_2, then annual returns (inclusive of timber harvests) would be $75-$80 per hectare per year, and if they rise to $28 per ton CO_2, then annual returns increase to $130-$140 per hectare per year. The increase in returns to planting forests when the embodied carbon is valued is substantial, for higher carbon prices, it quickly makes forest competitive with some crop and grazing land.

Many estimates of the sequestration potential for afforestation have been made over the years. Sedjo (1989) presented the first economic analysis of the potential, finding that forest plantations could sequester up to 10.7 billion tons CO_2 per year for less than $2 per ton CO_2. That study assumed that crop and grazing land was very cheap and could readily be converted to forests. Subsequent analysis suggests that these estimates may be too optimistic – at least with respect to the costs. For example, a global land use model by Sohngen and Mendelsohn (2003, 2007) suggested that 0.7 – 2.2 billion tons CO_2 can be sequestered globally per year for $8-$30 per ton CO_2. Richards and Stokes (2004), in one of the most thorough reviews of the literature to date, find that 7.0 billion tons CO_2 per year may be sequestered globally, but the costs could be as much as $41 per ton CO_2. All of the estimates discussed in this section account for opportunity costs, and installation and management costs, but not for MMV costs, other transaction costs, or system-wide costs.

Reductions in deforestation

Since 2005, much attention has focused on the idea that reductions in deforestation could reduce emissions of carbon dioxide into the atmosphere, and also be a relatively low cost option for mitigation. Of course, deforestation has always been an important contributor to carbon emissions, so it is surprising it took the policy makers so long to get engaged in the issue. Given the scale of deforestation globally, interests among some developing countries to achieve larger reductions in net emissions sooner rather than later, and the interests of environmental non-governmental organizations, avoided deforestation is now widely recognized as a vital ingredient for international climate negotiations.

Deforestation causes about 5 billion tons CO_2 emissions per year, or around 17% of total global emissions (IPCC, 2007). From a technical standpoint, avoiding deforestation makes great sense. Standing tropical forests may contain 300-400 tons CO_2 per hectare in biomass (see Kindermann et al., 2008). If these standing forests are converted to agriculture, some wood may make its way into markets, but the vast majority of it will be burned on site when the land is converted. Other wood will decompose over time. Either way, when standing tropical forests are converted to agriculture there is a relatively quick emission of carbon into the atmosphere. Holding that carbon on the landscape in trees can substantially alter net global emissions each year.

The value of holding this carbon on the landscape is exceedingly large. If carbon prices are $14 per ton CO_2, the annual rental value of the carbon embodied in a standing tropical forest with 350 tons CO_2 in measureable aboveground carbon is $245 per hectare per year.[3] If carbon prices double, to roughly $30 per ton CO_2, then rental values would be $525 per hectare per year. Values this high would compete with agricultural production in some of the world's most productive regions. They are sure to compete with agricultural production in the tropics at the forest-agricultural margin where, by definition, opportunity costs are low. Unlike afforestation, there are no up-front costs associated with planting and managing these forests. One needs to arrange to pay a rental fee to maintain the stock (i.e., to cover the opportunity costs), but these fees do not need to include large-scale outlays to plant and manage timber. The estimates of costs of avoided deforestation presented in this paper thus include only opportunity costs, and losses associated with not harvesting timber. It is widely recognized, however, that there may be some institutional difficulties associated with accomplishing deforestation reductions in developing countries, and thus there may be some other transactions costs that are important. These costs will alter the quantity of carbon obtained, as discussed in the analysis on transactions costs below.

Recent estimates indicate that slowing or stopping this deforestation could have important consequences for the atmosphere. Estimates by Kindermann et al. (2008) suggest that for $30 per ton CO_2, around 2.8 billion tons CO_2 emissions per year could be reduced in tropical regions by avoiding deforestation. These estimates in Kindermann et al (2008) are derived from global land use models and they tend to be higher than many other estimates that have so far been done (see Murray et al., 2009). However, even these estimates imply that there is great hope that avoided deforestation can be a low cost option that is meaningfully applied to climate policy. As noted in their paper, the estimates in Kindermann et al. (2008) do not account for MMV costs, other transaction costs, or system-wide adjustment costs.

3 Prices are assumed constant for these estimates of rents, and under those circumstances, the annual rental value is calculated as $r*P_c*$(t CO_2 per hectare), where r is the interest rate (assumed to be 5% in this case) and P_c is the price of carbon dioxide.

Forest management

The third mitigation option considered in this paper involves forest management. There is a surprisingly wide range of options available to increase carbon through forest management. Some of the options would provide carbon benefits in the near-term, while others would provide longer term benefits. In managed forests, the quickest way to increase carbon on the landscape is to increase the forest rotation age (Sohngen and Brown, 2008). Even small increases in forest rotations, when implemented over large areas with millions of hectares, could produce measurable increases in carbon stock on the landscape. Given that many of the world's intensively managed plantation forests are managed in rotations, with timber outputs in mind, these landowners could be persuaded to extend their rotations if the carbon price is high enough. Sohngen and Mendelsohn (2003), Murray et al. (2005), and Sohngen and Sedjo (2006) all suggest that increases in rotations could be an important component of any carbon policy that values carbon stored on the landscape.

Over the longer run, many additional management strategies can be undertaken to increase total carbon in the forest. For instance, it is always possible to bring new forests under management. Planting forests rather than relying on natural regeneration after harvest, or forest fire, or other disturbance can increase the rate of carbon accumulation in early years and increase the overall quantity of carbon on the site in the long run (Hoehn and Solberg, 1994). Alternatively, shifting forests from one type to another can increase total carbon sequestration across the landscape (Sohngen and Brown, 2006).

Summary Estimates of the Costs of Carbon Sequestration options.

A marginal cost curve for carbon sequestration in global forests, including estimates for temperate/developed regions and tropical regions separately, is shown in figure 1, using data derived from the IPCC (2007). The marginal costs in figure 1 are derived from three global

Figure 1: Marginal cost functions for carbon sequestration in 2030. Data from IPCC (2007). Cost estimates include opportunity costs, and implementation and management costs, but not MMV and other transactions costs.

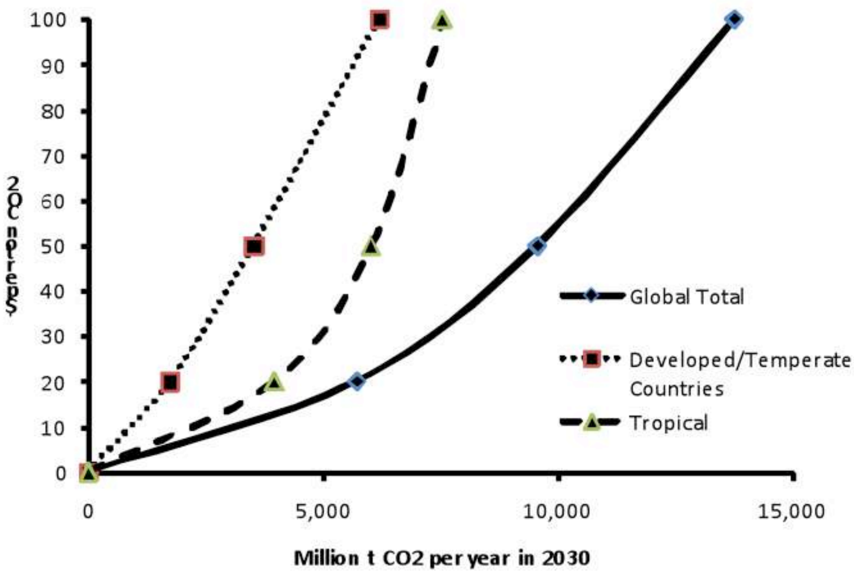


Table 1: Average annual potential net emissions reductions through forestry for the period 2020-2050.

	Afforestation	REDD[1]	Management	Total
	Million tons CO_2 per year for the period 2020-2050			
TEMPERATE				
US	471 (325-2,267)[3]	0	291 (268-314)[3]	7
Canada	87[2]	0	148[2]	234
Europe	32[2]	0	132[2]	164
Russia	25[2]	0	414[2]	439
China	104[2]	0	348[2]	451
Japan	34[2]	0	25[2]	59
Oceania	24[2]	0	21[2]	45
Total Temperate	777	0	1,378	2,155
TROPICS				
South & Central America	356[2]	1209 (800-1600)[4]	0	1,565
SE Asia	288[2]	402 (141-1153)[4]	696[2]	1,387
Africa	258[2]	1216 (884-1407)[4]	0	1,474
India	168[2]	0	2[2]	170
Total Tropics	1,070	2827	698	4,595
Total All	1,848	2827	2,076	6,751

Carbon price assumed to be constant at $30 per t CO_2. Compilation from various studies. Cost estimates include opportunity costs, and implementation and management costs, but not MMV and other transactions costs.

[1]REDD = reductions in emissions from deforestation and forest degradation; [2] Global Timber Model (Sohngen and Mendelsohn, 2003, 2007); [3] Range from Adams et al. (1994), Plantinga et al. (1999), Stavins (1999), Sohngen and Mendelsohn (2007), Murray et al. (2005), Lubowski et al. (2006).[4] Kindermann et al. (2008).

land use models, where the models are run under differing assumptions about current and future carbon prices. The results are summarized for the year 2030 only. Estimates shown in figure 1 indicate that up to 13 billion tons CO_2 per year may be sequestered in the world's forests in 2030 for $100 per ton CO_2 (Figure 1). For low carbon prices, e.g., $0-$20 per ton CO_2, most of the carbon is derived from activities undertaken in tropical countries. As prices rise, developed/temperate countries become a larger share of the total, but they don't exceed tropical potential over this range of carbon dioxide prices for the year 2030.

These results can be disaggregated by considering a single carbon price ($30 per ton CO_2), and calculating the carbon sequestered by different activities (afforestation, forest management, and reduced deforestation) in different regions of the world. For this disaggregation, only one of the models used to calculate the marginal cost curves in figure 1 is used, namely the global timber model of Sohngen and Mendelsohn (2003, 2007), but the results are supplemented with estimates of costs from regional studies where such studies have been conducted (Table 1). The annual sequestration potential is averaged for the period 2020-2050.

Table 1 illustrates that most of the carbon potential over the 2020-2050 time period results from avoided deforestation in tropical countries, followed by forest management in temperature and boreal regions, and finally by afforestation. At $30 per ton CO_2, 6.8 billion tons CO_2, or about 15% of the total emission of carbon dioxide and CO_2 equivalents currently can be sequestered. What is perhaps most surprising is that the economic estimates presented in Table 1 indicate that the largest share of carbon potential is derived from avoided deforestation (REDD) and forest management. The focus of policy over the past 10-15 years has been afforestation, and while afforestation is important, it represents the smallest potential share of carbon. The results in Table 1 are largely consistent with other compilations of results that have been conducted over the years (e.g., Sedjo et al. 1995 and Richards and Stokes, 2004; van Kooten et al. 2004). Estimates for REDD are based on Kindermann et al. (2008), and the estimates in that study are substantially more expensive than other recent estimates, such as Blaser and Robledo (2008), Eliasch (2008), and Grieg-Gran (2008), for example.

FORESTRY PROGRAM IMPLICATIONS

To assess the implications of the forestry program for the overall control of greenhouse gasses, it is useful to combine these results with an integrated assessment model. Sohngen and Mendelsohn (2003) conducted the first such analysis by linking their global forestry model with the DICE model of Nordhaus and Boyer (2000). They found forestry could efficiently accomplish 30% of the total abatement across the century (e.g., from the present to 2100). A subsequent analysis by Tavoni et al. (2007) utilized an updated version of the same land use model, but a different integrated assessment model, considered how forestry would affect the costs of meeting a 550 ppmv CO_2 concentration target. That study found that forestry would also be about 30% of the total mitigation effort over the century, but that it could reduce the costs of meeting the fairly strict carbon cap by around 40%.

For this paper, the earlier analysis of Sohngen and Mendelsohn (2003) is updated using a new version of the land-use model described in Sohngen and Mendelsohn (2007), and the new version of the DICE model described in Nordhaus (2009). Two scenarios are conducted. First, an "optimal" scenario is considered, in which the original optimal policy scenario from Nordhaus (2009) is adjusted to account for land-based sequestration. Because land-based sequestration is fairly large, the models are iterated until the prices and quantities of sequestration in the two models are the same.[4] Second, a scenario that limits the overall temperature increase to 2° C above pre-industrial levels is examined. The resulting carbon prices, carbon sequestration, and temperature change over the coming century are shown in Table 2.

4 See Sohngen and Mendelsohn (2003) for the methods used.

Table 2: Carbon sequestration pathways for combined forestry and DICE model for the optimal scenario and a maximum 2°C temperature change.

	No Controls	Optimal Scenario			2° C Limit		
	Δ° C	Sequestration t CO_2/yr	\$/t CO_2	Δ°C	Sequestration t CO_2/yr	\$/t CO_2	Δ°C
2010	0.85	5,727	\$7.23	0.83	5,471	\$8.51	0.83
2020	1.09	5,552	\$11.07	1.02	5,952	\$13.16	1.02
2030	1.34	6,076	\$14.09	1.21	6,508	\$17.50	1.20
2040	1.59	5,998	\$17.54	1.39	7,134	\$23.10	1.37
2050	1.84	6,114	\$21.45	1.56	6,877	\$30.50	1.53
2060	2.08	4,679	\$25.87	1.74	7,299	\$40.56	1.67
2070	2.33	3,951	\$30.85	1.91	8,817	\$54.45	1.80
2080	2.57	3,658	\$36.43	2.08	10,580	\$73.68	1.90
2090	2.81	4,762	\$42.69	2.24	14,234	\$99.49	1.96
2100	3.05	5,078	\$49.68	2.39	15,192	\$130.83	1.99

Table 3: Benefit-cost estimates for the optimal scenario and the scenario that limits temperature increase to 2° C, with interest rate (r) = 5%; and the same two scenarios with lower interest rates (r= 3%), both assuming no transaction costs.

	r=5%		r=3%	
	Optimal	2° C Limit	Optimal	2° C Limit
	Billions US\$ (present Value)			
Benefits				
Consumption Gain	(\$29)	\$832	\$164	\$4,970
Reduction in Damage	\$1,042	\$496	\$10,247	\$2,436
Reduction in Energy Costs	\$68	\$2,679	\$2,191	\$13,294
Total Benefit	\$1,081	\$4,007	\$12,602	\$20,701
Forest Cost	\$1,062	\$2,297	\$11,651	\$11,918
Benefit Cost Ratios				
All Benefits	1.02	1.74	1.08	1.74

In this analysis, estimates of three potential benefits associated with including forestry in the greenhouse gas control program are calculated for each scenario: Changes in consumption, changes in damages, and changes in energy abatement costs. Note that in some cases, changes in consumption could be negative, resulting in losses rather than gains. In all cases, the value of the benefits presented in the paper are present value calculations, using the internal interest rates (rate of return on capital) calculated by the DICE model. These interest rates start around 5.6% and fall over time to about 5.0% by 2100. The costs of the forestry program are calculated as the quantity of the carbon sequestration provided times the current carbon market price. For forestry program costs, present value calculations are also made using the internal interest rates calculated by DICE.

Under the optimal scenario, the introduction of forestry amounts to a cumulative 516 billion tons CO_2 sequestered in forests (additional to the baseline) or an increase of about 17% relative to the baseline, and an increase in about 900 million hectares of forestland. As in Sohngen and Mendelsohn (2003), carbon prices fall only modestly in the optimal scenario, by around 2-3% over the decade. With this small decrease in carbon prices, energy abatement costs decline by only 7%, or $66 billion, relative to the baseline case. Forestry has important implications for the temperature change experienced over the century. The increase in total abatement effort reduces the temperature change by the end of the century by about 0.2° C (2.39° C versus 2.59° C in the optimal case with energy only). This leads to a reduction in damages of $1,042 billion (Table 3). While the reduction in damages ordinarily would increase consumption over time, to get these benefits, society must spend money on the forestry program. In net, consumption declines modestly, by $29 billion. The sum of these benefit categories is therefore $1081 billion ($1042+$68-$29). The forestry program costs $1,062 billion, suggesting a benefit cost ratio of around 1.02 if all of these benefits are considered.

In the 2° C limiting scenario, carbon prices are substantially higher and the forestry program is substantially bigger, particularly towards the end of the century when the 2° C temperature limit ultimately becomes binding (Table 2). The size and scope of the forestry program in the 2° C limiting scenario is very similar to the optimal scenario for the first 40 years, however, it diverges after that as carbon constraints on the economy become more binding. From an economic perspective, the most important implication of the forestry program is that it reduces overall costs of meeting this very stringent temperature limitation dramatically. For example, when forestry is included as a control, carbon prices fall by over 50% over the century (Figure 2).

Due to the relatively large reduction in carbon prices, energy abatement costs fall substantially more than the optimal scenario, by 56%, or $2,679 billion in present value terms. Because both the scenarios with and without forestry have similar temperature profiles (due to the ultimate 2° C limit), the reduction in damages when comparing this case with and without the forestry program included is only $496 billion in this scenario. The change in consumption, however, is positive, and it amounts to an increase of $832 billion. The sum of these three benefits is $4,007 billion. The cost of the forestry program is $2,297 billion, suggesting a benefit cost ratio of 1.74 (Table 3).

These results have important implications for policy design. First, the results indicate that if policies are designed to incorporate forestry, the three primary forest actions can have strong effects on carbon prices when strict limits on emissions are in place. In the case of the 2° C limiting scenario, carbon prices fall by more than 50% when forestry is included in the global control strategy. A reduction in carbon prices by such a large amount would have enormous benefits for society by directly reducing compliance costs, and freeing resources for other productive investments. If society undertakes a much more modest control strategy closer to the optimal strategy in Nordhaus (2009), the market benefits are not as great, although forestry still provides benefits greater than the costs.

Figure 2: Carbon price paths under three scenarios (r=5%).

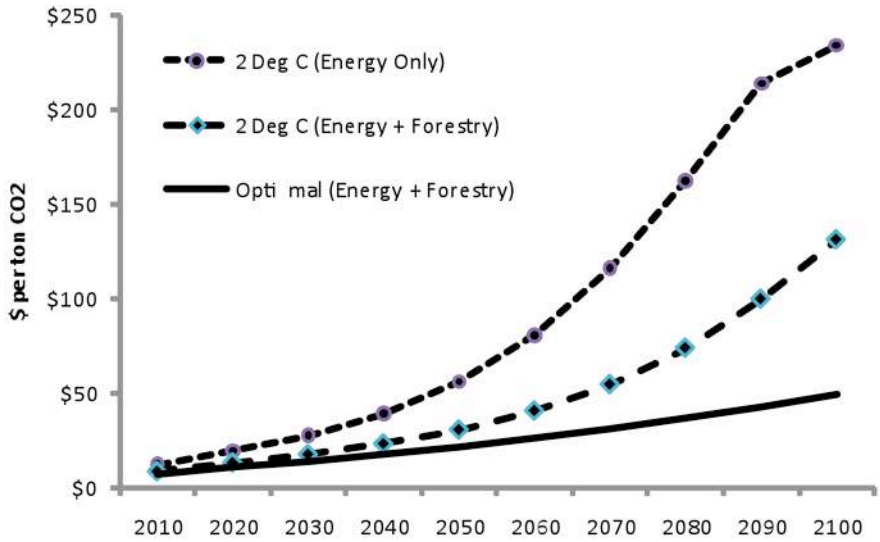


Table 4: Cumulative Abatement and proportion from forests and energy sectors under the two scenarios.

	2030	2050	2100
	Optimal		
Cumulative (Gt CO_2)	225	515	1616
% Forest	65%	52%	30%
% Energy	35%	48%	70%
	2 deg		
Cumulative (Gt CO_2)	238	575	2410
% Forest	63%	50%	34%
% Energy	37%	50%	66%

Table 5: Method of sequestration in temperature and tropical forests under the two policies

	Optimal			2° C Limiting		
	Temperate	Tropics	Total	Temperate	Tropics	Total
	Million tons CO_2 per year					
2020						
Afforestation	404	832	1,236	453	946	1,400
REDD	0	3,030	3,030	0	3,123	3,123
Management	1,273	13	1,286	1,429	1	1,430
Total	1,677	3,874	5,552	1,883	4,070	5,952
2050						
Afforestation	689	1,380	2,069	1,026	1,825	2,851
REDD	0	1,680	1,680	0	1,343	1,343
Management	632	1,732	2,364	964	1,720	2,684
Total	1,321	4,793	6,114	1,990	4,887	6,877
2100						
Afforestation	1,009	1,186	2,195	3,158	4,851	8,009
REDD	0	489	489	0	734	734
Management	1,497	897	2,393	5,404	1,043	6,448
Total	2,506	2,572	5,078	8,563	6,629	15,192

Second, forestry is not just a bridge to the future – it should be an important part of any control strategy across the entire century. Cumulative abatement required and the proportion accomplished by forestry and the energy sectors over the century is shown in Table 4. The pattern is similar under both control strategies (optimal and 2° C limiting). Forestry accomplishes roughly 64% of the total control by 2030, 50% by mid-century, and 34% by the end of the century. While the results do show how important it is to integrate a forest strategy into climate policy right away, the results also show that any forest policy should be enduring – that is, it should be something that lasts for an entire century. Building and maintaining carbon stocks in forests will be important for long-term climate stabilization.

Third, reductions in emissions from deforestation are the largest source of abatement in the first 20-30 years of the program (Table 5). REDD in tropical countries amounts to 52-54% of total abatement in the two scenarios in 2020. By 2050, REDD is still important, but it represents only about 15-25% of total abatement effort, and by the end of the century, it is a very small part of the total abatement effort. In contrast, afforestation grows in importance over time, rising from around 20% of the effort initially to over 50% of the effort by the end of the century.

Summary of Benefit Cost Estimates and Interest Rate Sensitivity

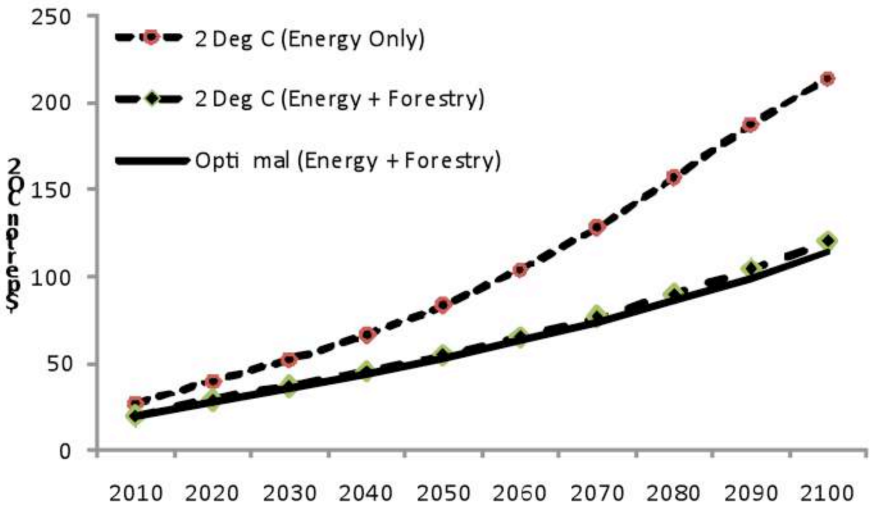
A summary of the estimates of benefits and costs under a "5%" interest rate assumption are shown in Table 3 for the scenarios described in the preceding section. One of the tricky issues associated with calculating the present value of benefits and costs in this study is that interest rates are an endogenous variable in the DICE model, and they change over time, while they are an exogenous variable in the forestry model and they are assumed to be fixed over time. The baseline assumptions for the DICE model resolve interest rates at about 5.6% initially, declining to about 5% by the end of the century. The forestry model uses a 5% interest rate in the baseline. The analysis uses the original assumptions on interest rates used in Nordhaus (2009), and a constant 5% interest rate for the forestry model for the baseline case. This scenario represents the "r=5%" assumption in Table 3.

To analyze a lower interest rate, several important parameters in the DICE model are changed. First, I assume that the pure rate of time preference is 0.1%, compared to the baseline assumption of 1.5%. Second, I changed the elasticity parameter on the utility function to 1.8, compared to a baseline level of 2.0. Under these assumptions, a new baseline is calculated with the DICE model. Interest rates are endogenous in this alternative scenario and they initially are at about the same level as the original baseline, 5.6%, but they fall more rapidly to a lower level of around 2.7% by 2100. They average about 3.0% over the first 150 years. In order to reflect lower interest rates in the forestry model, I shift the forestry model interest rate to 3% and hold that level constant (as before) in the forestry model. These alternative assumptions are used to calculate alternative scenarios, called the "r=3%" assumption. As before, interest rates are not set strictly at 3% in all periods in the DICE model, but they are lower in all periods than in the previous set of scenarios. The optimal policy and a 2 C limiting policy are both examined with and without forestry in the control, and the results are shown in Table 3.

It is not surprising that the value of the benefits and the value of costs are greater under the lower discount rate assumption than the higher discount rate assumption. Despite the change, the benefit cost ratios are similar to the 5% case. If forestry makes sense under the higher discount rate, it also makes sense under the lower discount rate. The benefit cost ratio in the 2ºC limiting case is slightly greater under the higher discount rate because forestry provides its most important benefits in the near-term, when the benefits of reducing expenditures on energy abatement are greatest.

Nordhaus (2009) discusses a number of important implications of the lower interest rate assumptions. Lower interest rates lead to more savings and lower productivity growth in the future than historically. Lower interest rates also lead to more climate control, e.g., carbon prices are higher, and forestry carbon sequestration is greater. One of the more interesting results of the lower interest rate scenario is that when forestry is included, the optimal scenario and the 2º C limiting scenario result in similar temperature trajectories, and similar carbon price paths under the lower interest rate assumption (Figure 3).

Figure 3: Carbon price paths under three scenarios (r=3%).



IMPLEMENTING FORESTRY SEQUESTRATION PROGRAMS

These results illustrate that forestry can be a cost-effective component of international climate policy. Any policy that tackles climate change should also tackle forestry and land use change. At a carbon price of $30 per ton CO_2, forestry could provide up to 6.7 billion tons CO_2 of annual net emission reductions globally. Around 42% of this carbon would be derived efficiently from avoided deforestation in the next 30-50 years, an additional 31% from forest management adjustments, and the rest from afforestation. The analysis of optimal policy design indicates that forestry has an important role to play whether the policy follows the optimal policy of Nordhaus (2009), who suggests an initial carbon tax of about $7.50 per t CO_2, rising at around 2-3% per year, or whether the policy attempts to place strict limits on temperature increases or carbon dioxide quantities in the atmosphere.

The surprising importance of forestry raises several “inevitable” questions about whether or not these estimates are even realistic. The results in this paper imply that society could sequester up to 151 billion tons CO_2 in forests by 2030 by shifting management, and by converting an additional 376 million hectares of land that would otherwise be used for crops into forests. Changes of this scale imply changing land use on 18-19 million hectares per year, or stopping 11 million hectares per year of tropical deforestation, and afforesting in the temperate zone by 7-8 million hectares per year. While we do not have much experience with government programs this large that have been successful, the experience of stopping and reversing deforestation in North America over the past century does suggest that markets can play an important role. In that case, reversion of croplands to forests in the Northeast, Southern, and Midwestern US resulted mainly from economic forces that lowered crop prices over time and increased opportunity costs of land in other uses (e.g., houses on woodlots). If market forces can be harnessed in the case of carbon, it is possible that a large land use change program could achieve the large-scale changes needed.

Assuming that a program of this, or smaller, scale is undertaken, how does one design such a program to actually obtain carbon? Won't problems like measuring, monitoring and verification ultimately become too expensive? Does society run the risk that other transactions costs will emerge that will ultimately raise costs to an unsustainable level? Won't leakage, additionality and permanence problems lead to large scale inefficiencies? The discussion below addresses these questions in turn, but the paper recognizes that many of these questions remain unanswered. Answering these questions actually represents the frontier of research on carbon sequestration through forests and forestry.

Measuring, Monitoring, and Verification

As discussed in the first section of the paper, a forestry carbon program can only work if a valid system of measuring, monitoring and verifying carbon credits on the landscape can be developed and implemented cost-effectively. While much is made of this issue, it actually seems to be fairly straightforward. Estimates of the costs of measuring carbon in biological systems are around $1-2 per t CO_2 (see Antinori and Sathaye, 2007; Antle et al 2003). These are important, but if carbon prices really are going to rise to the levels described in the scenarios above, measuring, monitoring and verification costs will represent only a small proportion of the total value of carbon in forests. Further one would expect these costs to decline over time as new methods are developed to measure and monitor carbon. It is likely that the actual costs of measuring, monitoring and verifying carbon will be no more than $1 per t CO_2 over the long run.

Transactions Costs

Transactions costs encompass other issues than measuring, monitoring and verification. Consider the following example. Given the sheer number of actors in the land using sectors, aggregators are likely to emerge. These aggregators will work with individual landowners to create carbon assets, and the aggregators will then bundle the carbon assets of individuals with carbon assets of other individuals. The aggregators will then sell the bundles to people who value the carbon. The activity of bundling is technical and administrative in nature, but it will use resources that will reduce the net value of the carbon asset to the landowner.

It is not yet clear how large or important the costs of this bundling activity will be. At first blush, one imagines that it could in fact be fairly large. The aggregators need to be fairly well trained, for instance, to know how to organize a measurement system of their own and implement it (or to evaluate some external measurement system). They need to have a working knowledge of accounting. They will need to be able to negotiate. Hiring individuals with all these talents could take real resources. Unfortunately, there simply are not many examples of programs that do what a carbon sequestration program is supposed to do, so it is hard to determine how extensive these activities will be. There are few studies so far that have examined how large transactions costs may be. One of the few is Cacho and Lipper (2007), who suggest that for projects involving many small landholders in developing countries, transactions costs for the buyers alone could be $5-$7 per ton CO_2, including MMV costs.

There is some information available from existing government programs in developed countries. For example, in the United States, the Conservation Reserve Program (CRP) is widely acknowledged as a successful government run program that has changed land use on over 12 million hectares in the US since the early 1980's. Sohngen (2008) estimates the costs of running the CRP in the US, and suggests that the transactions costs of that program, ignoring MMV costs, would amount to less than $2 per t CO_2. In the case of the CRP, the transactions costs include the costs of the government office-workers and engineers who do the work that aggregators do. This program likely presents a close analogy to the case of a government run program for carbon sequestration.

The United States, as a developed country, may be an optimal place to try a large-scale land use change program. Other regions of the world may be less suitable. Much has been made of the lack of tenure and secure property rights in many frontier regions where deforestation is occurring. If society is unable to secure the rights to maintain forests in those regions, or if large sums of money are squandered unsuccessfully in trying to do so, then society will not be able to rely on forestry to help mitigate climate change as projected above.

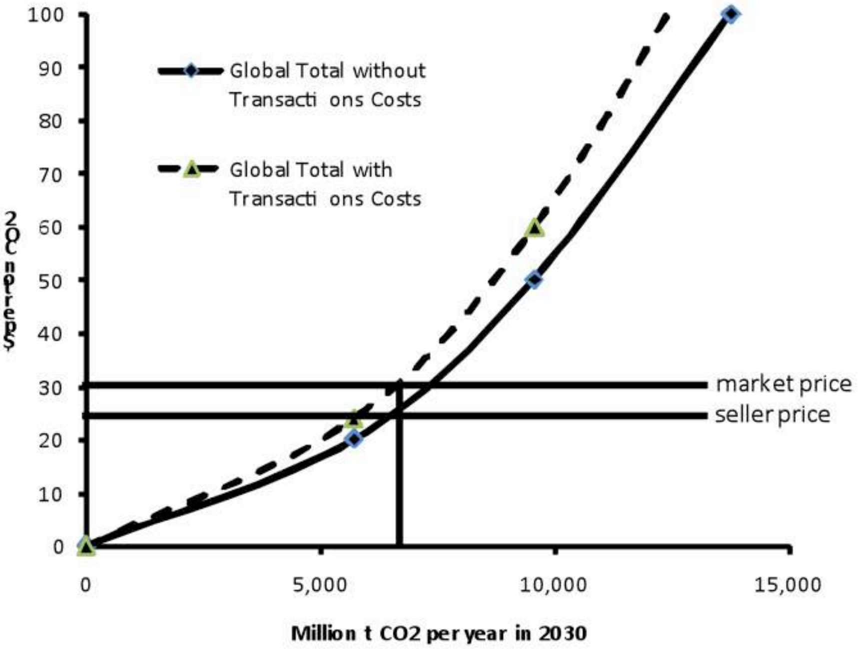
It is clearly useful to acknowledge that these difficulties could affect our ability to implement a large land-use change program in frontier regions where property rights are not well established, but it is also important to not over-sell these concerns. For relatively modest returns to grazing or growing marginal crops, landowners and others seem all too willing in these regions to convert land from one use to another. Imagine if there was a real market for standing forest stocks and those funds could make their way to the same decision makers. Carbon markets with carbon prices shown in Table 2 would generate land rents for forested land in tropical regions of greater than $400 per hectare per year in many regions. Such payments would provide exceedingly strong incentives to change land use, particularly when the marginal activity is grazing or some other currently low value use. They key likely lies less in designing government programs to pay for land use and more in figuring out clever ways to link the payments from demanders to those who actually control the land.

The main effect of MMV and transactions costs in markets will be to raise costs, but raising costs does not mean that forestry projects should not go forward. Accounting for the potential effect of transactions costs on the carbon sequestration programs can be done by shifting the cost functions. To the extent that transactions costs, including MMV costs, affect the market, they will insert a wedge between the market price and the price sellers receive. The DICE model resolves the market carbon price, and the forestry and land use model pays the carbon price to landowners. The price in the forestry model is thus the "seller price." Transactions costs will be eaten up by other institutions.

To account for these costs, the optimal and 2° C limiting scenarios are re-calculated with transactions costs included. The simplifying assumption that transactions costs represent 20% of the value of carbon on the market is made, e.g., the marginal cost curves are shifted upwards by 20%, as shown in figure 4. Thus, the price determined by the DICE model is reduced by 20% to determine the seller price, and this price is used in the forestry and land use model.

The results of the transactions costs scenarios are shown in columns A and B of Table 6 for the optimal and 2°C limiting scenario under interest rates of 5% only. Transactions costs do reduce total forest carbon sequestration in both scenarios. In the optimal scenario, forest carbon sequestration declines by 14% when the transactions costs are included, but forest

Figure 4: Global marginal cost curve for 2030 with and without transactions costs.



Transactions costs in this case are assumed to be 20% of the total costs. The without transactions costs marginal cost function shown here is the same as in figure 1.

Table 6: Benefit-cost estimates for the cases with transactions costs equaling 20% of the total cost of abatement.

	Col. A	Col. B	Col. C	Col. D
	Forest and Energy compared to Energy Only		Forestry Only compared to No Controls	
	Transactions Cost = 20% r=5%		Transaction Cost = 20%	
	Optimal	2º C Limit	r = 5%	r = 3%
	Billions US$ (present Value)			
Benefits				
Consumption Gain	($24)	$684	($52)	$1,128
Reduction in Damage	$901	$462	$946	$9,372
Reduction in Energy Costs	$66	$2,543	$0	$0
Total Benefit	$943	$3,690	$894	$10,501
Forest Cost	$917	$2,186	$917	$11,387
Benefit Cost Ratios				
All Benefits	1.03	1.69	0.97	0.92

Columns A & B compare a scenario with energy abatement only to a scenario with energy abatement and forestry sequestration. Columns C & D compare a no control scenario to a scenario that includes only forestry abatement.

carbon sequestration still amounts to 27% of the total (energy and forestry) abatement by the end of the century. In the 2° C limiting scenario, total forest carbon sequestration declines by 10% when transactions costs are included. Despite the transactions costs, benefits still outweigh costs in both the optimal and 2° C limiting scenario, and the benefit cost ratios are not substantially different than those shown in Table 3. This is perhaps surprising, at first glance, but note that if transactions costs are present, they reduce both the benefits and the costs. Costs are smaller because the less forestry carbon sequestration is obtained when transactions costs are present, and because the program is smaller, benefits decline. Because transactions costs reduce the benefits that landowners obtain by reducing the price they actually see for carbon (i.e., it is 20% less than the market price), transactions costs cause landowners to eliminate the highest cost (least "efficient") projects from the overall carbon sequestration portfolio. Thus, while transactions costs do have important implications– they reduce total carbon sequestration potential– they do not invalidate the use of forestry sequestration.

Additionality and Leakage

Much is made of additionality. Additionality is a problem because it is virtually impossible to determine, or know, what actions landowners will undertake with their land before the fact. We can perfectly well observe what they did with their land after the fact, but not before. However, the carbon we are actually interested in saving on the landscape is the carbon that someone actually will release into the atmosphere. Paying individuals who would not otherwise have released carbon to hold it raises the costs of a carbon sequestration program.

All of the cost estimates above assume that society is able to determine perfectly which carbon is truly additional. Obviously, there could be some additional costs associated with assessing the baseline for each person who enters a carbon contract. Such estimates have been undertaken for a number of different carbon projects (see Antinori and Sathaye, 2007 and Sohngen and Brown, 2004), so it is clearly plausible to determine baselines and use these estimates for contracting purposes. Estimating baselines and additionality would be considered to be part of the transactions costs discussed above, and thus already assessed in the paper.

Leakage is a far more important problem for carbon sequestration because it is unlikely that all countries will enter into a global climate treaty at the same time. Furthermore, many countries will have trouble developing system-wide carbon sequestration programs, so they will experience leakage within their boundaries. Because some countries remain outside the scope of the regulatory regime, and because some countries will develop programs that are geographically limited in scope, leakage will occur. Empirical estimates of leakage illustrate the seriousness of the problem. Estimates from the project level indicate that leakage could range from 10-90% (Murray et al. 2007). A recent paper by Sun and Sohngen (2009) using the same forestry model as used in this paper illustrates that leakage could be nearly 100% in the near-term under a global policy that seeks to set-aside forests with high carbon potential.

It is not possible to fully account for leakage in the benefit cost analysis framework used above because it is unclear which countries will and will not enter into a global climate treaty (and further, which countries will engage in carbon payments for trees). The optimal scenario and the optimization over the 2° C limiting scenario assume that all regions participate. This is an admittedly strong assumption, but it is maintained for all sectors in the analysis. The leakage problem in forestry, however, illustrates the problem with less than full action for carbon sequestration programs. All indications based on the current empirical analysis suggest that if countries do not participate in a global carbon sequestration program, significant inefficiencies could arise. These inefficiencies could be large enough to reduce benefit cost ratios to less than 1.0. It is thus important for policy makers to ensure that the largest possible number of countries is involved in the carbon sequestration program in order to avoid or reduce the scope for leakage.

Biofuels

Other policies will interact with forest based carbon sequestration in important ways. One important policy relates to biofuels. Current US and European legislation mandate increases in biofuel consumption. When considering these current policies, however, they are unlikely to have long-term consequences that are important for climate stabilization policy. Searchinger et al. (2008), for example, indicate that about 3.7 billion tons of additional CO_2 would be emitted as a result of the US and European biofuel mandates. While any increase in emissions is potentially bad, this is less than a year's worth of total emissions from deforestation. The results of Searchinger et al. (2008) certainly tell us that current biofuel policy is inefficient, but they do not suggest that biofuel policy as it is currently constructed will substantially raise the costs of climate mitigation via forests. On the contrary, if biofuel policies can be promoted so that each hectare of biofuel land provides an equal benefit to the atmosphere as a hectare of forests, then biofuel will be just as efficient a means to achieve climate policy as sequestration policies (or some combination of the two may be most efficient). Analyzing such policy is beyond the scope of this paper, although this will be important to examine in the future.

Forests alone?

One interesting question remains: how much could forestry do alone? As a "stand alone" option against climate change, can forestry substantially reduce climate change? To address this question, a final analysis is conducted in which the DICE model is run without any controls for 250 years, and then it is run with just forestry options and no energy abatement. Forestry is paid at the social cost of carbon calculated by the DICE model. The analysis is conducted for 5% and 3% interest rate cases, and in both cases, transactions costs of 20% are included in the analysis. The 2°C limiting case is not considered under these circumstances because it is not possible to use forestry alone to meet the 2°C limit.

The results of this analysis are presented in column C and D of Table 6. It turns out that if society decides to use just forestry, the benefit cost ratio is less than 1 under both interest rate assumptions. The benefit cost ratio is less than 1 in this case because there are no gains associated with avoiding or reducing energy costs (energy abatement is considered neither in the base, nor in the forest sequestration case). When the interest rate is 5%, the reduction in damages is at least greater than the costs of the forestry program, but consumption declines relative to the no control case, and the benefit cost ratio is only 0.97. The forestry program is the financial same size as under the optimal scenario with transactions costs (shown in Column A of Table 6) because the social cost of carbon is roughly the same in both scenarios.

These results show that, as a stand-alone policy for climate change, a large-scale forestry sequestration program is close, but it does not pass a benefit cost test. Forestry should be a complement with energy policy, but alone, forestry actions do not have a large enough effect on temperatures to substantially reduce damages. Under the optimal scenarios with only energy abatement, the temperature increase in 2100 is 2.59° C, and with forestry and energy together (assuming 20% transaction costs), the temperature change is 2.42° C in 2100. By the end of the century, when forestry is a complement to energy abatement, it has a 0.17° C effect on temperatures. Under the no control for 250 years case, the temperature change in 2100 is 3.05° C, but when forestry is included, the temperature change in 2100 is 2.90° C. When forestry acts alone, it has a smaller effect on temperatures.

CONCLUSION

This paper examines the potential for establishing a global forest carbon sequestration policy as part of a global effort to combat global warming. The paper begins by describing important categories to consider when measuring the costs of forestry carbon sequestration, including opportunity costs, implementation and management costs, MMV costs, other transactions costs and system-wide costs (e.g., leakage or impacts in other markets). Then, the paper briefly examines three forestry options— afforestation, forest management, and reductions in emissions from deforestation— and describes current cost estimates available in the literature. The economics of these options have been widely explored in the literature, and the paper describes the results of a number of studies considering the costs and quantity of carbon that may be sequestered in each of these activities. One issue noted in the paper, however, is that the current studies have focused largely on the opportunity costs and implementation and management costs. Other categories of costs have not been addressed as completely to date.

The current research indicates that the three key forestry activities can sequester large quantities of carbon. Over the next 30 years, the upper limit of potential sequestration could be as much as 15 billion tons CO_2 at more than \$100 per ton CO_2. At \$30 per ton CO_2, it may be possible to obtain around 6.7 billion tons CO_2 per year, with around 40% of this arising from avoided deforestation, 31% from forest management activities, and the rest from afforestation. A global sequestration program really is global, with potential contributions from virtually every region of the world. The largest share of sequestration is derived from avoided deforestation, but the roles of forest management and afforestation cannot be discounted.

To conduct benefit cost analysis, the paper combines a global forestry and land use model (which estimates carbon sequestration potential), with an integrated assessment model (which estimates the implications of this sequestration on carbon markets). Two global climate policies are considered in a "with" and "without" forest carbon sequestration comparison. One policy is the optimal policy suggested by Nordhaus (2009) and the other limits global carbon emissions such that global temperatures remain below 2° C over all time. Forestry turns out to be about 30% of the global abatement effort in each case. When carbon emissions are adjusted in a way to meet the 2° C limitation, the market implications are astounding. The inclusion of forestry in the control of greenhouse gases reduces carbon prices by 50%. This large reduction in compliance costs allows society to invest in other productive activities and provides a strong benefit in terms of increased consumption. The benefit cost ratio is 1.0 under the optimal scenario and 1.7 under the 2° C limiting scenario. The baseline interest rate is 5%, and sensitivity analysis is conducted over a lower interest rate, roughly 3%, does not alter these results. The benefit cost ratio in the optimal scenario is a bit bigger in the 3% case as the 5% case, but in the 2° C limiting scenario, the benefit cost ratio is about the same (1.7) in the 3% case.

The results establish the importance of including forestry and land use, but they also shown the importance of thinking long-term about these options. Forestry can provide carbon mitigation services in the near term through reductions in deforestation and increased forest management, but with the right incentives (e.g., rising carbon prices) it continues to provide mitigation services throughout the century. There is no evidence that the role of forestry saturates, in fact, in the 2° C limiting case, forestry becomes a larger and larger program throughout the century as the carbon constraint becomes more binding. The type of actions undertaken over the century will change, but forestry remains important.

Of course, it is also important to acknowledge that there will be difficulties associated with starting and running carbon sequestration programs. Measuring monitoring and verification protocols must be established and implemented. People will have to learn how to sell their carbon credits onto a market. There could be some inefficiencies associated with leakage and additionality. Based on the current literature, the known MMV costs plus other transactions costs appear to be less than $3 per ton CO_2. One of the problems with current cost estimates of forestry options is that these additional costs are often ignored. While it is beyond the scope of this paper to actually estimate these, the paper present additional scenario analysis taking potential transactions costs into account. The results of this analysis show that transactions costs will reduce the size of the forestry program, and some of the benefits will accrue to bureaucratic functions, but at the levels considered in the paper, transactions costs do not negate the central conclusions about the importance of forestry in a global climate policy.

The paper does not address questions related to leakage, particularly in the benefit-cost analysis framework, although literature review on this subject shows that it clearly will be a problem if climate policy is incomplete (e.g., some regions are left out of the control). This may be a bigger issue for forestry and land use than other abatement options because of the international nature of markets for end products. Given the scale of potential leakage, with some analyses suggesting that it could be as much as 90%, this represents one of the most important uncertainties to resolve. One related issue to leakage relates to impacts in other markets. For example, if forestland area increases over time and cropland area decreases, crop prices may rise, causing welfare losses in the food sector. This paper implicitly accounts for these impacts by using opportunity costs, although the full range of potential price impacts in the agricultural sector is not calculated here.

The paper also does not address the other benefits that would accrue with a forestry carbon sequestration program. Most of the forestry programs imply an increase in overall global forestland of up to 1.0 billion additional hectares over the century. From an ecological perspective, these forests would provide habitat for countless species, including many species that are presently endangered. Further, forest cover could help moderate water flows in large drainage basins and provide other hydrologic benefits. These benefits have not been quantified and addressed in this paper, although they certainly would be important.

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COPENHAGEN CONSENSUS ON CLIMATE

The science is clear. Human-caused global warming is a problem that we must confront.

But which response to global warming will be best for the planet? The Copenhagen Consensus Center believes that it is vital to hold a global discussion on this topic.

The world turned to scientists to tell us about the problem of global warming. Now, we need to ensure that we have a solid scientific foundation when we choose global warming's solution. That is why the Copenhagen Consensus Center has commissioned research papers from specialist climate economists, outlining the costs and benefits of each way to respond to global warming.

It is the Copenhagen Consensus Center's view that the best solution to global warming will be the one that achieves the most 'good' for the lowest cost. To identify this solution and to further advance debate, the Copenhagen Consensus Center has assembled an Expert Panel of five world-class economists – including three recipients of the Nobel Prize –to deliberate on which solution to climate change would be most effective.

It is the Copenhagen Consensus Center's hope that this research will help provide a foundation for an informed debate about the best way to respond to this threat.

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