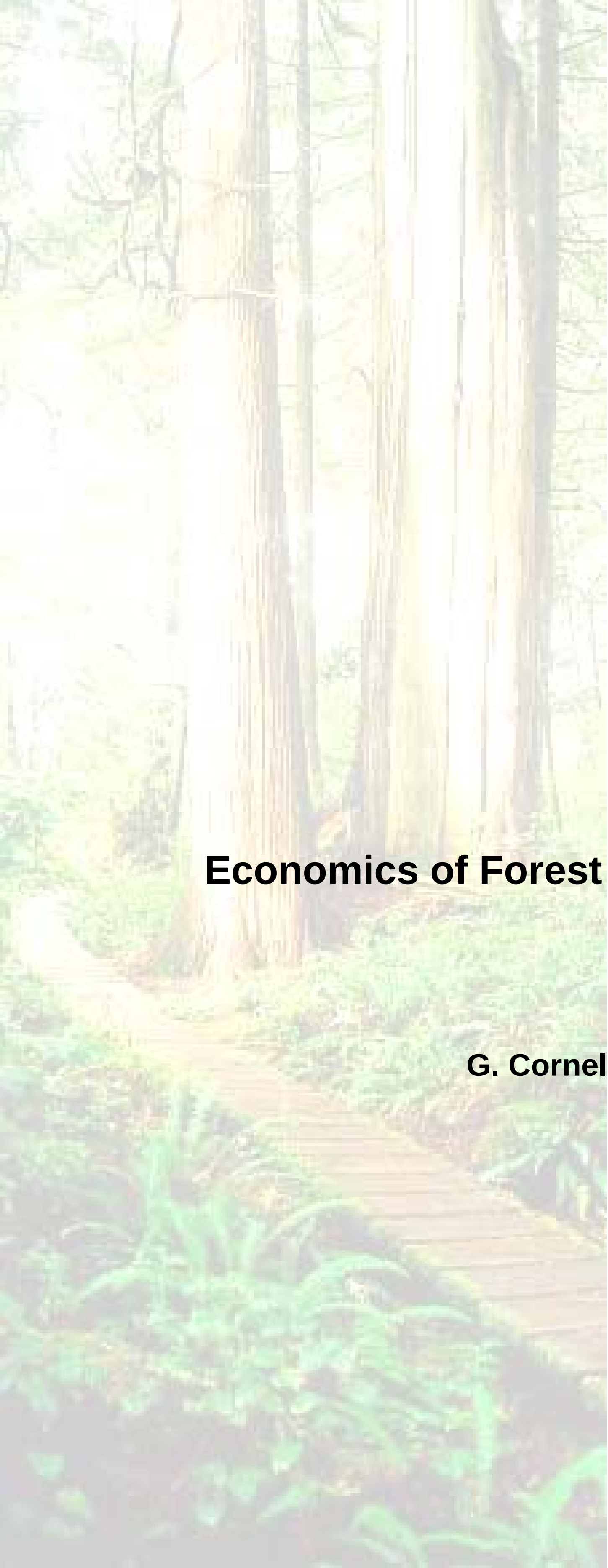

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# Economics of Forest Ecosystem Carbon Sinks: A Review

G. Cornelis van Kooten and Brent Sohngen

April 2007

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# Economics of Forest Ecosystem Carbon Sinks: A Review

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## Abstract

Carbon terrestrial sinks are seen as a low-cost alternative to fuel switching and reduced fossil fuel use for lowering atmospheric $CO_2$. In this study, we review issues related to the use of terrestrial forestry activities to create $CO_2$ offset credits. To gain a deeper understanding of the confusing empirical studies of forest projects to create carbon credits under Kyoto, we employ meta-regression analysis to analyze conditions under which forest activities generate $CO_2$-emission reduction offsets at competitive ‘prices’. In particular, we examine 68 studies of the costs of creating carbon offsets using forestry. Baseline estimates of costs of sequestering carbon are some US\$3–\$280 per $tCO_2$, indicating that the costs of creating $CO_2$-emission offset credits through forestry activities vary wildly. Intensive plantations in the tropics could potentially yield positive benefits to society, but in Europe similar projects could cost as much as \$195/$tCO_2$. Indeed, Europe is the highest cost region, with costs in the range of \$50-\$280 per $tCO_2$. This might explain why Europe has generally opposed biological sinks as a substitute for emissions reductions, while countries rush to finance forestry sector CDM projects. In Canada and the U.S., carbon sequestration costs range from a low of about \$2 to nearly \$80 per $tCO_2$. One conclusion is obvious: some forestry projects to sequester carbon are worthwhile undertaking, but certainly not all.

**Key Words:** climate change; Kyoto Protocol; meta-regression analysis; carbon-uptake costs; forest sinks

**JEL Code:** Q2, Q25, H43, C19

# Economics of Forest Ecosystem Carbon Sinks: A Review

## 1. Introduction

Scientists are widely enthusiastic about the potential of agricultural and forest ecosystems to provide options for removing carbon dioxide ($CO_2$) from the atmosphere that could obviate the need for lifestyle-changing reductions in fossil fuel use in mitigating climate change. Soil scientists, for example, claim that loss of soil carbon can be reduced and soil organic carbon (SOC) increased if farmers adopt recommended management practices (such as zero tillage and better management of crop residues), restore degraded soils, and convert marginal croplands to permanent grasslands or forests. This could offset 20% or more of countries' fossil fuel emissions (Lal 2004a, 2004b; Antle and McCarl 2002). Others think it is a foregone conclusion that biomass will make a major contribution to many countries' energy requirements, beginning in the not too distant future (Baral and Guha 2004). The only issues that seem to be up for debate concern the form of the energy currency (ethanol, biodiesel, biomass to generate electricity) and the source crop for biomass, whether wood, corn, hemp or crop residues (although use of crop residues conflicts with improved crop management to enhance SOC, water retention, etc.) (van Kooten 2004). Finally, there are the storage proponents who advocate locking carbon up in terrestrial ecosystems, abandoned oil and gas wells, or the deep oceans (including the dumping of all crop residues into the ocean) (Herzog et al. 2003; Keith 2001; Keith and Rhodes 2002).

Although there have been some prominent examples of carbon capture and storage (CCS), most notably in wells in Southern Saskatchewan and off the coast of Norway, we ignore this development and focus solely on terrestrial ecosystem sinks, particularly forest sinks, that involve removal of $CO_2$ from the atmosphere via plant/tree growth, storage of carbon in biomass, soils and post-harvest product pools, and post-harvest use of biomass as energy. The reason for ignoring CCS is that little is known about its costs, including the cost associated with the future risk of a sudden release of $CO_2$ that kills a significant number of people – a cost evaluated by the willingness of people to pay to avoid such a risk and not unlike that associated with long-term storage of nuclear waste, which Riddel and Shaw (2003, 2006) indicate could be substantial.

The Kyoto Protocol (KP) explicitly permits and even appears to encourage countries and/or firms to use terrestrial carbon offset credits in lieu of emissions reductions during the first commitment period (2008-2012). But in this review we argue that, while terrestrial offset credits can potentially reduce the need to limit $CO_2$ emissions from fossil fuel in the short term, serious problems are associated with managing and implementing a $CO_2$ trading system that includes terrestrial sinks, and sinks are likely more expensive than initially recognized. We begin in the next section with a background discussion of how carbon sinks entered into the Kyoto picture to begin with. This is followed, in section 3, with an analysis of the problems that $CO_2$ offset credits from forest activities pose for $CO_2$ trading schemes under Kyoto. In section 4, we provide a broad-brush overview of studies that have examined the costs of creating $CO_2$-offset credits, arguing that, despite numerous studies, estimates are largely inconsistent. The evidence that does exist indicates that costs of some forest sink projects are significantly higher than originally anticipated, so much so that emissions reductions are a cheaper alternative. This does not imply, however, that sinks should be ruled out entirely, as costs are low enough in some circumstances to justify their use. Finally, in section 5, we employ meta-regression analysis using 68 studies to say something more definitive about the costs of creating $CO_2$ offsets via forestry activities. Some concluding remarks ensue.

## 2. Background to Carbon Terrestrial Sinks

The December 1997 Kyoto Protocol requires industrialized countries to reduce $CO_2$-

equivalent greenhouse gas emissions[1] by an average 5.2% from the 1990 level by 2008-2012, or by some 250 megatons ($10^6$ metric tons) of carbon, denoted Mt C, or 920 Mt $CO_2$ per year. Land use, land-use change and forestry (LULUCF) activities can lead to carbon offset credits or debits.[2] Such offsets have taken on great importance under the KP despite the EU-15's initial opposition to their inclusion. As a result, carbon offsets need to be taken into account in any $CO_2$ trading scheme. The Marrakech Accords of November 2001 lay out the basic legal framework for including offset credits (Hannam 2004; IPCC 2001). Tree planting and activities that enhance tree growth clearly remove carbon from the atmosphere and store it in biomass, and thus should be eligible activities for creating carbon offset credits. However, since no industrial countries had embarked on large-scale afforestation and/or reforestation projects in the past decade, harvesting trees during the five-year KP commitment period (2008-2012) will cause them to have a debit on the afforestation-reforestation-deforestation (ARD) account. Thus, Marrakech permits countries, in the first commitment period only, to offset up to 9.0 Mt C (33 Mt $CO_2$) each year through (verified) forest management activities that enhance carbon uptake. In the absence of any ARD debit, a country cannot generally claim this credit. Yet, some countries were permitted to claim carbon credits from business-as-usual forest management that need not be offset against ARD debits. Canada can claim 12 Mt C (44 Mt $CO_2$) per year, the Russian Federation 33 Mt C (121 Mt $CO_2$), Japan 13 Mt C (48 Mt $CO_2$), and other countries much lesser amounts. Of course, countries can simply choose not to include LULUCF activities in their calculations of base and first commitment period emissions.

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[1] Carbon dioxide ($CO_2$), methane ($CH_4$), nitrogen oxide ($N_2O$), hydrofluoro-carbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride ($SF_6$) are the principal greenhouse gases that the FCCC seeks to control. They are collectively referred to as $CO_2$-equivalent gases.

[2] Carbon uptake in biological sinks is measured in units of carbon (C), while emissions reductions are measured in units of $CO_2$. We convert between these measures where appropriate in order to facilitate easy comparisons between costs of removing $CO_2$ from the atmosphere (carbon sequestration) and reducing emissions of $CO_2$. Based on molecular weight, 44 $tCO_2$ contain 12 tC.

Agricultural activities that lead to enhanced soil organic carbon and/or more carbon stored in biomass can also be used to claim offset credits. Included are revegetation (establishment of vegetation that does not meet the definitions of afforestation and reforestation), cropland management (greater use of conservation tillage, more set asides), and grazing management (manipulation of the amount and type of vegetation and livestock produced). Since $CO_2$ emissions and terrestrial carbon sequestration, broadly defined, do not have equivalent impacts on the atmosphere, the Marrakesh Accords placed an overall cap of 219 Mt C (803 Mt $CO_2$) on the amount of carbon that could be sequestered annually in biological sinks.

The potential of biological sinks to meet KP targets is indicated in Table 1. From the table, it is clear that Marrakesh potentially allows countries to claim nearly 195 Mt C (715 Mt $CO_2$) of offset credits through LULUCF activities, or about three-quarters of industrialized countries' KP-mandated 251 Mt C (920 Mt $CO_2$) reduction from base-year emission levels. That is, countries could meet their $CO_2$-emission reduction targets almost entirely with biological sinks. The IPCC (2000) further estimates that biological sinks have the potential to mitigate some 100 gigatons ($10^9$ metric tons) of carbon (denoted Gt C), or 367 Gt $CO_2$, between now and 2050, amounting to 10-20% of fossil fuel $CO_2$ emissions over the same period.

## 3. Terrestrial Carbon Sinks: Issues

Efforts to include terrestrial carbon sequestration have caused significant confusion over the years. The essential problem is that countries have, through negotiations, treated forests solely as sink opportunities, and not as potential emission sources whose emissions need to be capped. This philosophical approach pervades the rules established under Kyoto and the subsequent Marrakech Accords. There it was recognized that national-level estimates of annual net emissions or uptake by forests could only be measured with great uncertainty. Parties to the

KP could decide to measure carbon changes over time on existing forests, and those changes (if positive) could be credited against emissions elsewhere in the economy. In addition, countries could count credits by planting trees on previously un-forested land, which would yield even greater credits than activities on existing forestland. Similarly, there was great hope that reforestation and afforestation projects in non-industrial (developing) countries could meet the same standards as those in industrial countries, and thus be included under the KP's Clean Development Mechanism (CDM).

The failure to treat forests like other potential emission sources has had several important consequences. First, it contributed to an international project-based approach that fails to take into proper account additionality, monitoring and leakage issues (discussed below); this failure cannot be taken lightly in the current policy context where environmental groups are keen to ensure that atmospheric concentrations of $CO_2$ truly decline. These problems are unlikely to disappear with legitimate national-level accounting for forest carbon, because countries may themselves adopt project-based approaches. Thus, it has caused confusion about the legitimacy of carbon sequestration opportunities. Properly measured, rising stocks of carbon in biomass would reduce $CO_2$ in the atmosphere, but developing proper measures when looking only at specific projects is difficult at best (as discussed below). Second, the pace of developing legitimate measuring and monitoring systems at the national level has been extremely slow. Third, large international bureaucracies have been developed to ensure the legitimacy of carbon credits, but this has greatly increased transaction costs. Thus, for example, forestry projects in developing countries need approval from the CDM Executive Board, but the first such project was only accepted in November 2006 (UNFCCC 2006).[3] Legitimacy is clearly a worthy goal,

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[3] The report is an exercise in obfuscation. It describes a 30-year project to establish 2,000 ha of multiple-use forests on degraded lands in China that will sequester 773,842 $tCO_2$ (about 25,800 $tCO_2$ annually) at a

but society may be better served with well-designed national monitoring systems wherever carbon sequestration is valued.

### *Additionality, Monitoring and Leakages*

In principle, a country should get credit only for carbon uptake over and above what occurs in the absence of carbon-uptake incentives, a condition known as 'additionality' (Chomitz 2000; Garcia-Oliva and Masera 2004).[4] Thus, if it can be demonstrated that a forest would be harvested and converted to another use in the absence of specific policy to prevent this from happening, the additionality condition is met. Carbon sequestered as a result of incremental forest management activities (e.g., juvenile spacing, commercial thinning, fire control, fertilization) would be eligible for carbon credits, but only if the activities would not otherwise have been undertaken (say, to provide higher returns or maintain market share). Similarly, afforestation projects are additional if they provide environmental benefits (e.g., regulation of water flow and quality, wildlife habitat) not captured by the landowner and would not be undertaken in the absence of economic incentives, such as subsidy payments or an ability to sell carbon offset credits.

It is difficult at best to determine whether an activity is truly additional. For example, farmers have increasingly adopted conservation tillage practices because costs of chemicals to control weeds have fallen, fuel and certain machinery costs have risen, and new cultivars reduce the impact of yield reductions associated with conservation tillage. If farmers adopt conservation tillage practices in the absence of specific payments for carbon uptake, they should not be provided with offset credits. Likewise, farmers who have planted shelterbelts should not be

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cost of about \$2.15/t$CO_2$. While the timing of carbon uptake is provided (although uncertainty about tree growth is ignored), there is no information about the timing of outlays and revenues, how temporary offset credits exchange for permanent ones, and $CO_2$ release after 30 years.

[4] Clearly, the ARD credits provided under Marrakech to industrial countries such as Canada are not additional because they credit incremental tree growth from ongoing forest management activities.

provided carbon subsidies unless it can be demonstrated that such shelterbelts are planted for the purpose of sequestering carbon and would not otherwise have been planted.

Determining whether large-scale tree planting projects are additional may be difficult. During the 1980s, Canada embarked on a major program to replant forestlands that had previously been harvested but had not regenerated 'valuable' species within a 15-year period. These lands were considered not sufficiently restocked, and substantial investments were made to clear weed species and establish more desirable ones. Had those trees been planted after 1990, the activity would have been eligible for carbon offset credits. Yet, this was clearly not an 'additional' activity. What is clear is that the international community is on a slippery slope when sanctioning creation of carbon offsets from tree planting activities – many such credits are nothing more than 'smoke and mirrors' enabling countries and firms to claim compliance with Kyoto requirements when they have not made sufficient efforts to reduce $CO_2$ emissions.

A cursory investigation indicates that there are now many 'traders' selling $CO_2$ offsets that enable individuals or companies to claim that their activities are carbon neutral. In some cases, traders sell opportunities to participate in tree planting projects. Examples include:

- Greenfleet (http://www.greenfleet.com.au/greenfleet/objectives.asp, viewed 3 Nov 2006): a project to plant native species in Australia;
- Trees for Life (http://www.treesforlife.org.uk/tfl.global_warming.html, viewed 3 Nov 2006): a conservation charity dedicated to the regeneration and restoration of the Caledonian Forest in the Highlands of Scotland; and
- Haida Gwaii Climate Forest Pilot Project (http://www.haidaclimate.com/, viewed 3 Nov 2006): a First Nation project to replant logged over areas and re-establish ancient old-growth forest.

While some of these ‘projects’ are certified, so that the buyer knows that carbon is truly being sequestered, it is not clear that these projects are truly additional. Given that the Haida Gwaii are committed to restoring ancient forests because they are part of their cultural heritage, and that Trees for Life is committed to restoring the Caledonian Forest, the sale of carbon credits is no more than a marketing technique to solicit funds for a project that would proceed in any event. Such projects would be additional only if they would not proceed in the absence of $CO_2$ offset payments, and that is difficult to demonstrate.

The question of additionality becomes more complex when one entertains the notion of co-benefits. Co-benefits may include wildlife benefits, habitat or water quality improvements, and other amenities that occur with carbon-enhancing forestry projects (see, e.g., Plantinga and Wu 2003). Current programs that seek to alter land use in order to provide benefits other than carbon sequestration, such as the Conservation Reserve Program in the U.S., would not provide additional carbon benefits simply because the land-use changes these programs bring about would have occurred without carbon payments. However, numerous programs or activities might not pass a benefit-cost test without consideration of their carbon benefits (e.g., payments for conservation tillage or private habitat restoration undertaken by non-governmental agencies like The Nature Conservancy). In these cases, carbon is a valuable co-benefit and carbon financing may in fact provide a valuable vehicle for accomplishing the project.[5]

In addition to determining whether a LULUCF project is indeed additional, it is necessary to determine how much carbon is actually sequestered and for how long. Measuring carbon uptake is a difficult task and can be even more difficult if the carbon sink is short lived. Monitoring and enforcement are costly and measurement is an inexact science in the case of

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[5] Of course, this raises among others the issue of determining when to include co-benefits, and how to measure them. Given the complexity of the co-benefit subject, we do not address it further here.

carbon sequestration. Research reporting differences in soil organic carbon between conventional and conservation tillage practices, for example, finds that these depend on soil type, the depth to which soil carbon is measured, location, and other factors (Manley et al. 2005). But if SOC needs to be constantly measured and monitored, as appears likely for more ephemeral sinks (grasslands, short-rotation tree plantations, etc.), transaction costs could greatly exceed the value of the sequestered carbon.

Payments that promote direct changes in land uses for the purpose of carbon sequestration often result in indirect changes in land use that release $CO_2$, something known as a 'leakage'.[6] Leakage estimates for forestry projects are exceedingly wide (5% to 93%), suggesting that project developers need to consider carefully leakages when designing carbon sequestration projects (Murray et al. 2004; Sohngen and Brown 2004).[7] Leakages are often ignored when individual projects to create terrestrial offset credits are evaluated, but failure to include a 25% leakage factor, for example, underestimates costs by one-third (Boyland 2006). Nonetheless, leakages are generally ignored in bottom-up (or engineering cost) analyses. Since top-down models take into account changes in prices and, thereby, indirect effects on land use, one would expect estimates of carbon uptake costs from bottom-up (technology) models to be lower than those from top-down models. We investigate whether this is the case in our meta-regression analysis (section 5).

*Discounting Physical Carbon*

By discounting carbon, one acknowledges that it matters when $CO_2$ emissions or carbon uptake occur – $CO_2$ removed from the atmosphere (emissions avoided) today is more important

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[6] Examples of leakage occur at the micro and macro levels. At the micro-level, a landowner who is paid to plant trees might compensate for the loss in agricultural output by cutting trees at another location. At a macro-scale, tree planting causes agricultural output to decline, raising prices and causing landowners to expand cultivation onto marginal lands currently in permanent pasture or forest, thereby releasing $CO_2$.

[7] Leakage estimates for conservation tillage are substantially less than this (Pattanayak et al. 2005).

and has greater potential benefits than that removed (avoided) at some future time. Yet, the idea of discounting physical carbon (or $CO_2$) is anathema to many who would discount only monetary values. However, the idea of weighting physical units accruing at different times is entrenched in the natural resource economics literature, going back to economists' definitions of conservation and depletion (Ciriacy-Wantrup 1968). One cannot obtain consistent estimates of the costs of carbon uptake unless both project costs and physical carbon are discounted, even if different rates of discount are employed for costs and carbon (Boyland 2006). This is easy to demonstrate with an example where a project involves two or more sources of carbon flux with different time paths (see van Kooten 2004, pp.76-77).

The rate at which physical carbon should be discounted depends on what one assumes about the rate at which the damages caused by emissions of $CO_2$ increase over time (Herzog et al. 2003; Richards 1997a; Stavins and Richards 2005). If the damage function is linear so that marginal damages are constant – damages per unit of emissions remain the same as the concentration of atmospheric $CO_2$ increases – then the present value of reductions in the stock of atmospheric $CO_2$ declines at the social rate of discount. Hence, it is appropriate to discount future carbon uptake at the social rate of discount. "The more rapidly marginal damages increase, the less future carbon emissions reductions should be discounted" (Richards 1997a, p.291). The use of a zero discount rate for physical carbon is tantamount to assuming an exponential damage function with damages growing at the same rate as the social rate of discount. A zero discount rate on physical carbon implies that there is no difference between removing $CO_2$ from the atmosphere today, tomorrow or at some future time; logically, then, it does not matter if the $CO_2$ is ever removed from the atmosphere. The point is that use of any rate to discount physical flows of carbon depends on what one assumes about the marginal damages from further $CO_2$ emissions or removals from the atmosphere.[8]

The effect of discounting physical carbon is to increase the costs of creating carbon offset credits because discounting effectively results in 'less carbon' attributable to a project. Discounting financial outlays, on the other hand, reduces the cost of creating carbon offsets. However, since most financial outlays occur early on in the life of a forest project, one expects that the costs of creating carbon offsets are not as sensitive to the discount rate used for costs as to that used for carbon.

### *The Ephemeral Nature of Sinks*

Agricultural and forestry sequestration activities result in carbon storage that is, at best, ephemeral. One study found, for example, that all of the soil organic carbon stored as a result of 20 years of conservation tillage was released in a single year of conventional tillage (Lewandrowski et al. 2004). Likewise, tree plantations will release a substantial amount of their stored carbon once harvested, which could happen as soon as five years after first planting if fast-growing hybrid species are grown. Compared to not emitting $CO_2$ from a fossil fuel source, terrestrial sequestration of carbon is unlikely to be permanent.[9] This poses a particular challenge

The Kyoto process attempts to balance competing views of how best to address the non-permanence of terrestrial carbon uptake. Emissions and removals should be treated identically because there is no difference between 'removal' of $CO_2$ from the atmosphere and 'avoidance' of equivalent $CO_2$ emissions. The problem is that, once the $CO_2$ is removed and sequestered in a biological sink, release at a future date remains a very real possibility. But a counter argument is

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[8] There are other reasons for discounting, such as increasing uncertainty about whether the carbon will continue to be sequestered or not. Here, however, we simply consider a physical ton of carbon sequestered at a future date to be weighted less than one ton sequestered now.

[9] This is not to suggest that carbon sinks are not worthwhile. Temporary removal of carbon helps postpone climate change, buys time for technological progress, buys time to replace fuel-inefficient capital equipment, allows time for learning, and may lead to some permanent sequestration as the new land use continues indefinitely (Marland et al. 2001).

that, by leaving fossil fuels in the ground, their eventual use is only delayed and, as with carbon sequestered in a terrestrial sink, results in the same obligation for the future (Herzog et al. 2003).[10] Both these problems can be resolved by providing a credit whenever carbon is sequestered ($CO_2$ is removed from the atmosphere) and a debit whenever it is released. Even a project that sequesters carbon for a short period can provide benefits to the atmosphere and to an energy emitter during the time it is sequestered. For instance, a company may find it economically optimal to put off investments in emissions reductions by renting forest offset credits.

Whatever the case, carbon sequestered in a sink creates a liability for the future, with countries needing to insure that carbon entering a sink in the first commitment period is somehow covered (or still in place) in second, third and later commitment periods. Currently this is not a serious problem for a country, because the liability can be factored into a country's self-declared future commitment to emissions reductions, but it could become a problem if countries commit further into the future. It also implies continual monitoring as opposed to some initial determination of the carbon sequestration potential.

The ephemeral nature of terrestrial carbon uptake can be addressed by providing partial instead of full credits for stored carbon according to the perceived risk that carbon will be released from the sink at some future date. The buyer or the seller may be required to take out an insurance policy, where the insurer will substitute credits from another carbon sink at the time of default. Alternatively, the buyer or seller can provide some assurance that the temporary activity will be followed by one that results in permanent emissions reductions. For example,

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[10] Herzog et al. (2003) admit that fossil fuels left in the ground may not be used at some future date if society commits to de-carbonize energy, while carbon in a terrestrial sink always has the potential to be released in the future. The bigger problem of reduced fossil fuel use by some is that it causes others to use more since prices are lower (a type of leakage), while lower prices discourage new sources of energy.

arrangements can be put in place prior to the exchange that, upon default or after some period of time, the carbon sink offsets are replaced by purchased emissions reductions, an extension of the temporary credits, or new carbon sinks in the future. Again, insurance contracts can be used. Insurance can also be used if there is a chance that the carbon contained in a sink is released prematurely (e.g., due to wildfire). It is also possible to mark down the number of offset credits by the risk of loss (e.g., a provider may need to convert more land into forest, say, than needed to sequester the agreed upon amount of carbon).[11]

Three 'practical' approaches to non-permanence of sinks have been discussed in the literature. One is to specify a conversion factor that translates years of temporary carbon storage into a permanent equivalent. The concept of ton-years has been proposed to make the conversion from temporary to permanent storage (Dutschk 2002; Herzog et al. 2003; IPCC 2000). Suppose that one ton of $CO_2$ emissions are to be compensated for by a ton of permanent $CO_2$ uptake. If the conversion rate between ton-years of (temporary) $CO_2$ sequestration and permanent tons of $CO_2$-emission reductions is $k$, a LULUCF project that yields one ton of carbon uptake in the current year generates only $1/k$ tons of emission reduction – to cover the one ton reduction in emissions requires $k$ tons of $CO_2$ to be sequestered for one year.[12] The exchange rate ranges from 42 to 150 ton-years of temporary storage to cover one permanent ton.

Many observers have condemned the ton-year concept on various grounds. Herzog et al. (2003) argue that the value of storage is based on the arbitrary choice of an exchange rate, which is based on forest rotation age and has nothing to do with a scientific comparison of the effectiveness of temporary versus permanent removals of $CO_2$ from the atmosphere. On the other

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[11] This would be equivalent to increasing the rate used to discount physical carbon.

[12] This interpretation is slightly different from the original intent. The original idea is to count a temporary ton as equivalent to a permanent one only if the carbon is sequestered for the full period of time given by the exchange rate. The advantage of the interpretation here is that it enables one to count carbon stored in a sink for periods as short as one year (as might be the case in agriculture).

hand, Marland et al. (2001, p.266) point out that the ton-year accounting system is flawed because ton-year credits (convertible to permanent tons) can be accumulated while trees grow, but can be counted as a credit a second time if the biomass is subsequently burned in place of an energy-equivalent amount of fossil fuel, where the credit is the saving in $CO_2$ emissions from not burning fossil fuels. Yet, the concept of ton-years has a certain appeal, primarily because it provides a simple, albeit naïve, accounting solution to the problem of permanence. The choice of an exchange rate is somewhat arbitrarily based on rotation length, and hence a political decision in many ways, but so is much of climate change policy. Once an exchange rate is chosen, carbon uptake credits can be traded in a $CO_2$-emissions market in straightforward fashion. Yet, the ton-years approach has been rejected by some countries, primarily because it disadvantages carbon sinks relative to emissions avoidance (Dutschke 2002).

A second approach discussed extensively has been the notion of a 'temporary' carbon emission reduction unit, denoted TCER. The idea is that a temporary offset credit is purchased for a set period of time (say, one year or five years). Upon expiry, TCERs would have to be covered by substitute credits or reissued credits if the original project were continued. Compared to ton-years, monitoring and verification are more onerous because a complex system of bookkeeping will be required at the international level to keep track of credits. Countries favor this approach over other approaches because they can obtain carbon credits early, while delaying 'payment' to a future date. In essence, a country that uses TCERs to meet its $CO_2$-emissions reduction target in Kyoto's first commitment period (2008-2012) defers its obligations to future commitment periods. In the future period, the country must cover the current obligation to reduce emissions (which it has not yet done as TCERs have expired by then) plus any additional emissions reductions for following commitment periods.

A third approach to the problem of temporary versus permanent removal of $CO_2$ from the atmosphere is to employ a market device that would obviate the need for an arbitrary conversion factor or other forms of political maneuvering. Marland et al. (2001) and Sedjo and Marland (2003) propose a rental system for sequestered carbon. A one-ton emission offset credit is earned when the sequestered carbon is rented from a landowner, but, upon release, a debit occurs. "Credit is leased for a finite term, during which someone else accepts responsibility for emissions, and at the end of that term the renter will incur a debit unless the carbon remains sequestered and the lease is renewed" (Marland et al. 2001). In addition to avoiding the potential for double counting, the landowner (or host country) would not be responsible for the liability after the (short-term) lease expires. The buyer-renter employs the limited-term benefits of the asset, but the seller-host retains long-term discretion over the asset.

Rather than the authority establishing a conversion factor, the interaction between the market for emission reduction credits and that for carbon sink credits determines the conversion rate between permanent and temporary removals of $CO_2$ from the atmosphere. The rental rate for temporary storage is based on the price of a permanent energy emissions credit, which is determined in the domestic or international market. Assuming carbon prices are constant, the annual rental rate ($q$) is simply the market-determined price of a permanent emission credit ($P$) multiplied by the discount rate ($r$), which equals the established financial rate of interest (if carbon credits are to compete with other financial assets) adjusted for the risks inherent to carbon uptake (e.g., fire risk, slower than expected tree growth, etc.). Thus, $q = P \times r$, which is a well-known annuity formula. If emissions are trading for \$15 per $tCO_2$, say, and the risk-adjusted discount rate is 10%, then the annual rental for a terrestrial offset credit would be \$1.50 per $tCO_2$. If carbon prices were rising over time, the value of temporary carbon credits would be eroded.

Like the ton-year concept, a rental scheme makes terrestrial sink projects less attractive relative to emissions reduction (e.g., Chomitz and Lecocq, 2004; Keeler, 2005).

Notice that a rental system of the type proposed by Sedjo and Marland (2003) works best if we are dealing with credit trading as opposed to allowance trading. Under a cap-and-trade scheme (allowance trading), it would be necessary to set not only a cap on emissions from fossil fuel consumption, but also a cap on terrestrial carbon sinks (see van Kooten 2004, pp.34-37). In that case, one might expect separate markets to evolve for emissions and carbon sink allowances.

## 4. Forest Activities that Generate Carbon Offsets

In an uncertain world, knowledge about the costs of sequestering and storing carbon in forest ecosystems is useful if we are to have some idea regarding the potential supply of forest $CO_2$-offset credits in international markets. However, research on carbon sequestration is relatively young. Starting in the late 1980s, many U.S. researchers began studying the potential and costs of afforestation activities for sequestering carbon. Most early cost estimates were in the range of $US 1 to $US 50 per ton of carbon (tC), or $0.27 to $13.64 per ton of $tCO_2$.[13] For example, Dixon et al. (1994) estimated the cost to range from $4 to $41 per tC ($1.09-$11.18/$tCO_2$) in Brazil, while Masera et al. (1995) estimated it to be $10-$35/tC ($2.73-$9.55/$tCO_2$) in Mexico. Point estimates of carbon sequestration costs were and are widely used in developing country studies, with analyses have been carried out in China (Xu 1995), Brazil (Fearnside 1995), and India (TERI 1997; Poffenberger et al. 2001), among others.

More sophisticated studies have subsequently appeared, but, for a variety of reasons, significant differences and uncertainties surround specific quantitative estimates of mitigation costs (IPCC 2001). Current economic studies employ three methods to obtain carbon uptake and

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[13] US$ are employed throughout. To convert to $ per $tCO_2$, multiply $/tC by 12 tC/44 $tCO_2$.

storage estimates: bottom-up engineering cost studies, sector optimization models that seek to account for behavioral responses in the forest and agricultural sectors, and econometric analyses of the revealed preferences of landowners concerning the use of their land for alternative purposes, including forestry and agriculture (Stavins and Richards 2005). But neither the sector optimization nor econometric approaches can be considered true top-down methods, although they do contain elements of a top-down approach as discussed below.

Bottom-up studies calculate the cost-effectiveness of specific investments in various forestry activities, whether tree planting (usually afforestation), forest management or post-harvest utilization of wood fiber, or all three. The scope of 'projects' ranges from single plot to regional to global, although technological options usually confine projects to a particular geographical region (Moulton and Richards 1990; Dudek and Leblanc 1990; New York State 1991). Studies provide calculations of the costs of the activity (or activities) and the amount of carbon sequestered. At noted below, the main cost component relates to the opportunity cost of land, with researchers using a variety of estimates (e.g., land rental rates, annualized land prices) or ignoring land costs entirely due to the difficulty of finding appropriate data (which occurs in some jurisdictions). The treatment of carbon yields and the timing of capture are also not standardized in bottom-up studies. In general, financial costs and returns from harvest (if any) are discounted. Net discounted costs are then divided by the sum of total carbon sequestered over the life of the project or some discounted sum of total carbon uptake; or costs are annualized and divided by annual carbon uptake. Often the average and not marginal cost of the project is calculated, which will overestimate the amount of $CO_2$ sequestered for a given price.

Another approach that avoids the need to discount physical carbon sets the present value of the costs of a project (up-front implementation costs plus annual rental costs, monitoring costs, etc.) equal to the present value of project benefits (value of carbon multiplied by quantity of carbon).[14] The value of carbon is unknown, but is implicitly the marginal cost in each period, which can vary over time. For the project developer, the value of carbon is the opportunity cost of the next best alternative for avoiding emissions each year. The problem with marginal cost estimates is that we do not know the path of future marginal costs, but we require a point estimate today for a particular project. In effect, one calculates the 'break-even' carbon price – the carbon price for which the net present value of the project is zero (see, e.g., McKenney et al. 2004; Yemshanov et al. 2005).

Under this approach, project managers are in essence assessing the following:

(1) $$\sum_{t=0}^{T} K_t (1+r)^{-t} < \sum_{t=0}^{T} P_t^c S_t (1+r)^{-t}$$

where $K_\mathrm{t}$ is the cost in year $t$, $r$ is the discount rate, $P_\mathrm{t}$ is the price of carbon in year $t$, $S_\mathrm{t}$ is the annual carbon offset generated by the project, and $T$ is the lifetime of the project (which could be infinite). If the price of carbon rises at an annual rate $\gamma < r$, equation (1) becomes:

(2) $$\sum_{t=0}^{T} K_t (1+r)^{-t} < P_0^c \sum_{t=0}^{T} S_t \left(\frac{1+\gamma}{1+r}\right)^t .$$

One would invest in the project only if the discounted costs divided by the discounted gains are less than the current price (marginal cost):

(3) $$\frac{\sum_{t=0}^{T} K_t (1+r)^{-t}}{\sum_{t=0}^{T} S_t \left(\frac{1+\gamma}{1+r}\right)^t} < P_0^c .$$

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[14] With this approach, there is no difference between discount rates for financial and physical components.

The calculated value of $P_0^c$ provides an estimate of the (marginal) cost of carbon sequestration.

Leakages, landscape effects and a host of other considerations are addressed to varying degrees in the bottom-up approach (see Boyland 2006). Overall, it is clear that the bottom-up approach leads to many discrepancies in how costs of carbon uptake are calculated, and thus whether terrestrial carbon sink projects are competitive with $CO_2$ emissions reductions (Richards and Stokes 2004).

Sector optimization studies endogenize key variables, such as landowners' decisions and prices, and consider the dynamic effects of sequestration (Adams et al. 1999). When used to predict sequestration costs, these models combine the forest and agricultural sectors to allow for interaction in land uses. This is significant because it allows for the consideration of leakages, which occur if a plantation program leads to increased agricultural prices that, in turn, cause forestland to be converted to agriculture elsewhere (Richards and Stokes 2004).

Econometric studies consider past landowner behavior and use that to predict future behavior (Stavins 1999; Plantinga, Mauldin and Miller 1999; Newell and Stavins 2000). Modelers build upon traditional land-use studies by linking to them relevant elements (e.g., location and climate factors), management practice information, and the time path of sequestration (Stavins 1999). To the extent that econometric analyses include macroeconomic and other variables, they might be considered a top-down approach. This would be true of some econometric models, but not all. Empirically, one would be able to identify whether econometric approaches are top-down in a meta-regression analysis because they can be expected to have higher carbon uptake costs (as leakages are taken into account).

Not only do different methods provide different cost estimates, but also different underlying factors and assumptions lead to different estimates of the costs of sequestering carbon via forestry activities.

Carbon uptake is determined by forest management practices, age of the forest stock, tree species, geographic location, site attributes, the disposition of forest products, and other factors. Some estimates take into account only the commercial component of the tree, while others are concerned with all vegetation and non-tree components of the ecosystem, such as soil organic carbon (van Kooten et al 2004). Although diverse components of the forest ecosystem store carbon, such as tree trunks, branches, leaves and soils, many studies fail to account for all components. For example, the New York State study (1991) accounted only for carbon uptake in above and belowground tree biomass, excluding carbon in the soil, understory and litter.

If a project involves growing and harvesting timber, the decay rate of forest products is sometimes taken into consideration in determining how much carbon is sequestered over a given period of time. As Sedjo et al. (1995) point out, "the long-term effects on atmospheric carbon … are highly dependent upon the assumptions of the life-cycle of the wood products" (p.154). Whether or not timber harvesting is included is important to cost estimates, because harvests are a source of revenue and thereby lower marginal costs (Stavins and Richards 2005). Thus, Adams et al. (1993) found that the estimated marginal cost of sequestering 35 Mt C (128 Mt $CO_2$) per year declined from \$13.90/tC to \$8.13/tC (\$3.79 to \$2.22/t$CO_2$) when harvests were allowed. These savings are accompanied by an increase in consumer surplus from lower-priced wood products together with a gain in producer surplus accruing to investments in tree plantations, although forest sector firms experienced a loss caused by lower wood product prices (Stavins and Richards 2005).

Taking into account the opportunity cost of land has a profound effect on carbon-uptake costs. Studies provide a range of costs depending upon the land areas and carbon volumes involved. For example, Moulton and Richards (1990) found costs to range from \$16 to \$62 per ton of carbon for a U.S. program that sequestered about one-half of annual U.S. net carbon emissions; they estimated available land area, forest carbon accumulation rates, and land costs for hypothetical sequestration programs. From these, they then estimated the total amount of carbon that could be captured and the cost per ton of sequestration. Parks and Hardie (1995) estimated a range of \$10 to \$82 per ton of carbon by substituting estimates of foregone net revenues from agricultural production for observed sale and rental prices of agricultural land.

The scope of projects also affects estimates of carbon sequestration costs. Boyland (2006) points out those costs can vary substantially even in comparing what happens at the single-stand versus landscape levels. Some global studies exist, mainly looking at carbon sequestration potentials and costs differentiated by continents or climatic zones (Martina 2003). At a global level, research has been limited, but a study by Sohngen and Mendelsohn (2003) is pioneering; they developed an optimal control model of carbon sequestration and energy abatement to explore the potential role of forests in greenhouse gas mitigation. They showed that if $CO_2$ accumulates in the atmosphere, the rental price for carbon sequestration should rise over time. The analysis by Hauer et al. (2004) finds that when carbon prices reach \$20/t $CO_2$ (\$73.33/tC) the supply curve of carbon from forestry activities appears to become very inelastic. Although they conduct a landscape analysis, the area considered is still relatively small (an experimental forest on the eastern slope of the Rocky Mountain in Canada) and options for sequestration are limited.

In conclusion, it is difficult to get a clear overview concerning the costs of carbon uptake and storage via forestry activities because existing studies are so diverse. In a recent review, Stavins and Richards (2005) develop an understanding of U.S. forest-based costs by examining a variety of studies, investigating the factors that influenced cost estimates and synthesizing the results. However, their focus is narrow and confined to a select number of U.S. studies. In order to develop a more comprehensive comparison, we apply meta-regression analysis to a database of 68 studies published between 1989 and 2006. In so doing, we update the results of van Kooten et al. (2004), who reviewed 55 studies that estimated the costs of carbon uptake and storage as a result of forestry activities using meta-regression analysis.

## 5. A Meta-Regression Model of Forestry Carbon Uptake Costs: Results and Analysis

Meta-regression analysis (MRA) is one type of meta-analysis offering a means of objectively explaining why, and quantifying how, estimates from a range of empirical studies differ (Roberts 2005). MRA tends to objectify processes that produce empirical economic results as though they were any other social scientific phenomenon (Stanley 2005). But the difference among the reported empirical results of economic research is substantial, with various researchers having different ideas about key concepts in the research. MRA provides a framework for replication and offers a sensitivity analysis for model specification. Its intent is to summarize the results of many individual studies, where key estimates differ in significance, magnitude and even sign. MRA provides a more general description of the relationship between the variables, and can identify a significant trend from a large number of studies, even where individual studies might have failed to find such evidence (Mann 1990, 1994).

Cost of carbon uptake and storage studies provide estimates of the marginal or average costs of carbon uptake. Lacking information on the potential form of the marginal and average cost curves, the following full meta-regression model is employed:

$$(4) \qquad y_j = \gamma_0 D_j + \delta_1 C_i + \delta_2 C_j^2 + \alpha_0 + \alpha_1 x_{1j} + \cdots + \alpha_k x_{kj} + \varepsilon_j, \ (j = 1, \ldots, N)$$

where $y_j$ refers to the average or marginal per unit cost of carbon uptake ($/tC) by project $j$, $D_j$ is a dummy variable that takes on a value of 1 if the study reports marginal cost (0 otherwise), $C$ refers to carbon standardized to a per hectare basis (tC/ha), there are $k$ non-carbon regressors (specified below), and $\varepsilon_j$ is the random $N\times 1$ error vector.[15]

We gathered information on costs of carbon uptake and storage in forest ecosystems from 68 studies. Observations are from over 30 countries, but most studies were in the following countries: U.S. (21), Canada (7), Brazil (5), and India (3). Four studies employed data from Europe and 31 from developing countries (in conjunction with Kyoto's Clean Development Mechanism). A summary of the studies used in the MRA is provided in Table 2.

More than three-quarters of the studies investigated used a bottom-up approach, 18% used an optimization approach and only 6% an econometric approach. Only the latter two might be considered top-down approaches, although for the most part they employed a regional focus. Nearly 12% of studies attempted to provide global estimates of carbon uptake, but most of these employed bottom-up methods. This suggests that leakages are probably nowhere adequately dealt with in the studies we investigated.

The quality of the data available from studies varies tremendously. The 68 studies examined in our sample provided all of the required information needed for the MRA, or sufficient data to enable us to calculate the required information. A significant number of studies that we examined were not included in the analysis because they provided too little detail; yet, many of these constituted background information for serious efforts to sell $CO_2$ offset credits.

Consider that the Food and Agricultural Organization of the United Nations examined 49 terrestrial sequestration projects that were underway or proposed to create carbon offset credits (FAO 2004). One project was in the United States, three in Australia and two in Europe, with the

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[15] A cubic version of regression equation (4) was also considered, but it yielded no additional insights.

remainder in developing countries and thus potentially eligible for credits under the CDM. There were 38 forestry projects, of which 17 involved forest conservation and thus would not be eligible under current Kyoto rules. Nonetheless, these projects had local or offshore sponsors (country or company) that invested funds in the project. Only 33 of the 49 projects provided some information on the amount of carbon to be sequestered, with two of these providing no information on the area involved. Information on the amount of carbon sequestered was considered ‘good’ for only 24 projects, although none provided an indication of the timing of carbon benefits. Further, information on costs was provided for only 11 projects, with only eight providing information on carbon uptake as well. In essence, it is next to impossible to determine the cost-effectiveness of the projects reviewed by the FAO (2004), although in some cases one could make some crude calculations. Worse still was the fact that sponsors would be claiming credits for offsetting $CO_2$ emissions on the basis of what could only be considered flimsy data.

Even for studies that provided the requisite data (and thus are included in our analysis), one is left wondering how the calculations were made in cases where details are sparse. This was true of both peer-reviewed and non-reviewed studies. For example, Lasco et al. (2002) examine forest conservation as a means to offset $CO_2$ emissions from power generation in the Philippines, concluding that this can be done for as little as $0.12/tC.[16] It is not clear how they came up with such a low cost, but it appears they may have attributed all carbon left standing in a particular year by not harvesting to the cost of avoiding harvests in that year, and then ignored as well the foregone opportunity of land in agriculture. It also appears that, when we tried to reproduce his calculations, Swisher (1991) may have failed to discount costs even though the equations used in the calculations indicate otherwise! There is clearly a trade-off between including observations

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[16] This is only one of several observations in this study. For each study, only an average value is used. Also recall the discussion (section 3 and footnote 3) pertaining to the first forest-sink project approved under the CDM mechanism (UNFCCC 2006).

with different levels of quality and the resulting potential for heteroskedasticity to affect efficiency, and the possibility of bias to occur if some known observations are left out. We made the decision to retain all observations with information as provided.

In our model, the dependent variable consists of cost scaled to a per ton basis, and is measured in 2005 $US, with values for other years deflated using the U.S. consumer price index. A model with the logarithm of cost scaled to a per ton basis as dependent variable is also employed. In addition to the costs of carbon sequestration, data were collected on publication date, type of forestry project, region, discount rate on financial (cost) measures, discount rate on physical carbon, whether the opportunity cost of land was included, post-harvest use of fiber, whether soil carbon was included, scope of study, and method used to calculate carbon sequestration costs. Summary statistics are provided in Tables 2 and 3.

We consider four types of forestry projects: plantation programs (expanding forest ecosystems by increasing the area of plantation forests), forest conservation (avoiding deforestation, protecting forests in reserves, changing harvesting regimes), forest management that contributes to the growth of forests (e.g., silvicultural strategies such as fertilization), and agroforestry programs where farmers intersperse trees on agricultural land and crop underneath them. We choose agroforestry as the baseline program, but if any of the other three types (which are included as dummy variables) turned out not to be statistically different from the baseline it was excluded in the final regression model (and thus included in the intercept term).

Studies are catalogued into North America, Europe and other countries (e.g., Australia, Russia), with the latter included in the intercept term. We also distinguish studies according to soil conditions, employing tropical, boreal, Great Plains or U.S. cornbelt categories, with other regions included in the intercept term. We consider geographic scope using dummy variables to distinguish studies according to whether they estimate costs of carbon uptake at the regional, national or global levels.

We distinguish three carbon pools: carbon in tree biomass (including above and below ground), soils and wood products – in furniture, paper, and wood materials for construction and buildings. In addition, forest biomass can be used for energy production and timber products can replace energy intensive materials like aluminum and steel in construction (Marand and Schlamadinger 1997). Dummy variables are used for each of these categories, with the base case being no consideration of carbon post harvest. We also classify three methods for calculating carbon uptake costs: sectoral optimization, econometrics and bottom-up (engineering) methods, with the latter taken as the base case.

Aside from the marginal cost indicators and the dummy variables above, our MRA model for carbon sequestration also includes the following: dummy variables for opportunity cost of land (=1 if opportunity cost is included) and whether the study was peer reviewed (=1 if peer reviewed), and a general intercept term.

### *Estimation Results*

The regression results are provided in Table 4. A variety of different models were examined. Level and (semi-) logarithmic versions of the model are presented as they provide some indication of the range of estimation results; within each of these models, results turned out to be relatively robust. Contrary to the earlier finding by van Kooten et al (2004), none of the regression results indicated that refereed studies tended to provide higher cost estimates; the estimated coefficient on the dummy variable for peer-reviewed studies was statistically insignificant in all cases. Unlike the earlier finding and perhaps related to the finding on peer review, some evidence (from the levels model) indicates that more recent studies find costs of carbon uptake in forest ecosystems to be somewhat lower than originally supposed.

The evidence indicates that marginal costs of carbon sequestration are generally higher than average costs, but this result is only statistically valid in the levels model. Unexpectedly, we find no evidence that the (average or marginal) costs of sequestration increase as the amount of carbon stored per hectare rises, except at unrealistically high levels of carbon uptake. Indeed, costs appear to decline slightly over a wide range of uptake levels. This result holds even when a cubic functional form is employed, when interaction terms between carbon uptake and the marginal cost dummy are included, and when an interaction term between carbon uptake and the carbon discount rate is employed. This finding suggests that there is a great deal of inconsistency across studies in how carbon uptake and costs are measured.

The discount rate on financial costs also turns out to have no statistically significant influence on carbon-uptake costs, although this is not surprising given that most forestry projects had costs skewed towards the present. What is surprising is that studies that discounted carbon had lower calculated costs, although this result holds only for the level and not the semi-logarithmic model.

Regression results for other variables are easier to interpret (Table 4). One statistically powerful result is that projects in Europe are the most expensive to implement, with costs some \$777/tC (\$212/t$CO_2$) higher than they are elsewhere, ceteris paribus. This could be the result of higher land prices in Europe that are not completely captured by the opportunity cost of land term (see below) and slower rates of tree growth. Overall, the statistical results indicate that projects in tropical ecosystems can generate $CO_2$-emission offset credits at lower cost than projects in other regions. The evidence also suggests that forestry activities in the U.S. cornbelt region generate somewhat less costly $CO_2$ offsets than other non-tropics projects, while those in the North American Great Plains or the boreal forest region are somewhat more expensive. However, these results are certainly not conclusive as they depend on the functional form of the regression model, and the significance of this result for the boreal forest zone is weak.

Tree planting leads to lower costs of creating $CO_2$ offset credits than do activities such as forest management, forest conservation and agroforestry. Indeed, the regression results in Table 4 indicate that tree planting costs are some \$180/tC (\$49/$tCO_2$) lower, ceteris paribus, while forest management projects lower costs by some \$55/tC (\$15/$tCO_2$), although the statistical significance of this result is weak. On the other hand, conservation activities might actually be more expensive than agroforestry projects, by some \$78/tC (\$21/$tCO_2$). This evidence comes only from the levels model and is not supported by the semi-logarithmic regression results (where the coefficient on tree planting is negative but statistically insignificant).

The result on tree planting found in the levels model is in sharp contrast to those of van Kooten et al. (2004), who found that the costs of carbon uptake in tree planting projects were significantly higher than costs of other activities. One would not expect such a dramatic turnabout in the statistical results pertaining to a key variable in going from 55 studies to 68 studies. Several reasons could account for this. First, van Kooten et al. employed a semi-logarithmic functional form; in the current analysis, the coefficient on tree planting is only statistically significant for the levels and not the semi-logarithmic model. Second, upon revisiting the earlier data, we found several inconsistencies in data entry that were subsequently corrected, although one their own these would not account for the reduced cost associated with tree planting activities. Finally, in our meta-regression analysis we use study averages, while van Kooten et al. used individual observations. It is not clear which approach is more appropriate to employ in meta-regression analysis, with most researchers using study averages (Stanley and

Jarrell 2005), but it is beyond the scope of the current study to address this issue.

The meta-regression result concerning soil carbon sinks provides no statistical support for including them in the calculation of costs of carbon sequestration. Soil carbon may be a relatively large component of total terrestrial ecosystem carbon, but a small part of the change in ecosystem carbon resulting from a change in land use (e.g., from pasture to forest, or from one type of forest to another). Thus, their importance may be overrated so that, from a policy standpoint, the transaction costs associated with their inclusion might well exceed the benefits of taking them into account. The evidence on post-harvest use of fiber is mixed. One suspects that it would be important to take into account carbon going into product pools (lumber, paper, etc.), but the statistical evidence indicates that taking into account product pools does not have a noticeable effect on estimated costs. The story regarding the use of fuel substitution is quite the opposite. Substituting wood biomass for fossil fuels in the generation of electricity, say, will reduce the costs of reducing $CO_2$ emissions by nearly \$190/tC (or some \$50 per $tCO_2$).

The effect of taking opportunity cost of land into account is also important. In both models, the opportunity cost of land dummy variable is statistically significant and, taking this factor into account, adds some \$25/$tCO_2$ to costs. By considering the opportunity cost of land, one captures the net economic benefits that are foregone by diverting land from other uses so as to establish a carbon sink (Stavins and Richards 2005). In some regions, the opportunity cost of land is indeed small because forestry is the best use of the land, but in others, such as Europe, it is very large. The empirical result regarding the opportunity cost variable is partly taken into account by the regional dummy variables, with regression results not reported here indicating a larger and more significant impact of opportunity cost when regional variables are removed.

Finally, we find that projects that are global in scope tend to find higher costs of sequestering carbon in forest ecosystems, ceteris paribus. To the extent that such studies take into account price effects (that are not captured with the 'method of analysis' variables), this result provides some evidence that top-down models give higher carbon uptake costs (by some \$32/t$CO_2$) than bottom-up approaches. We also find some evidence to indicate that studies that used an econometric approach find higher cost estimates than optimization models and 'engineering-type' bottom-up calculations, although this result only holds for the semi-logarithmic model. This is not to suggest, however, that econometric models are top-down, as none of the studies investigated here truly employed a top-down method.

### *Estimating Costs of Creating Carbon Offset Credits*

The regression analyses are used to provide some indication of the potential costs of carbon uptake from forestry activities. Results are reported in Table 5 for both the level and logarithmic models. The level model is preferred for this exercise because it has a somewhat better goodness-of-fit and estimated coefficients are generally more statistically significant (see Table 4). We provide projections of potential costs of carbon uptake for both models to ensure a broad range of estimates and wide geographic scope.

As indicated in Table 5, the costs of creating $CO_2$-emission offset credits through forestry activities vary wildly. Strategic planting projects in tropical regions can possibly yield positive benefits to society, while planting and forest management activities in the U.S. cornbelt region are likely able to compete with emissions reduction projects (assuming these can reduce emissions for \$30/t$CO_2$ or less). In other regions, even the least costly planting projects that include the opportunity cost of land are unlikely to be competitive with efforts to reduce emissions. An exception might be the boreal region if harvested wood biomass is used as a substitute for fossil fuels. Europe is the most costly place to implement forestry projects whose aim is to produce $CO_2$ offset credits. As the regression results showed, the highest cost region is Europe, with costs of carbon sequestration in the range of \$48-\$280 per $tCO_2$ (\$176-\$1027/tC). This might explain why Europe has generally opposed biological sinks as a substitute for greenhouse gas emission reductions.

Costs in tropical regions are lowest, with the most expensive alternatives likely costing no more than \$35/$tCO_2$ (\$128/tC). This might explain why there is a rush for countries and companies to finance forestry sector CDM projects to meet Kyoto obligations (e.g., UNFCC 2006). As noted by Moura-Costa et al. (1999), there is a preponderance of low-cost forestry investments in developing countries, which have high growth rates and relatively low land and labor costs. The cost of carbon sequestration in North America is also reasonable, ranging from as little as about \$2 to \$77 per $tCO_2$ (\$7 to \$282/tC). Finally, costs in the boreal zone are similar to those in the North American Great Plains and the U.S. cornbelt, but perhaps a bit higher as they can range to nearly \$100/$tCO_2$ (\$367/tC). The implication of these results is that some projects are worthwhile undertaking, but certainly not all.[17]

## 6 Discussion

There have now been a plethora of economic studies on costs of sequestering carbon in forest ecosystems. In this review, we examined issues related to the creation of $CO_2$ offset credits via forestry activities and problems associated with their integration into a larger $CO_2$ emissions trading scheme. As part of our review, we found that many serious efforts to create $CO_2$ offsets using a project-based approach failed to meet standards of accountability: Studies violated additionality considerations, failed to account for leakages, and/or provided too little information to enable an outside analyst to determine how much carbon was to be sequestered and at what

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[17] $CO_2$ offsets were trading for some \$5 to nearly \$30 per $tCO_2$, as indicated at (as viewed 18 October 2006): http://www.ecobusinesslinks.com/ carbon_offset_wind_credits_carbon_reduction.htm.

cost. For studies that provided the needed data, we conducted a meta-regression analysis to determine factors that affected costs of carbon uptake and whether and under what conditions $CO_2$ offsets from forestry activities could compete with emissions reductions.

There is a huge disparity in methods used to calculate carbon-uptake costs. In the meta-regression analysis, we used all of the data available to us to attempt to sort out the various cost estimates. We found that our explanatory variables explain some 60-70% of the variation in costs, but we have no way of knowing to what extent our explanatory variables are representative of others that truly cause the observed variation. Given the regressors available to us, the most important factors affecting the costs of carbon sequestration in forestry are the location of the forestry activity, whether the opportunity cost of land is taken into account, and whether or not the scope of the estimates is global. Other factors that affect cost estimates include the type of activity, what carbon pools are included in the analysis, and post-harvest use of fiber. Given the diverse set of factors that affect the cost and quantity of potential forest carbon sequestration, it is not surprising that cost studies have produced a broad spectrum of estimates. MRA results suggest that forestry activities may be able to deliver offset credits that are competitive with emissions reductions in some cases, but that this is not unambiguously the case. In many situations, the costs of carbon uptake in forest ecosystems are substantial, even with the inclusion of soil and wood product carbon pools, or substitution of fossil fuels with biomass in energy.

It is clear that location (Europe, tropics) and type of activity (in particular, tree planting) have a very large influence on the estimated costs of carbon uptake, while other variables that we thought would affect cost estimates (such as whether soil and product sinks were included, whether or not a bottom-up approach was used) had no strong influence. These results are important in and of themselves. For example, they go a long way to explaining why the EU opposed terrestrial sinks from the outset and why there is currently greater effort to get forest sinks in tropical countries accepted under CDM.

In light of this study, therefore, the widely-held notion evident from Table 1 and the IPCC's report on LULUCF activities (IPCC 2000) that forestry activities are a low-cost means for reducing atmospheric $CO_2$ needs to be reassessed. While forests do have a role to play in carbon policy, it is clear that the extent to which society is willing to pay for carbon sequestration ultimately depends on the extent to which politicians are willing to adopt harsh measures to address climate change. Targets that seek to limit atmospheric $CO_2$ concentrations or global average temperature change this century could lead to carbon prices well above the estimates shown in Table 5 (Weyant et al. 2005).

One issue that we have not addressed in this paper relates to the relationship between carbon uptake and biodiversity. There is growing recognition that incentive systems focused on carbon sequestration could have implications for biodiversity (e.g., Matthews et al. 2002; Caparros and Jacquemont 2003). Boscolo and Vincent (2003) suggest that alternative management regimes would evolve depending on which values were most important in particular forest estates. Additional research should continue to clarify links between these two important outputs from forests.

Finally, our review raises concerns about the use of terrestrial carbon sinks as a mechanism for addressing climate change. We do not deny that plants and trees remove $CO_2$ from the atmosphere, thereby offsetting $CO_2$ emissions from fossil fuels and mitigating global warming. Rather, we question the effectiveness of sinks within the Kyoto framework. Countries that use carbon sequestration credits to achieve some proportion of their $CO_2$ emissions-reduction target during Kyoto's first commitment period have avoided emissions reductions. But a country that relied on carbon sinks is technically liable for ensuring that the stored carbon remains there. This will be difficult given the ephemeral nature of forest and other terrestrial sinks. Since that country failed to reduce $CO_2$ emissions, it is obligated to do so in subsequent commitment periods. Suppose, for example, that in the first commitment period a country meets half of a 6% emissions-reduction target with sinks, and then commits to reducing emissions a further 6% from the 1990-base in the next commitment period (for a total reduction of 12% from the 1990 base). Since emissions are only 3% below base, the country must still reduce $CO_2$ emissions by 9% while ensuring no loss of the stored carbon for which it is liable. The temporal shifting in the emissions-reduction burden caused by reliance on carbon sinks results in an onerous obligation for future generations, one which they may not be willing to accept.

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**Table 1: Potential role of terrestrial carbon sinks in meeting KP first commitment period targets, based on Marrakech Accords (Mt C per year)**

| Item | Total Annex B |
|---|---:|
| KP Article 3.3 net increase in sinks | 12.28 |
| Maximum sinks due to forest management | 97.87 |
| Increase in sinks due to agricultural activities | 33.56 |
| Maximum use of sinks under KP Article 12 | 49.83 |
| **Estimated potential use of sinks to meet KP target (TOTAL)** | **193.54** |

Source: van Kooten (2004, p.75)

## Table 2: Forest Carbon Sink Studies that Estimate Costs of Carbon Sequestration

| Forest carbon sink studies | Total carbon (Mt) | Total area (mil ha) | Cost ($/ha)[a] | Cost ($US/tC)[a] |
|---|---:|---:|---:|---:|
| Adams et al. (1993) | 350.00000 | 58.999056 | 442.28 | 73.20 |
| Adams et al. (1999) | 2023.07692 | 145.596613 | 401.52 | 29.16 |
| Andrasko, Heaton & Winnett (1991) | 806.00000 | 6.716000 | 1101.94 | 8.88 |
| Baral & Guha (2004) | 316.75000 | 1.000000 | 18602.34 | 63.30 |
| Benitez & Obersteiner (2003) | 2503.33333 | 237.000000 | 698.81 | 66.16 |
| Benitez et al. (2006) | 8183.66667 | 2975.000000 | 354.11 | 128.73 |
| Boscolo & Buongiorno (1997) | 0.00123 | 0.000050 | 2911.45 | 118.03 |
| Boscolo, Buongiorno & Panayotou (1997) | 0.00140 | 0.000050 | 1371.29 | 49.13 |
| Brown, Cabarle & Livernash (1997) | 8.90000 | 0.560801 | 10.29 | 1.84 |
| Cacho, Hean & Wise (2003) | 0.00010 | 0.000001 | 773.64 | 7.79 |
| Callaway & McCarl (1996) | 119.31818 | 29.624646 | 143.39 | 34.09 |
| Darmstadter & Plantinga (1991) | 155.97333 | 0.523667 | 1056.39 | 3.30 |
| Dixon et al. (1993) | 5.98500 | 0.029840 | 180.72 | 4.73 |
| Dixon et al. (1994) | 0.81357 | 0.010000 | 27.91 | 27.91 |
| Dudek & Leblanc (1990) | 1721.91805 | 4.896803 | 1562.43 | 4.44 |
| Dutschke (2000) | 1.08088 | 0.135750 | 363.02 | 32.43 |
| FAO (2004) | 1.37713 | 0.094178 | 171.12 | 77.11 |
| Fearnside (1995) | 0.00002 | 0.000001 | 2004.77 | 89.78 |
| Healey et al. (2000) | 0.01578 | 0.000406 | 2772.95 | 71.34 |
| Hoen & Solberg (1994) | 0.77847 | 0.575000 | 2407.49 | 1778.25 |
| Houghton, Unruh & Lefebvre (1991) | 1277.77780 | 27.722223 | 447.48 | 12.95 |
| Huang & Kronrad (2001) | 0.05625 | 0.001000 | 838.78 | 44.63 |
| Krcmar & van Kooten (2003) | 3.02600 | 1.236390 | 370.14 | 151.23 |
| Lasco et al. (2002) | 2.59761 | 0.020438 | 610.38 | 4.81 |
| Lashof & Tirpak (1989) | 834.58333 | 138.650000 | 83.00 | 13.76 |
| Makundi & Okiting'ati (1995) | 30.27400 | 0.186380 | 324.90 | 2.00 |
| Masera et al. (1995) | 150.66771 | 1.295429 | 3038.74 | 48.63 |
| McCarl & Callaway (1995) | 243.88372 | 47.390233 | 383.74 | 72.36 |
| McCarney, Armstrong & Adamowicz (2006) | 50.00000 | 0.888713 | 142.71 | 11.04 |
| Moulton & Richards (1990) | 472.68069 | 1.988651 | 5227.11 | 26.77 |
| Moura Costa et al. (1999) | 11.60644 | 0.210933 | 202.93 | 4.37 |
| New York State (1991) | 0.50250 | 0.804341 | 17.33 | 29.51 |
| Newell & Stavins (1999) | 7.66417 | 2.074701 | 699.79 | 181.13 |
| Nordhaus (1991) | 3550.00000 | 85.000000 | 4144.36 | 115.75 |
| Olschewski & Benitez (2005) | 18.05400 | 0.102000 | 2576.21 | 14.55 |
| Parks & Hardie (1995) | 29.96400 | 6.576285 | 967.26 | 260.29 |
| Plantinga & Mauldin (2001) | 41.54904 | 0.275678 | 5457.40 | 36.28 |

**Table 1: Continued**

| Forest carbon sink studies | Carbon (Mt) | Area (mil ha) | Cost ($/ha)[a] | Cost ($US/tC)[a] |
|---|---:|---:|---:|---:|
| Plantinga, Mauldin & Miller (1999) | 12.79848 | 0.188260 | 4596.33 | 67.61 |
| Poffenberger et al. (2001) | 0.45980 | 0.011000 | 983.05 | 23.52 |
| Poffenberger et al. (2002) | 13.58974 | 0.048155 | 11.34 | 0.46 |
| Putz & Pinard (1993) | 0.00005 | 0.000001 | 182.78 | 3.97 |
| Ravindranath & Somashekhar (1995) | 603.00000 | 6.750000 | 171.96 | 1.90 |
| Richards (1997b) | 4079.54545 | 266.000000 | 2136.11 | 150.70 |
| Richards, Moulton & Birdsey (1993) | 42903.00000 | 86.402266 | 3446.72 | 6.94 |
| Schroeder, Dixon & Winjum (1993) | 16428.64857 | 192.857857 | 330.38 | 23.94 |
| Sedjo & Solomon | 72860.00000 | 465.000000 | 5975.33 | 38.14 |
| Sohngen & Brown (2006) | 2.28500 | 0.219699 | 1921.95 | 130.00 |
| Sohngen & Haynes (1997) | 29.00000 | 198.000000 | 7.34 | 50.10 |
| Sohngen & Mendelsonh (2003) | 32233.33333 | 381.316667 | 4585.09 | 70.74 |
| Solberg & Hoen (1996) | 2.73873 | 0.173000 | 2190.05 | 185.76 |
| Spinney, Prisley & Sampson (2004) | 0.09476 | 0.009200 | 192.09 | 20.36 |
| Stavins & Richards (2005) | 3157.62208 | 35.425101 | 2740.67 | 27.31 |
| Stavins (1999) | 238.20327 | 70.044409 | 418.05 | 127.62 |
| Stennes & McBeath (2005) | 0.25740 | 0.580000 | 134.59 | 303.28 |
| Stennes (2000) | 1.12500 | 1.236400 | 29.96 | 32.93 |
| Stuart & Moura Costa (1998) | 1.12975 | 0.096471 | 24.80 | 2.10 |
| Swisher (1991) | 6.47606 | 0.093950 | 293.10 | 7.96 |
| TERI (1997) | 1.35056 | 0.033151 | 525.75 | 18.13 |
| Totten (1999) | 6.03226 | 0.127463 | 52.13 | 4.60 |
| van Kooten & Bulte (2000) | 8.92154 | 0.150000 | 22809.55 | 494.55 |
| van Kooten & Hauer (2001) | 1.13793 | 1.236400 | 79.31 | 86.17 |
| van Kooten et al. (1999, 2000) | 19.58841 | 4.290617 | 57.17 | 38.39 |
| van Kooten, Arthur & Wilson (1992) | 120.93605 | 4.718333 | 537.03 | 63.78 |
| van Vliet et al. (2003) | 1.17942 | 0.039155 | 68.19 | 2.45 |
| Volz et al. (1991) | 31.47143 | 3.892857 | 772.00 | 248.10 |
| Winjum, Dixon & Schroeder (1993) | 100.03500 | 1.947143 | 536.98 | 15.83 |
| Xu (1995) | 490.51000 | 10.015000 | 209.68 | 5.14 |
| Zelek & Shively (2003) | 2.00151 | 0.000001 | 2398.82 | 24.65 |
| **Mean** | **2886.47572** | **80.971894** | **1783.95** | **87.89** |
| **Maximum** | **72860.00** | **2975.00** | **22809.55** | **1778.25** |
| **Minimum** | **0.00002** | **0.000001** | **7.34** | **0.46** |
| **Standard deviation** | **10937.63216** | **367.295889** | **3658.28** | **224.49** |

[a] Costs are in 2005 dollars

**Table 3: Explanatory Variables, Means and Ranges**

| Variable | Mean or count | Std. Dev. | Minimum | Maximum |
|---|---|---|---|---|
| **Dependent Variable** | | | | |
| Cost of carbon uptake (2005 US $ per tC) | 87.89 | 224.489 | 0.46 | 1778.70 |
| **Explanatory Variables** | | | | |
| Years since 1989 | 8.559 | 4.931 | 0 | 17 |
| Carbon per hectare (tC/ha) | 102.04 | 246.259 | 0.15 | 1955.08 |
| Discount rate on carbon (%) | 2.88 | 3.066 | 0 | 10.00 |
| Discount rates on costs (%) | 4.57 | 4.047 | 0 | 17.25 |
| **Forest activity dummy variables** | | | | |
| Planting of forest (=1, 0 otherwise) | 54 | 0.407 | 0 | 1 |
| Agroforestry project (=1, 0 otherwise) | 12 | 0.384 | 0 | 1 |
| Forest conservation project (=1, 0 otherwise) | 23 | 0.477 | 0 | 1 |
| Forest management project (=1, 0 otherwise) | 33 | 0.504 | 0 | 1 |
| **Geographic scope dummy variables** | | | | |
| Global (=1, 0 otherwise) | 8 | 0.325 | 0 | 1 |
| National (=1, 0 otherwise) | 41 | 0.493 | 0 | 1 |
| Regional (=1, 0 otherwise) | 25 | 0.486 | 0 | 1 |
| **Methods dummy variables** | | | | |
| Optimization (=1, 0 otherwise) | 12 | 0.384 | 0 | 1 |
| Econometrics (=1, 0 otherwise) | 4 | 0.237 | 0 | 1 |
| Other/bottom-up (=1, 0 otherwise) | 52 | 0.427 | 0 | 1 |
| **Carbon pools dummy variables** | | | | |
| Carbon in products (=1, 0 otherwise) | 27 | 0.493 | 0 | 1 |
| Soil carbon (=1, 0 otherwise) | 45 | 0.477 | 0 | 1 |
| Wood used for fuel (=1, 0 otherwise) | 9 | 0.341 | 0 | 1 |
| **Other items dummy variables** | | | | |
| Opportunity cost of land (=1, 0 otherwise) | 43 | 0.486 | 0 | 1 |
| Marginal cost (=1, 0 otherwise) | 23 | 0.477 | 0 | 1 |
| Peer reviewed (=1, 0 otherwise) | 44 | 0.481 | 0 | 1 |

**Table 4: Meta-Regression Analysis, Ordinary Least Squares Results (n=68)**[a]

| Dependent Variable → | Cost per tC | | | Logarithm of cost per tC | | |
|---|---|---|---|---|---|---|
| Explanatory Variable | Est. coef. | t-stat | Prob>t | Est. coef. | t-stat | Prob>t |
| Marginal cost | 95.0596 | 1.62 | 0.111 | 0.2077 | 0.65 | 0.517 |
| Carbon per ha (t) | -0.3591 | -1.69 | 0.097 | -0.0052 | -2.63 | 0.011 |
| Carbon per ha squared | 0.0002 | 1.67 | 0.102 | 0.000002 | 2.38 | 0.021 |
| Date of study | -10.5697 | -1.85 | 0.071 | — | — | — |
| European location | 777.1504 | 2.71 | 0.009 | 2.1680 | 5.68 | 0.000 |
| Tree planting activity | -180.5518 | -2.11 | 0.040 | -0.5129 | -1.22 | 0.228 |
| Forest conservation | 77.6194 | 1.63 | 0.109 | — | — | — |
| Forest management | -55.4411 | -1.42 | 0.163 | — | — | — |
| Carbon discount rate | -27.0579 | -1.97 | 0.054 | 0.0313 | 0.49 | 0.628 |
| Discount rate on costs | 5.0977 | 0.77 | 0.444 | -0.0302 | -0.56 | 0.576 |
| Fossil fuel substitution | -186.6625 | -1.69 | 0.098 | — | — | — |
| Soil carbon sink | -35.7492 | -0.94 | 0.353 | -0.1489 | -0.48 | 0.632 |
| Opportunity cost of land | 95.9133 | 1.64 | 0.108 | 1.0945 | 2.74 | 0.008 |
| Regional scope | 37.4949 | 1.14 | 0.258 | — | — | — |
| Global scope | 118.1417 | 1.77 | 0.082 | 1.4113 | 3.10 | 0.003 |
| Econometric method | — | — | — | 1.1590 | 2.56 | 0.013 |
| Optimization method | 42.3236 | 0.87 | 0.391 | — | — | — |
| Tropical location | -159.3768 | -2.34 | 0.024 | -1.0050 | -2.06 | 0.044 |
| N. American Great Plains | — | — | — | 0.8920 | 1.72 | 0.091 |
| U.S. cornbelt | — | — | — | -1.2074 | -2.69 | 0.010 |
| Boreal location | 80.5219 | 1.47 | 0.148 | — | — | — |
| Intercept | 355.0763 | 2.49 | 0.016 | 3.7764 | 5.19 | 0.000 |
| F statistic | 3.62 | | 0.0002 | 28.02 | | 0.0000 |
| (degrees of freedom) | (18, 49) | | | (13, 54) | | |
| $R^2$ | 0.7174 | | | 0.6439 | | |
| Root mean square error | 139.55 | | | 1.0419 | | |

[a] Probabilities and t-statistics are based on robust standard errors.

**Table 5: Marginal Costs of Creating Offset Credits through Forestry Activities (\$/t $CO_2$)**

| | Predicted cost | |
|---|---|---|
| Scenario[a] | Level | Logarithm |
| **Europe** | \$278.79 | \$79.90 |
| Planting | \$229.55 | \$47.84 |
| Planting & opportunity cost of land | \$255.70 | \$142.93 |
| Planting, opportunity cost of land & fuel substitution | \$195.05 | n.a. |
| Forest management | \$253.92 | \$92.73 |
| Forest management & opportunity cost of land | \$280.07 | \$277.55 |
| Forest management, opportunity cost of land & fuel substitution | \$229.17 | n.a. |
| **Tropics (CDM Projects)** | \$13.62 | \$3.35 |
| Planting | -\$25.87 | \$2.00 |
| Planting & opportunity cost of land | -\$9.46 | \$5.99 |
| Forest management | \$8.25 | \$3.88 |
| Forest management & opportunity cost of land | \$24.66 | \$11.60 |
| Conservation | \$34.79 | n.a. |
| Conservation & opportunity cost of land | \$60.95 | n.a. |
| **North American Great Plains** | n.a. | \$22.30 |
| Planting | n.a. | \$13.36 |
| Planting & opportunity cost of land | n.a. | \$39.90 |
| Forest management | n.a. | \$25.89 |
| Forest management & opportunity cost of land | n.a. | \$77.34 |
| **U.S. Cornbelt** | n.a. | \$2.73 |
| Planting | n.a. | \$1.64 |
| Planting & opportunity cost of land | n.a. | \$4.89 |
| Forest management | n.a. | \$3.17 |
| Forest management & opportunity cost of land | n.a. | \$9.48 |
| **Boreal Region** | \$79.05 | n.a. |
| Planting | \$39.56 | n.a. |
| Planting & opportunity cost of land | \$55.96 | n.a. |
| Planting, opportunity cost of land & fuel substitution | \$5.06 | n.a. |
| Forest management | \$73.68 | n.a. |
| Forest management & opportunity cost of land | \$99.83 | n.a. |
| Forest management, opportunity cost of land & fuel substitution | \$48.93 | n.a. |

[a] 2005 US dollars. Multiplying by 12/44 converts carbon prices to $CO_2$ prices. The base case for each of the three regions includes discounting of carbon and financial costs (at average values), inclusion of soil carbon, regional/national scope, and optimization/bottom-up method. Notation n.a. implies the model does not produce this estimate as it is included in the intercept term.