Carbon Sequestration in Forest Ecosystems as a Strategy for Mitigating Climate Change

by

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ABSTRACT

Under Kyoto, forestry activities that sequester carbon can be used to create CO_2 offset credits that could obviate the need for lifestyle-changing reductions in fossil fuel use. Credits are earned by storing carbon in forest ecosystems and wood products, although CO_2 emissions are also mitigated by delaying deforestation, which accounts for one-quarter of anthropogenic CO_2 emissions. Non-permanent carbon offsets from forest activities are difficult to compare with each other and with mitigation strategies because they differ in how long they prevent CO_2 from entering the atmosphere. In this paper, we investigate issues of carbon sequestration in detail, but in particular we expand in comprehensive fashion on earlier work comparing carbon mitigation activities according to how long they can lower atmospheric CO_2 levels. The duration problem is modeled theoretically. Meta-regression analysis with 1047 observations from 68 studies is then used to determine whether the duration problem leads to inconclusive results between carbon-uptake costs and carbon sequestration. In addition, from the regression analysis, it is possible to estimate potential costs of carbon uptake via forestry activities for various scenarios. It turns out that forestry activities are competitive with emissions reduction in tropical regions and, perhaps, in boreal regions, but certainly not in Europe.

Keywords: climate change, carbon offset credits from forestry activities, meta-regression analysis

JEL Categories: Q54, R15, Q23, Q27

1. INTRODUCTION

Scientists and engineers are particularly enthusiastic about the possibility of sequestering carbon in terrestrial ecosystems or storing it in geological reservoirs, thereby creating CO_2 offsets that could obviate the need for lifestyle-changing reductions in fossil fuel use. Some scientists claim that, by converting marginal croplands to permanent grasslands or forests, the accompanying increase in biomass and soil organic carbon can offset 20% or more of countries' fossil fuel emissions (Sathaye et al. 2001; Lal 2004a, 2004b). The Government of Canada (2002) had planned to rely on tree planting and improved forest management for meeting some one-third of its Kyoto commitment, although subsequent losses of large swaths of timber to Mountain Pine Beetle and wildfire has caused some re-thinking of the contribution to be expected from forests. More recently, proponents of CO_2 capture and storage in deep underground aquifers and abandoned oil/gas fields indicate that there is enough available storage to trap decades of CO_2 emissions (Parson and Keith 1998). The costs of this option are unknown as there is a risk of a sudden release of deadly concentrations of CO_2 in the future – 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) indicate could be substantial.

Given that carbon offset credits from agricultural activities are particularly ephemeral and that CO_2 capture and storage occurs underground, forestry activities are considered the most promising land-based activity for creating offset credits. Credits are earned by storing carbon in forest ecosystems and wood products, although harvested fibre can also be burned in lieu of fossil fuels, thereby reducing CO_2 emissions. It is also possible to mitigate CO_2 emissions by delaying (perhaps indefinitely) deforestation that accounts for more than one-quarter of all anthropogenic greenhouse gas emissions. With the exception of biomass burning in place of fossil fuels, sink activities create ephemeral offsets – terrestrial carbon storage is somehow less permanent than CO_2 emission reductions. Most commentators believe that the carbon embodied in forests and, especially, agricultural ecosystems (grass and soils) is always at risk of accidental or deliberate release, but that avoided emissions are 'permanent', despite the fact that 'saved' fossil fuels might release stored CO_2 at some future date (Herzog et al. 2003).

There is no denying that forestry activities create non-permanent carbon offsets, which creates problems for policy makers who wish to compare mitigation strategies that differ in the length of time they prevent CO_2 from entering the atmosphere. How should emerging markets for emissions trading value permanence? What is the implication of this for cost-benefit analyses that seek to rank alternative policy options? More specifically, how have producers of carbon offsets from forestry activities determined the value of these credits? And what guarantees do buyers have that forest-generated credits are cheaper than emission reduction offsets?

The purpose of this paper is to investigate these issues in greater detail. We do so by expanding in comprehensive fashion on earlier work by Marland et al. (2001), Sedjo and Marland (2003), and Herzog et al. (2003). In particular, we compare carbon mitigation activities according to how long they are able to lower CO_2 levels in the atmosphere. This is important because storage times differ even among forestry activities, with some being more 'permanent' than others. As a result, we also re-visit an earlier meta-regression analysis of carbon uptake costs by van Kooten et al. (2004). The relevant regression model in the earlier study employed 781 observations from 43 studies, while the current meta-regression analysis uses 1047 observations from 68 studies.

We proceed as follows. In the next section, we consider the main economic issues regarding the role of terrestrial carbon sinks for mitigating climate change. Then, in section 3, we investigate the implications of non-permanence of biological sinks in a formal fashion to determine whether the stop-gap nature of forestry activities makes it more burdensome for producers and buyers of temporary carbon offsets to value such credits, thereby adding to transaction costs (say, by thwarting some trades). This is not the same as asking whether forestry activities can make a reasonable and useful contribution to a country's overall mitigation strategy, although it does shed light on this issue. In section 4, we discuss the meta-regression model and its implications for our research problem.

2. NON-PERMANENCE OF GREENHOUSE GAS MITIGATION

The comparison of relevance in this study is between biological sink (especially forestry) activities and emissions reduction as two means for reducing atmospheric CO_2. We ignore carbon capture and storage for reasons discussed above, although much of the analysis in this section would apply to it as well.

Biological Sinks

Land use, land-use change and forestry (LULUCF) activities can lead to CO_2 offset credits (or debits). Tree planting and activities that enhance tree growth clearly remove carbon from the atmosphere and store it in biomass, and thus are eligible activities for creating CO_2 offset credits. However, there is concern that tree plantations will release a substantial amount of their stored carbon once harvested, which could happen as soon as five years after establishment if fast-growing hybrid species are planted. Sequestered carbon might also be released as a result of wildfire, disease and/or pests (e.g., Mountain Pine Beetle infestation in British Columbia).

In addition to forest ecosystem sinks, agricultural activities that lead to enhanced soil organic carbon and/or more carbon stored in biomass can be used to claim offset credits.

Included under Kyoto are re-vegetation (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). Most of these activities provide temporary CO_2 offsets only. One study reported, 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, there is concern that soil management practices could be stopped by farmers at any time as a consequence of changes in prices and technologies. Finally, given that costs of conservation tillage have declined dramatically in the past several decades, it is questionable whether increases in soil carbon that result from conservation tillage can be counted towards Kyoto targets, simply because they cannot be considered 'additional' as they are being undertaken by farmers to reduce costs and conserve soil (not to sequester carbon per se).

Emission Reductions

While the Kyoto Protocol permits various terrestrial options, particularly ones related to biological sinks, its main focus is on the avoidance of greenhouse gas emissions, especially CO_2 emissions associated with the burning of fossil fuels. What are the long-term consequences of reducing current fossil fuel use? Some argue 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). The reasoning behind this is that the price path of fossil fuels will be lower in the future because, by reducing use today, more fossil fuels are available for future use than would otherwise be the case. However, fossil fuels left in the ground may not be used in the future, because, if society commits to de-carbonizing the economy, behaviour may change and technology evolve in ways that reduce future demand for fossil fuels, much as the demand for wood used by locomotives was replaced by coal and then by diesel. Carbon in terrestrial sinks, on the other hand, always has the potential to be released.

Discounting Physical Carbon

By discounting carbon, one acknowledges that it matters when CO_2 is emitted or carbon sequestered – CO_2 removed from the atmosphere today is more important and has greater potential benefits than that removed at some future time. While the idea of discounting physical carbon is anathema to many who would discount only monetary values, the notion of weighting physical units accruing at different times is entrenched in the 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 (see van Kooten 2004, pp.76-77; Boyland 2006).

The effect of discounting physical carbon is to increase the costs of creating CO_2 offset credits because discounting effectively results in 'less carbon' attributable to a terrestrial carbon project. Discounting financial outlays, on the other hand, reduces the cost of creating carbon offsets. Since most financial outlays occur early on in the life of a forest or CO_2 storage project while carbon uptake is spread over time, costs of creating carbon offsets are not as sensitive to the discount rate used for costs as to that used for carbon. Discounting physical carbon has important implications. For example, it implies that temporary carbon storage is more valuable.

Addressing the Permanence Issue

The permanence problem can be addressed by providing partial instead of full credits for stored carbon according to the perceived risk that carbon will be released from a sink at some future date. The buyer or seller may be required to take out an insurance policy, where the insurer will compensate for the losses associated with unexpected carbon release (Subak 2003). Alternatively, the buyer or seller can provide some assurance that the temporary activity will be followed by one that results in permanent emission reductions. Again, insurance contracts can be used if there is a chance that the carbon contained in a sink is released prematurely. To address the risk of loss, a provider of offsets may be required, for example, to convert more land into forest than needed to sequester the contracted amount of carbon, or the rate used to discount physical carbon could be increased to account for uncertainty.

Three 'practical' approaches to non-permanence of sinks have been discussed in the literature. First, one ton of carbon-equivalent CO_2 emissions can be compensated for by a ton of carbon uptake with the conversion rate between ton-years of (temporary) carbon sequestration and permanent tons of carbon emissions reductions specified in advance (Dutschke 2002; IPCC 2000). If k is the conversion rate, then a LULUCF project must sequester k tons of carbon for one year to cover the one ton reduction in emissions.[1] The exchange rate ranges from 42 to 150 ton-years of temporary storage to cover one permanent ton. The ton-year concept has been condemned on various grounds (Herzog et al. 2003; Marland et al. 2001), but it 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 arbitrarily based on rotation length and is effectively a political decision. Once an exchange rate is chosen, carbon uptake credits can be traded in a CO_2-emissions market in straightforward fashion. But, clearly, the ton-years approach disadvantages carbon sinks relative to emissions avoidance (Dutschke 2002).

[1] 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 this interpretation is that one can count carbon stored in a sink for periods as short as one year, as might be the case in agriculture.

A second approach that has been adopted for Clean Development Mechanism (CDM) forestry projects is the creation of a 'temporary' certified emission reduction (CER) unit, denoted tCER. The idea is that a tCER is purchased for a set period of time and would, upon expiry, 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 more complex system of bookkeeping will be required at the international level to keep track of credits. Under this approach, countries can obtain carbon credits early, while delaying their 'payment' to a future date.

A third approach employs a market device that would obviate the need for an arbitrary conversion factor or other forms of political manoeuvring. 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 for a finite term, but, upon expiry, the renter incurs a debit unless the rental contract is renewed. The buyer-renter employs the limited-term benefits of the asset, but the seller-host retains long-term discretion over the asset, including responsibility for the liability after the (short-term) lease expires. Rather than the authority establishing a conversion factor, the interaction between the market for emission reduction credits and that for carbon sink credits can determine 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 emissions credit, which is determined by the market. Like the ton-year concept, a rental scheme makes terrestrial sink projects less attractive relative to emissions reduction.

3. SUPPLY OF CARBON OFFSET CREDITS AND THE 'PERMANENCE' ISSUE

Consider a comparison between two climate change mitigation options, neither of which results in permanent removal of CO_2 from the atmosphere. Suppose that the more permanent of the two, say a policy that leads to a lower current rate of CO_2 emissions, leads to an increase in CO_2 emissions N years from now, as argued by Herzog et al. (2003); the more ephemeral project generates temporary offset credits through sequestration of CO_2 in a forest ecosystem, but releases the CO_2 in n years.[2] What then is the value of forest-sink offset credit relative to an emissions reduction credit? Suppose that a unit of CO_2 not in the atmosphere is currently worth $\$q$, but that the shadow price rises at an annual rate $\gamma<r$, the discount rate. Then the value of emissions reduction is:

$$P = \sum_{t=1}^{N} \frac{(1+\gamma)^t q}{(1+r)^t} = \frac{1+\gamma}{r-\gamma} q \left[1 - \left(\frac{1+\gamma}{1+r} \right)^N \right], \tag{1}$$

while a sink offset would be worth some proportion α of the emissions reduction, or:

$$\alpha P = \sum_{t=1}^{n} \frac{(1+\gamma)^t q}{(1+r)^t} = \frac{1+\gamma}{r-\gamma} q \left[1 - \left(\frac{1+\gamma}{1+r} \right)^n \right]. \tag{2}$$

Upon taking the ratio of (2) to (1) and simplifying, we obtain the value of 'temporary' relative to 'permanent' storage:

$$\alpha = \frac{1 - \left(\frac{1+\gamma}{1+r} \right)^n}{1 - \left(\frac{1+\gamma}{1+r} \right)^N}, \tag{3}$$

which depends on the discount rate (r), the time it takes a ton of CO_2 stored in a forest ecosystem to return to the atmosphere (n), and the time it takes a ton of CO_2 not emitted today to increase emissions at a future date (N). Notice that the value does not depend on the price of carbon (q).

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[2] The comparison could just as well be between two forestry carbon sequestration projects with different degrees of 'permanence'.

As indicated in Table 1, the proportional value of a sink credit to an emissions reduction credit (α) varies depending on the relationship between n and N, the discount rate (r), and the growth rate (γ) in damages from CO_2. It is possible to prove some general results.

Proposition 1: *For fixed and finite N>0, as n/N→0, the value of temporary storage relative to permanent emissions reduction goes to zero.*

Proof: Differentiate equation (3) with respect to n and N, and sign the results.

$$\frac{\partial \alpha}{\partial n} = -\frac{\left(\frac{1+\gamma}{1+r}\right)^{n} \ln\left(\frac{1+\gamma}{1+r}\right)}{1-\left(\frac{1+\gamma}{1+r}\right)^{N}} > 0 . \tag{4}$$

$$\frac{\partial \alpha}{\partial N} = \frac{\left[1-\left(\frac{1+\gamma}{1+r}\right)^{n}\right]\left(\frac{1+\gamma}{1+r}\right)^{N} \ln\left(\frac{1+\gamma}{1+r}\right)}{\left[1-\left(\frac{1+\gamma}{1+r}\right)^{N}\right]^{2}} < 0 . \tag{5}$$

The reason for the signs is that the natural logarithm of a number less than 1 is negative (recall $\gamma<r$). Clearly, as the length of temporary storage increases relative to the 'permanence' of a CO_2 emission reduction (because of the *ceteris paribus* condition), the value of a temporary sink relative to an emission reduction increases; thus, as $n/N\rightarrow 0$, $\alpha\rightarrow 0$. The value of a temporary sink decreases as the 'permanence' of an emission reduction increases, *ceteris paribus*, because the period of sequestration (n) becomes too small to have any value. This might well be the case for carbon stored in soil due to conservation tillage.

Proposition 2: *For fixed n/N, an increase in N narrows the difference in importance between an emissions reduction and a carbon sequestration activity, ceteris paribus. An increase in N 'lengthens' n so that, with discounting, the eventual release of stored carbon (at time n) is valued much less today. If N→∞ so that an emission reduction is truly permanent, then the value of* *temporary storage depends only on the length of time that carbon is sequestered.*

Proof: The second term in the denominator of (3) approaches 0 as $N\rightarrow\infty$, so that the value of a temporary sink credit relative to a permanent one depends only on n (given γ and r). Since storage is not infinite, temporary offsets are still less valuable than permanent emission reductions.

Proposition 3: *The value of storage increases with the discount rate (∂α/∂r>0), as illustrated in Table 1. The reason that ephemeral activities are more important relative to emission reductions as the discount rate increases is because the inevitable release of sink* CO_2 *at some future date is weighted much less than the early sequestration. Thus, a policy requiring the use of low discount rates for evaluating climate change activities militates against carbon uptake in terrestrial sinks.*

Proof: Differentiate (3) with respect to r:

$$\frac{\partial\alpha}{\partial r}=\frac{\left(\frac{1+\gamma}{1+r}\right)^{n} n}{(1+r)\left(1-\left(\frac{1+\gamma}{1+r}\right)^{N}\right)}-\frac{\left(1-\left(\frac{1+\gamma}{1+r}\right)^{n}\right)\left(\frac{1+\gamma}{1+r}\right)^{N} N}{\left(1-\left(\frac{1+\gamma}{1+r}\right)^{N}\right)^{2}(1+r)} \tag{6}$$

The sign of $\frac{\partial\alpha}{\partial r}>0$ as long as $\frac{n}{N}>\frac{\left(\frac{1+r}{1+\gamma}\right)^{n}-1}{\left(\frac{1+r}{1+\gamma}\right)^{N}-1}$, which holds for all n, $N>0$, $n<N$, if $\gamma<r$. The proof is numerical. Clearly, if $n=N$, $\frac{\partial\alpha}{\partial r}=0$. Assume $r=0.04$ and $\gamma=0.02$. Then, if $n=1$ and $N=2$, we find ½ >0.4951; if $n=50$ and $N=100$, ½ >0.2747; if $n=250$ and $N=500$, ½ >0.0077; and so on.

Proposition 4: *As the rate at which the shadow price of carbon (γ) increases, the value of temporary storage relative to a 'permanent' emission reduction decreases. This implies that landowners would supply less carbon when the price of carbon is rising over time. The reason is* *that the supply of offset credits is a positive function of α and ∂α/∂γ < 0.*

Proof: Differentiate (3) with respect to γ:

$$\frac{\partial\alpha}{\partial\gamma} = -\frac{\left(\frac{1+\gamma}{1+r}\right)^{n} n}{(1+\gamma)\left(1-\left(\frac{1+\gamma}{1+r}\right)^{N}\right)} + \frac{\left(1-\left(\frac{1+\gamma}{1+r}\right)^{n}\right)\left(\frac{1+\gamma}{1+r}\right)^{N} N}{\left(1-\left(\frac{1+\gamma}{1+r}\right)^{N}\right)^{2}(1+\gamma)} \tag{7}$$

The result ∂α/∂γ<0 can only be proven numerically, but is easier to do by rearranging (7) (with ∂α/∂γ<0) as: $\frac{n}{N} > \frac{\left(\frac{1+r}{1+\gamma}\right)^{n}-1}{\left(\frac{1+r}{1+\gamma}\right)^{N}-1}$. Denote by $S(\alpha,\boldsymbol{P};\boldsymbol{Z})$ the supply of carbon offset sink credits, where α is the relative price of 'temporary' versus 'permanent' credits (as before), **P** is a vector of carbon input prices and the price of a permanent credit, and **Z** is a vector of characteristics that describes the offset project. Since $\frac{\partial S(\alpha,\boldsymbol{P};\boldsymbol{Z})}{\partial\alpha} > 0$, $S(\alpha,\boldsymbol{P};\boldsymbol{Z})$ shifts up with an increase in the price of carbon offset credits relative to emission reduction credits because ∂α/∂γ<0.

Proposition 5: *The minimum value of a carbon sink credit relative to an emission reduction credit equals the ratio of the lifetimes of the 'temporary' and 'permanent' credits, n/N.*

Proof: Only γ<*r* is possible because, if *γ*>*r*, economic agents would pursue climate mitigation (by purchasing carbon sink credits) to such an extent that the rate of growth in atmospheric CO_2 (the price of carbon credits) falls enough to equalize *γ* and *r*. Consider $r \to^{+} \gamma$. In that case, (1) becomes $P = \sum_{t=1}^{N} q = Nq$ and (2) becomes $\alpha P = \sum_{t=1}^{n} q = nq$, so that $\alpha = n/N$.

Policy Implications

The forgoing results have important policy implications that arise from the non-permanence associated with some policy instruments and the necessity of discounting physical carbon. It is clear that sink offset credits cannot generally be traded one-for-one for emission reduction credits, even if the latter are not considered permanent. The conversion rate will depend on the length of time that each keeps CO_2 out of the atmosphere, and, crucially, on the discount rate. For example, if a sequestration project can ensure that carbon remains sequestered for 10 years, it is worth only 0.11 of an emission reduction that ensures no future increase in emissions for 200 years if the discount rate (r) is 2% and the growth rate of damages (γ) is 1% (Table 1). Given the difficulty of determining not only the discount rate but the uncertainty surrounding n and N, it is not possible for the authority to determine a conversion factor. Rather, one must rely on the market to determine the exchange rate. Lack of market data for use in cost-benefit analysis requires that the analyst make some arbitrary judgments about the conversion rate between permanent and temporary removal of CO_2 from the atmosphere. While it is possible that carbon prices will increase over time, the value of temporary sequestration will be even lower. As a consequence, there might be a reduced demand for short-term sequestration.

While some advocate for the use of low discount rates, we demonstrated that rates can go no lower than the rate of increase in global environmental damage resulting from anthropogenic emissions of CO_2 – that is, no lower than the rate of increase in the shadow price of carbon. When discount rates are set at their lowest value, CO_2 offset credits are only worth n/N of an emission-reduction credit. This implies that ‘temporary’ offsets related to biological sink activities are overvalued because, as $N\rightarrow\infty$, the value of a temporary offset credit falls to zero. It is reasonable to assume that $N\rightarrow\infty$ if a carbon tax, say, results in behavioural changes that cause permanent reductions in CO_2 emissions (e.g., people trade in their SUV for a smaller vehicle).

Many CDM-initiated forestry activities seek to sell CO_2 offsets in international markets. Forestry projects in developed nations have the same objective. Although some projects are simply funded by international agencies, or 'picked up' by companies seeking to improve their corporate image, the forgoing analysis indicates the impossibility of determining the true cost of providing these types of offsets. Indeed, because most studies make ad hoc assumptions about the future path of prices, carbon uptake, harvests, risks of forest denudation and so on, it is impossible to judge adequately the true costs of carbon sequestration through forestry activities. Nonetheless, forestry offset credits are deemed acceptable for meeting Kyoto targets. To investigate how estimates of the costs of creating forestry offset credits are affected in practice by the issues indicated above, we employ meta-regression analysis.

4. META-REGRESSION ANALYSIS OF COSTS OF FOREST CO_2 OFFSETS

Meta-analysis synthesizes previously documented empirical results by combining or re-analyzing them in order to increase the power of statistical hypothesis testing (Koetse et al. 2005). Meta-regression analysis (MRA) is a type of meta-analysis that objectively explains why and quantifies how estimates from a range of empirical studies differ (Roberts 2005). MRA provides a framework for replicating results from different studies and offers a sensitivity analysis for model specification (Stanley 2005). 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 fail to find such evidence (Mann 1990, 1994).

In meta-regression analysis, statistical summary indicators are referred to as effect-sizes.

In the non-experimental set-up typical in economics, the effect-size indicator is typically an elasticity or nominal value (Florax 2002). The non-experimental setting introduces specific methodological challenges, however, because the meta-analysis is intrinsically heteroskedastic as the effect-sizes originate from studies with differing numbers of observations, which results in different estimated standard errors (Travisi et al. 2004). The true data generating process is often unknown, which leads to a mix of correct and erroneous effect-size measures, and the varying sets of control variables across the studies induce omitted variable bias and/or multicollinearity in at least a subset of the available primary studies (Koetse et al. 2005). Recent methodological advances help considerably in mitigating these challenges.

Many meta-analyses employ averaged values of the dependent and independent variables within a given source, so that the number of observations equals the number of studies investigated, but this could lead to aggregation bias in the meta-model if nonlinear specifications are employed (Stoker 1984, 1993). Additionally, using average values does not make use of all the information available in the primary studies. On the other hand, when multiple estimates are included, estimates originating from the same primary study are not independent of each other and studies with a larger number of estimates receive more weight if each of the estimates is treated as a separate observation.

A fixed- or random-effects specification can be used to address the issue related to multiple estimates. There has been considerable debate about whether it is appropriate to assume that heterogeneity can be fully explained by employing a fixed-effects model (Sutton et al. 2000, pp.83-84).[3] In environmental economics, most MRAs use fixed-effects models that permit some

[3] The meaning of terms fixed and random is somewhat different in the MRA literature than in the standard econometrics literature on panel data. In the meta-analysis literature, fixed and random effects relate to the weights in the meta-analysis (Weichselbaumer and Winter-Ebmer 2005).

heterogeneity in the meta-analysis, although it might be more desirable to assume that the underlying population effect-sizes differ between studies and that those effect-sizes are seen as random draws from a normal distribution (Florax 2002). The random-effects model is an attractive specification because, due to the randomly drawn effect-sizes, the results are easier to generalize and substantially higher degrees of freedom are left (Travisi et al. 2004).

As a response to the debate, we estimate regression models that (1) use only the averages of the various studies, (2) weight the average study values by the number of observations, and (3) use all of the observations from each study within a fixed- or random-effects framework. We subsequently expand the analysis by examining the robustness of MRA by dropping observations attributable to one author. Finally, we provide estimates of the marginal costs of carbon uptake in various forest ecosystems.

Regression Equation

As discussed earlier, the costs of sequestering carbon and providing CO_2 offsets from forestry activities have significant policy implications. In order to integrate and analyze previously estimated costs, we perform the following meta-regression analysis for the set of cost estimates generated by a given source study:

$$y_{is} = \alpha + \sum_{k=1}^{K} \beta_k Z_{k,js} + \varepsilon_{js} + u_s \quad s = 1,2, \dots S, \tag{8}$$

where y_{is} is the reported estimate of sequestration costs stemming from study s, S is the total number of primary studies, js is the number of estimates originating from study s, α is the intercept term, $Z_{k,js}$ is the meta-independent variable, and β_k is the meta-regression coefficient. Multiple estimates originating from the same study lead to a nested error structure that is decomposed into errors at the measurement level ε_{js} and the study level u_s, which are assumed to be normally distributed with zero mean and variances σ^2_e and σ^2_u, respectively (Bijmolt and Pieters 2001).

The studies we review have estimated the marginal or average costs of carbon uptake. Lacking information on the potential form of the marginal and average cost curves, we assume, for simplicity, that the full regression model would take the following form:

$$y_i = \gamma_0 D_i + \gamma_1 C_i + \gamma_2 C_i^2 + \alpha_0 + \alpha_1 x_1 + ... + \alpha_K x_K + \varepsilon_i, \; (i = 1, \ldots, N) \qquad (9)$$

where y_i refers to the total cost of carbon-uptake project i, D is a dummy variable that takes on a value of 1 if the study reports marginal cost and zero otherwise, C refers to carbon normalized to a per hectare basis, and there are K non-carbon regressors.

Data

Since the quality of a MRA depends on the quality of the data collection and the metrics chosen, we consider data issues at length. Selection bias occurs if the literature retrieval is such that the likelihood of sampling a study is correlated with the effect-size measure (Florax 2002). Thus, there should be an emphasis on including all studies, published or not, as a way of reducing potential biases introduced by any non-random selection of studies (Stanley 2001).[4] We collected information from 68 studies from various sources that provide estimates on costs of carbon uptake and storage in forest ecosystems. These yielded 1047 observations that were from over 30 countries, although most studies used data for the U.S. (21), Canada (7), Brazil (5) and India (3). Four studies employed data from Europe and 31 from developing countries (primarily in conjunction with Kyoto's Clean Development Mechanism). The quality of the data available from studies varies tremendously, even among the 44 peer-reviewed articles in our sample. A

[4] Publication bias occurs when researchers, referees or editors prefer statistically significant results, with insignificant findings left in the researcher's 'file drawer' (Rose and Stanley 2005).

summary of the studies is provided in Table 2. Each of the studies provides the required information needed for MRA, or sufficient data to have enabled us to construct the needed information. However, a significant number of studies that we considered were eliminated from further analysis and not included in Table 2, because they provided too little detail; yet, many of these constituted serious efforts to sell CO_2 offset credits.

The following illustrates an example of this. In a major review of terrestrial sequestration, the FAO (2004) examined 49 projects that were underway or proposed to create offset credits. One project was in the United States, with three in Australia and two in Europe, and the remainder in developing countries and thus eligible for CDM credits. There were 38 forestry projects, of which 17 involved forest conservation (and currently not Kyoto eligible, although rules are being revised) that, nonetheless, had local or offshore sponsors and/or investors (a country and/or company). 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 extent of the area involved. Data on the amount of carbon sequestered was considered 'good' for only 24 projects, although none provided an indication of the timing of carbon benefits. 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.[5]

Even for studies providing the requisite data (and thus are included in our analysis), details in some cases are sparse, making it difficult to assess how the calculations were made. 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 (although costs were much higher in other scenarios that they considered). 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 to the low annual management cost of avoiding harvests, ignoring both benefits from sale of timber and agriculture. Nonetheless, for these and similar studies, we retained observations with information as provided because we had no grounds for rejecting them – we could neither refute nor duplicate the cost estimates provided.

In our analysis, 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. In addition to the costs of carbon uptake and the amount sequestered per hectare, data were collected on publication date, type of forestry project, region, discount rate on financial (cost) measures, discount rate on physical carbon, whether opportunity cost of land was included, post-

[5] Consider also the first CDM forestry project accepted for approval in November 2006 (UNFCCC 2006). The 30-year project to establish 2,000 ha of multiple-use forests on degraded lands in Huanjiang County of Guangxi province of China involves Italy and Spain. The project's internal rate of return is 8.5% (below the 12% cut-off required by China), but 15.0% if CO_2 offsets are sold for \$4/tCO_2. By extrapolation, the cost of creating offset credits is low, about \$2.15/tCO_2. But, despite details in UNFCCC (2006), we could not determine the true cost of carbon uptake. A total of 773,842 tCO_2 is expected to be sequestered over the 30-year life of the project, which is converted to annual removals of 25,795 tCO_2 (while potential loss of CO_2 in 2036 is ignored). We lack sufficient information about the timing of outlays and revenues and the manner in which temporary offset credits are exchanged for permanent ones. Yet, Spain and Italy will each claim a share of the total credits that are to be created.

harvest use of fibre, whether soil carbon was included, scope of study, and method used to calculate carbon sequestration costs. With four exceptions, each of the studies in our sample provided multiple estimates of one or more projects and/or regions. For the 'study-level' regressions, we employed averaged values across a study for the level variables and permitted multiple dummy values where a study covered more than one location, employed different methods, and so on. 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.

Studies are catalogued into North America, Europe, tropics and other countries (e.g., Australia, Russia). We also distinguish whether studies are located in the boreal, Great Plains or U.S. cornbelt zones. We consider geographic scope using dummy variables to discern whether studies estimate costs of carbon uptake at the regional, national or global levels.

We use dummy variables to identify three carbon pools: carbon in tree biomass (including above and below ground), soils and wood products – in furniture, paper and wood materials that replace energy intensive materials like aluminium and steel in construction (Marland and Schlamadinger 1997). In addition, forest biomass can be used post-harvest to produce energy. We also classify three methods for calculating carbon uptake costs: sectoral optimization, econometrics and other (bottom-up) methods, with the latter taken as the base case.

Our MRA models also include dummy variables for opportunity cost of land (=1 if opportunity cost is included), marginal cost (=1 if marginal cost is included) and whether the study was peer reviewed (=1 if peer reviewed), and a general intercept term.

5. ESTIMATION RESULTS

Study Averages

The study-level regression results are provided in Table 4, while results using individual observations are provided in Table 5. A variety of models were examined, with the results quite robust with respect to model specification. Consider first the study-level results in Table 4. When results are weighted by the number of observations in each study, the R^2 goodness-of-fit measure is higher as is the statistical significance of estimated coefficients.

The level of carbon sequestered per hectare appears to have no significant effect in explaining costs, and this result holds over all the models that we examined. This finding supports our earlier discussion, indicating that there is a great deal of inconsistency across studies in how carbon uptake and costs are measured. Contrary to the earlier finding by van Kooten et al. (2004), the evidence indicates that estimates of carbon uptake costs that are more recent are lower, but only slightly.

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. However, this result is statistically insignificant in all of the models.

Regression results for other variables are easier to interpret, as shown in Table 4. One statistically powerful result is that projects in Europe are the most expensive to implement, with costs some \$300 per ton of carbon (\$82 per tCO_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 term (see below) and/or slower rates of tree growth. Overall, the results indicate that projects in the tropics can generate CO_2 offset credits at lower cost than projects in other regions (by some \$35-\$80/tCO_2). There is no statistical evidence that forestry activities in other regions can generate more or less costly CO_2 offsets.

Tree planting leads to significantly lower costs of creating CO_2 offsets than other activities. Indeed, the regression results indicate that tree planting costs are some \$210-\$460/tC (\$58-\$125/tCO_2) lower than for agroforestry projects (the baseline), *ceteris paribus*, while forest management projects lower costs by some \$150/tC (\$41/tCO_2). On the other hand, conservation activities (preventing deforestation) might actually be more expensive than agroforestry projects, by some \$120/tC (\$33/tCO_2).

The meta-regression analysis provides no statistical support for including soil carbon sinks in the calculation of costs of carbon sequestration. While soil carbon may be a relatively large component of total terrestrial carbon, it is only a small part of the change in ecosystem carbon resulting from a change in land use. Thus, its importance may be overrated so that, from a policy standpoint, the transaction costs associated with its inclusion might well exceed the benefits of taking it into account. Post-harvest use of fibre is important, however, in determining the cost of providing CO_2 offsets via forestry activities. Substituting wood biomass for fossil fuels in the generation of electricity, say, will reduce the costs of creating CO_2 offsets by some \$260/tC (\$70/tCO_2), but inclusion of product sinks actually increases costs of carbon uptake (by approximately \$53-\$58/tCO_2), contrary to expectation. The latter result may simply reflect the fact that timber suitable for wood products grow slower.

The effect of taking opportunity cost of land into account is also important. Taking opportunity cost into account adds some \$30/tCO_2 to costs. In some regions, the opportunity cost of land is indeed small because forestry is the best use of the land. However, 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 regional in scope tend to find higher costs of sequestering carbon in forest ecosystems compared to national level estimates, *ceteris paribus*. Regional level analyses result in costs that are some \$11-\$21/tCO_2 higher than national level analyses. The more relevant result is that, to the extent that global studies take into account price effects, the negative coefficient on the global dummy variable in the non-weighted model suggests that top-down models give lower carbon uptake costs than bottom-up approaches by some \$4-\$13/tCO_2. However, this coefficient estimate is highly statistically insignificant. We also find some slight statistical evidence to indicate that studies that used an econometric approach find lower cost estimates than optimization models and 'engineering-type' bottom-up calculations.

All Observations

In Table 5, we present the results of the fixed- and random-effects models using all of the 1047 observations provided by the 68 studies. The Breusch and Pagan Lagrangian multiplier tests for random effects indicate that the assumptions underlying the random-effects model are not met. Hausman tests for random- and fixed-effects also imply that the random-effects estimators are not consistent, while F-tests for the fixed-effects models indicate that there are significant study-level effects. The p-values for the fixed-effects models further suggest that a significant amount of variation in the costs of carbon sequestration is associated with study differences.

As is the case in the model using study averages, coefficients for both carbon sequestered per hectare and the carbon sequestered per hectare squared are very close to zero, but they are completely insignificant. The marginal cost dummy has a greater statistical impact in raising costs of carbon sequestration.

The results with respect to project location concur with the earlier study-average results in that sequestration projects in Europe add costs to carbon uptake while projects in the tropics result in lower costs.

The project activities seem to have a varied impact on the costs of carbon uptake. Tree planting continues to give lower costs in carbon sequestration than does agroforestry. Contrary to our results from the study-averages analysis, forest conservation now appears to lead to reductions in cost. There is little statistical significance in the coefficient on forest conservation, while forest management is estimated to add to carbon uptake costs, again contrary to the findings in Table 4. This latter result supports previous studies that indicated management activities are unlikely to be a cost effective way to sequester carbon (Caspersen et al. 2000).

The carbon discount rate again has little statistical effect on the cost of carbon uptake. We now find that the direction in which a small change in the discount rate for costs impacts the cost of carbon is positive, as anticipated.

Whereas the fossil fuel substitution dummy had an impact in the weighted model, this variable has little effect on cost in both the fixed- and random-effect models. Previously, our finding that the inclusion of product carbon sinks increases costs was not significant in the non-weighted OLS regression model. Now taking into account product carbon sinks has statistical significance in the fixed-effects model. We find it is even more important to consider the opportunity cost of land in our specification as the coefficient estimate of the relevant dummy is statistically significant in both the fixed- and random-effects models.

Contrary to our earlier results, we find here that studies employing an econometric method tend to report higher estimated costs than studies using other approaches, but the finding is not statistically significant.

Testing for Robustness

In refining our analysis and checking the robustness of the MRA, we removed five studies by one specific author (van Kooten; see Table 2), who focused on both Europe and North America. In Table 6, we provide the study-level regression results from the weighted model with 63 observations and those based on the fixed-effects model with 846 individual observations.

For the weighted model, the R^2 measure is improved when only 63 observations are included (compare Tables 4 and 6). We continue to find that sequestration projects located in Europe are more expensive than projects elsewhere, but the estimated addition in costs is now lower than in the original analysis. This is likely due to the inclusion of a Dutch study in Table 4 that was excluded in Table 6. We find comparable results that tree planting and forest management lower costs of creating CO_2 offset credits while forest conservation raises costs compared to the agroforestry baseline project, *ceteris paribus*.

Although we removed some one-fifth of the original 1047 observations in Table 6, the results remain quite robust with respect to model specification. While the coefficient for carbon sequestered per hectare is now statistically significant in the fixed-effects model, the estimate remains close to zero. Our earlier finding that more recent studies lead to lower cost is now also statistically significant in the fixed-effects model. Project location continues to be important as projects in Europe lead to higher costs, by some \$510-\$520/tC (\$139-\$143/tCO_2). Our findings for the effect of project activities on cost concur with previous results. Contrary to the MRA in

Table 4, we now find an anticipated negative sign on the discount rate on costs (although the estimated coefficient is statistically insignificant). We also find a more pronounced increase in costs than previously suggested from fossil fuel substitution as well as from the inclusion of the opportunity cost of land. Finally, our results from using 846 observations indicate studies employing econometric methods tend to give lower cost estimates than studies using other methods. Despite some differences between the results in Tables 4 and 6, the overall conclusions remain fairly robust.

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. Our calculations are provided in Table 7. Although cost estimates vary widely from one model to the next, and by region and activity, some general conclusions can be drawn. Assuming a threshold of about \$30/tCO_2 (the emissions reduction backstop), tree planting activities in particular are generally competitive with emissions reductions, particularly in tropical and boreal regions. In the latter, tree planting is much more competitive if it is combined with the substitution of biomass as fuel in lieu of fossil fuels. Given that conversion of wood biomass into liquid fuel is not yet economically feasible, this implies greater reliance on thermal power plants that burn biomass, usually co-fired with coal. Also note that forest management and forest conservation are, in general, not a competitive means of creating CO_2 offset credits, which is likely why the Kyoto process has resisted inclusion of efforts to reduce deforestation. And no forest activities in Europe are worth undertaking, at least not solely on the basis of their carbon uptake – such projects are simply too costly. This likely explains why Europe initially resisted efforts to include forest and other sinks in Kyoto accounting.

6. CONCLUDING REMARKS

The main argument of this paper is that forest activities to generate CO_2 offset credits should not be permitted in international agreements to mitigate climate change. We demonstrated that there are too many issues relating to, among others, the duration problem to enable analysts to provide clean estimates of the cost of carbon uptake in forest sinks. A review of studies indicates that many serious efforts to create forest CO_2 offsets failed to meet standards of accountability: Studies provided too little information to enable an outside analyst to determine how much carbon was to be sequestered and at what cost, mainly because authors failed to address the duration problem.[6] 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. As a result, we expected a priori that, even where adequate data are available, a general failure to address the duration problem would preclude discovery of a strong relationship between costs and amount of carbon sequestered, and between costs and discount rates for physical carbon and financial outlays. Consequently, one expects and finds a huge disparity in methods used to calculate carbon-uptake costs, and the meta-regression analysis confirms this.

Nonetheless, the MRA does provide some useful insights. For example, it is clear that location (Europe, tropics) and type of activity (in particular, tree planting, substitution of fossil fuels with biomass) 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

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[6] Studies also failed to take into account leakages, ignored issues of 'additonality' and overlooked other issues as well.

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.

Of course, since we employed data from only 68 studies, it might be worthwhile to add to the number of studies that are currently available, as well as assess studies that provide much less than the requisite information used in the meta-analysis. That is, what does one do with incomplete information, especially given that such information is used as the basis for determining whether firms or governments invest millions of dollars in forestry activities that seek to meet Kyoto obligations?

One cannot escape the fact that our review raises concerns about the use of forest activities and forest carbon sinks as a mechanism for addressing climate change. While not denying that plants and trees remove CO_2 from the atmosphere, thereby mitigating global warming, we question the effectiveness of sinks within the Kyoto framework. A country that use carbon sequestration credits to achieve some proportion of its CO_2 emissions-reduction target during Kyoto's first commitment period has avoided emissions reductions. If it is to remain committed to long-term climate mitigation, the country must increase its emission-reduction target in the next commitment period. It must meet that target plus the shortfall from the previous period – it still needs to reduce the emissions that were covered by forestry activities. Further, the country is technically liable for ensuring that the stored carbon remains there, which will be difficult given the non-permanence of forest sinks. The temporal shifting in the emissions-reduction burden caused by reliance on carbon sinks therefore results in an onerous obligation for future generations, one which they may not be willing to accept.

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Table 1: Value of a Temporary Relative to a Permanent Carbon Credit (α), Various Scenarios

n to *N* ratio	*N*=100 years Discount rate 2%	5%	10%	*N*=200 years Discount rate 2%	5%	10%	*N*=500 years Discount rate 2%	5%	10%
Growth rate of shadow price of carbon, γ=0									
0.01	0.023	0.048	0.091	0.040	0.093	0.174	0.094	0.216	0.379
0.05	0.109	0.218	0.379	0.183	0.386	0.614	0.390	0.705	0.908
0.10	0.208	0.389	0.615	0.333	0.623	0.851	0.629	0.913	0.991
0.15	0.298	0.523	0.761	0.457	0.769	0.943	0.774	0.974	0.999
0.20	0.379	0.628	0.851	0.558	0.858	0.978	0.862	0.992	1.000
0.25	0.453	0.710	0.908	0.641	0.913	0.991	0.916	0.998	1.000
0.30	0.520	0.775	0.943	0.709	0.947	0.997	0.949	0.999	1.000
Growth rate of shadow price of carbon, γ=0.01									
0.01	0.016	0.039	0.082	0.023	0.075	0.157	0.048	0.177	0.347
0.05	0.077	0.180	0.347	0.109	0.322	0.574	0.220	0.621	0.882
0.10	0.150	0.329	0.574	0.208	0.540	0.819	0.392	0.857	0.986
0.15	0.219	0.451	0.722	0.297	0.688	0.923	0.526	0.946	0.998
0.20	0.285	0.551	0.819	0.378	0.789	0.967	0.631	0.979	1.000
0.25	0.348	0.634	0.882	0.452	0.857	0.986	0.713	0.992	1.000
0.30	0.408	0.703	0.923	0.519	0.903	0.994	0.778	0.997	1.000
Growth rate of shadow price of carbon, γ=0.02									
0.01	n.a.	0.030	0.073	n.a.	0.056	0.140	n.a.	0.135	0.314
0.05	n.a.	0.143	0.315	n.a.	0.252	0.530	n.a.	0.516	0.849
0.10	n.a.	0.266	0.530	n.a.	0.441	0.779	n.a.	0.765	0.977
0.15	n.a.	0.373	0.678	n.a.	0.583	0.896	n.a.	0.886	0.997
0.20	n.a.	0.466	0.780	n.a.	0.688	0.951	n.a.	0.945	0.999
0.25	n.a.	0.546	0.849	n.a.	0.768	0.977	n.a.	0.973	1.000
0.30	n.a.	0.615	0.897	n.a.	0.827	0.989	n.a.	0.987	1.000
Growth rate of shadow price of carbon, γ=0.04									
0.01	n.a.	0.015	0.055	n.a.	0.022	0.106	n.a.	0.047	0.245
0.05	n.a.	0.076	0.245	n.a.	0.107	0.429	n.a.	0.215	0.754
0.10	n.a.	0.148	0.431	n.a.	0.204	0.674	n.a.	0.383	0.939
0.15	n.a.	0.217	0.571	n.a.	0.293	0.814	n.a.	0.516	0.985
0.20	n.a.	0.283	0.677	n.a.	0.373	0.894	n.a.	0.621	0.996
0.25	n.a.	0.345	0.757	n.a.	0.446	0.939	n.a.	0.704	0.999
0.30	n.a.	0.405	0.817	n.a.	0.512	0.965	n.a.	0.768	1.000

Table 2: Forest Carbon Sink Studies, Costs of Removing Atmospheric CO_2[a]

Study	# of Obs.	Total carbon (Mt)	Total area (mil ha)	Cost ($/ha)	Cost ($US/tC)
Adams et al. (1993)	12	350.00000	58.999056	442.28	73.20
Adams et al. (1999)	39	2023.07692	145.596613	401.52	29.16
Andrasko, Heaton & Winnett (1991)	9	806.00000	6.716000	1101.94	8.88
Baral & Guha (2004)	4	316.75000	1.000000	18602.34	63.30
Benitez & Obersteiner (2003)	6	2503.33333	237.000000	698.81	66.16
Benitez et al. (2006)	3	8183.66667	2975.000000	354.11	128.73
Boscolo & Buongiorno (1997)	3	0.00123	0.000050	2911.45	118.03
Boscolo, Buongiorno & Panayotou (1997)	29	0.00140	0.000050	1371.29	49.13
Brown, Cabarle & Livernash (1997)	6	8.90000	0.560801	10.29	1.84
Cacho, Hean & Wise (2003)	17	0.00010	0.000001	773.64	7.79
Callaway & McCarl (1996)	16	119.31818	29.624646	143.39	34.09
Darmstadter & Plantinga (1991)	3	155.97333	0.523667	1056.39	3.30
Dixon et al. (1993)	5	5.98500	0.029840	180.72	4.73
Dixon et al. (1994)	14	0.81357	0.010000	27.91	27.91
Dudek & Leblanc (1990)	1	1721.91805	4.896803	1562.43	4.44
Dutschke (2000)	4	1.08088	0.135750	363.02	32.43
FAO (2004)	8	1.37713	0.094178	171.12	64.03
Fearnside (1995)	3	0.00002	0.000001	2004.77	89.78
Healey et al. (2000)	21	0.01578	0.000406	2772.95	71.34
Hoen & Solberg (1994)	16	0.77847	0.575000	2407.49	1778.25
Houghton, Unruh & Lefebvre (1991)	18	1277.77780	27.722223	447.48	12.95
Huang & Kronrad (2001)	37	0.05625	0.001000	838.78	44.63
Krcmar & van Kooten (2003)	2	3.02600	1.236390	370.14	151.23
Lasco et al. (2002)	3	2.59761	0.020438	610.38	4.81
Lashof & Tirpak (1989)	6	834.58333	138.650000	83.00	13.76
Makundi & Okiting'ati (1995)	1	30.27400	0.186380	324.90	2.00
Masera et al. (1995)	7	150.66771	1.295429	3038.74	48.63
McCarl & Callaway (1995)	43	243.88372	47.390233	383.74	72.36
McCarney, Armstrong & Adamowicz (2006)	10	50.00000	0.888713	142.71	11.04
Moulton & Richards (1990)	70	472.68069	1.988651	5227.11	26.77
Moura Costa et al. (1999)	9	11.60644	0.210933	202.93	3.35
New York State (1991)	4	0.50250	0.804341	17.33	29.51
Newell & Stavins (1999)	46	7.66417	2.074701	699.79	181.13
Nordhaus (1991)	6	3550.00000	85.000000	4144.36	115.75
Olschewski & Benitez (2005)	6	18.05400	0.102000	2576.21	14.55
Parks & Hardie (1995)	4	29.96400	6.576285	967.26	260.29
Plantinga & Mauldin (2001)	45	41.54904	0.275678	5457.40	36.28

Table 2: Continued

Study	# of Obs.	Total carbon (Mt)	Total area (mil ha)	Cost ($/ha)	Cost ($US/tC)
Plantinga, Mauldin & Miller (1999)	21	12.79848	0.188260	4596.33	67.61
Poffenberger et al. (2001)	3	0.45980	0.011000	983.05	23.52
Poffenberger et al. (2002)	6	13.58974	0.048155	11.34	0.46
Putz & Pinard (1993)	1	0.00005	0.000001	182.78	3.97
Ravindranath & Somashekhar (1995)	4	603.00000	6.750000	171.96	1.90
Richards (1997b)	22	4079.54545	266.000000	2136.11	150.70
Richards, Moulton & Birdsey (1993)	4	42903.00000	86.402266	3446.72	6.94
Schroeder, Dixon & Winjum (1993)	7	16428.64857	192.857857	330.38	23.94
Sedjo & Solomon	6	72860.00000	465.000000	5975.33	38.14
Sohngen & Brown (2006)	30	2.28500	0.219699	1921.95	130.00
Sohngen & Haynes (1997)	2	29.00000	198.000000	7.34	50.10
Sohngen & Mendelsonh (2003)	6	32233.33333	381.316667	4585.09	70.74
Solberg & Hoen (1996)	16	2.73873	0.173000	2190.05	185.76
Spinney, Prisley & Sampson (2004)	6	0.09476	0.009200	192.09	20.36
Stavins (1999)	4	238.20327	70.044409	418.05	127.62
Stavins & Richards (2005)	2	3157.62208	35.425101	2740.67	27.31
Stennes (2000)	8	1.12500	1.236400	29.96	32.93
Stennes & McBeath (2005)	2	0.25740	0.580000	134.59	303.28
Stuart & Moura Costa (1998)	2	1.12975	0.096471	24.80	2.10
Swisher (1991)	18	6.47606	0.093950	293.10	7.96
TERI (1997)	54	1.35056	0.033151	525.75	18.13
Totten (1999)	8	6.03226	0.127463	52.13	4.63
van Kooten & Bulte (2000)	26	8.92154	0.150000	22809.55	494.55
van Kooten & Hauer (2001)	29	1.13793	1.236400	79.31	86.17
van Kooten et al. (1999, 2000)	120	19.58841	4.290617	57.17	38.39
van Kooten, Arthur & Wilson (1992)	24	120.93605	4.718333	537.03	63.78
van Vliet et al. (2003)	3	1.17942	0.039155	68.19	2.45
Volz et al. (1991)	7	31.47143	3.892857	772.00	248.10
Winjum, Dixon & Schroeder (1993)	14	100.03500	1.947143	536.98	15.83
Xu (1995)	20	490.51000	10.015000	209.68	5.14
Zelek & Shively (2003)	36	2.00151	0.000001	2398.82	24.65
Mean	**15.4**	**2886.47572**	**80.971894**	**1783.95**	**87.69**
Maximum	**120**	**72860.00**	**2975.00**	**22809.55**	**1778.25**
Minimum	**1**	**0.00002**	**0.000001**	**7.34**	**0.46**
Standard deviation	**19.42**	**10937.63216**	**367.295889**	**3658.28**	**224.51**

[a] Carbon sequestered, land area and costs are averaged over the observations in the study. Costs are in 2005 U.S. dollars

Table 3: Explanatory Variables, Means and Ranges, 1047 Observations

Variable	Mean	Std. Dev.	Minimum	Maximum
Dependent Variable				
Cost of carbon uptake (2005 US $ per tC)	92.035	531.259	0	14293.68
Explanatory Variables				
Years since 1989	8.592	4.315	0	17
Carbon per hectare (tC/ha)	61.412	119.989	0.146	2384.97
Discount rate on carbon (%)	3.75	3.72	0	15.00
Discount rates on costs (%)	5.47	3.88	0	17.25
Forest activity dummy variables				
Planting of forest (=1, 0 otherwise)	0.735	0.441	0	1
Agroforestry project (=1, 0 otherwise)	0.081	0.273	0	1
Forest conservation project (=1, 0 otherwise)	0.080	0.272	0	1
Forest management project (=1, 0 otherwise)	0.260	0.439	0	1
Location of study dummy variables				
Europe (=1, 0 otherwise)	0.075	0.264	0	1
Tropics (=1, 0 otherwise)	0.302	0.459	0	1
Boreal (=1, 0 otherwise)	0.212	0.409	0	1
U.S. Cornbelt (=1, 0 otherwise)	0.132	0.338	0	1
North American Great Plains (=1, 0 otherwise)	0.119	0.324	0	1
Other location (=1, 0 otherwise)	0.457	0.498	0	1
Geographic scope dummy variables				
Global (=1, 0 otherwise)	0.034	0.182	0	1
National (=1, 0 otherwise)	0.657	0.475	0	1
Regional (=1, 0 otherwise)	0.309	0.462	0	1
Methods dummy variables				
Optimization (=1, 0 otherwise)	0.185	0.389	0	1
Econometrics (=1, 0 otherwise)	0.111	0.314	0	1
Other bottom-up/engineering (=1, 0 otherwise)	0.704	0.457	0	1
Carbon pools dummy variables				
Carbon in products (=1, 0 otherwise)	0.479	0.500	0	1
Soil carbon (=1, 0 otherwise)	0.732	0.443	0	1
Wood used for fuel (=1, 0 otherwise)	0.082	0.275	0	1
Other items dummy variables				
Opportunity cost of land (=1, 0 otherwise)	0.742	0.438	0	1
Marginal cost (=1, 0 otherwise)	0.417	0.493	0	1
Peer reviewed (=1, 0 otherwise)	0.719	0.450	0	1

Table 4: Meta-Regression Analysis Results, Ordinary Least Squares Non-weighted and Weighted by Number of Observations in each Study (n=68)

Model →	Non-weighted				Weighted by number of observations			
Explanatory Variable	Est. coef.	Prob> stat[a]	Est. coef.	Prob> stat[a]	Est. coef.	Prob> stat[a]	Est. coef.	Prob> stat[a]
Intercept	397.520	0.089	310.072	0.071	652.371	0.023	589.198	0.020
Carbon per ha	-0.286	0.447	–	–	0.464	0.353	–	–
Carbon per ha sq'd	0.0002	0.110	–	–	0.00009	0.576	–	–
Marginal cost	65.080	0.362	71.333	0.217	56.433	0.266	72.582	0.087
Date of study	-14.386	0.188	-12.161	0.195	-24.048	0.057	-18.496	0.060
European location	301.813	0.051	310.914	0.044	436.635	0.004	457.686	0.003
Tropics	-187.067	0.120	-127.378	0.069	-294.726	0.044	-198.732	0.023
Boreal ecosystem	31.572	0.692	9.254	0.890	14.066	0.847	-6.530	0.922
Tree planting activity	-231.567	0.167	-212.001	0.154	-457.603	0.035	-429.987	0.040
Forest conservation	66.702	0.303	28.874	0.577	121.828	0.086	78.717	0.190
Forest management	-72.171	0.178	-71.478	0.172	-134.166	0.060	-168.010	0.045
Carbon discount rate	-11.240	0.463	-4.604	0.367	-9.127	0.526	-7.862	0.149
Carbon discount rate × carbon per ha	-0.051	0.505	–	–	-0.138	0.069	–	–
Discount rate on costs	-0.243	0.973	–	–	0.557	0.942	–	–
Fossil fuel substitution	-74.992	0.539	-42.703	0.618	-256.447	0.098	-242.324	0.100
Product carbon sink	98.200	0.209	119.250	0.105	195.017	0.043	213.791	0.034
Opportunity cost of land	99.437	0.146	76.861	0.206	108.314	0.109	79.242	0.159
Regional scope	40.820	0.410	45.898	0.294	75.415	0.268	66.805	0.216
Global scope	-15.073	0.832	-48.175	0.504	37.569	0.757	-16.844	0.874
Econometric method	-112.199	0.211	-139.459	0.127	-187.082	0.059	-221.632	0.043
F statistic	1.710	0.068	1.260	0.260	2.160	0.016	2.440	0.009
(degrees of freedom)	(19, 48)		(15, 52)		(19, 48)		(15, 52)	
R^2	0.483		0.452		0.676		0.646	
RMSE	190.640		188.610		153.730		154.250	

[a] Prob indicates the probability that the estimated coefficient is different from zero, based on robust standard errors.

Table 5: Meta-Regression Analysis Results, Ordinary Least Squares and Random Effects Models (n=1047)

Model →	OLS Regression				Random Effects			
Explanatory Variable	Est. coef.	Prob> stat[a]	Est. coef.	Prob> stat[a]	Est. coef.	Prob> stat	Est. coef.	Prob> stat
Intercept	148.491	0.042	118.937	0.040	148.491	0.042	118.937	0.084
Carbon per ha	-0.163	0.273	–	–	-0.163	0.659	–	–
Carbon per ha sq'd	0.0001	0.139	–	–	0.0001	0.671	–	–
Marginal cost	130.529	0.075	124.971	0.026	130.529	0.005	124.971	0.003
Date of study	-16.008	0.156	-13.382	0.151	-16.008	0.005	-13.382	0.012
European location	600.459	0.007	585.927	0.005	600.459	0.000	585.927	0.000
Tropics	-58.079	0.058	-31.832	0.024	-58.079	0.295	-31.832	0.521
Boreal ecosystem	-40.759	0.316	-32.859	0.459	-40.759	0.494	-32.859	0.569
Tree planting activity	-106.353	0.155	-113.364	0.137	-106.353	0.033	-113.364	0.021
Forest conservation	-14.357	0.433	-30.069	0.239	-14.357	0.827	-30.069	0.635
Forest management	41.177	0.223	26.853	0.194	41.177	0.399	26.853	0.560
Carbon discount rate	-10.030	0.256	-3.788	0.128	-10.030	0.254	-3.788	0.445
Carbon discount rate × carbon per ha	0.005	0.733	–	–	0.005	0.918	–	–
Discount rate on costs	1.415	0.622	–	–	1.415	0.826	–	–
Fossil fuel substitution	-7.445	0.892	16.428	0.672	-7.445	0.923	16.428	0.826
Product carbon sink	42.200	0.074	63.364	0.065	42.200	0.363	63.364	0.143
Opportunity cost of land	98.421	0.067	86.432	0.085	98.421	0.053	86.432	0.077
Regional scope	72.059	0.155	48.442	0.177	72.059	0.195	48.442	0.356
Global scope	-97.018	0.052	-113.531	0.066	-97.018	0.305	-113.531	0.223
Econometric method	17.582	0.353	8.759	0.659	17.582	0.805	8.759	0.902
F statistic	7.920	0.000	7.730	0.000				
(degrees of freedom)	(19, 1027)		(15, 1031)					
R^2	0.106		0.104					
RMSE	507.050		506.510					
σ_u					0.000		0.000	
σ_e					499.560		498.767	
Rho					0.000		0.000	
R^2: within					0.0003		0.0002	
between					0.520		0.512	
overall					0.1056		0.1041	
Wald $\chi^2(19)$					121.280	0.000	119.740	0.000
Breusch-Pagan LM $\chi^2(1)$					0.800	0.371	1.260	0.261

[a] Prob indicates the probability that the estimated coefficient is different from zero, based on robust standard errors.

Table 6: Meta-Regression Analysis Results, Ordinary Least Squares Weighted by Number of Observations in each Study (n=63) and Ordinary Least Squares (n=846)

Model →	Weighted by number of observations (n=63)				OLS Regression (n=846)			
Explanatory Variable	Est. coef.	Prob> stat[a]	Est. coef.	Prob> stat[a]	Est. coef.	Prob> stat[a]	Est. coef.	Prob> stat[a]
Intercept	692.690	0.027	513.465	0.028	203.367	0.063	135.133	0.068
Carbon per ha	-0.088	0.860	–	–	-0.336	0.045	–	–
Carbon per ha sq'd	0.0001	0.387	–	–	0.00003	0.508	–	–
Marginal cost	91.209	0.116	98.788	0.023	165.674	0.041	132.829	0.011
Date of study	-26.194	0.026	-20.204	0.029	-15.717	0.077	-11.168	0.072
European location	289.261	0.071	346.937	0.034	523.391	0.028	510.765	0.026
Tropics	-335.957	0.043	-180.015	0.040	-79.330	0.080	-19.026	0.259
Boreal ecosystem	176.111	0.144	126.171	0.210	135.639	0.262	123.526	0.276
Tree planting activity	-449.525	0.028	-405.156	0.034	-124.951	0.140	-137.921	0.125
Forest conservation	146.837	0.036	99.223	0.109	-20.601	0.473	-52.931	0.248
Forest management	-149.908	0.055	-182.049	0.047	-25.063	0.370	-48.955	0.260
Carbon discount rate	-25.406	0.122	-16.707	0.097	-24.227	0.123	-16.835	0.151
Carbon discount rate × carbon per ha	-0.055	0.409	–	–	0.051	0.161	–	–
Discount rate on costs	-2.582	0.817	–	–	-6.722	0.242	–	–
Fossil fuel substitution	-135.767	0.286	-99.029	0.365	59.499	0.251	62.411	0.222
Product carbon sink	185.892	0.043	228.694	0.025	58.205	0.131	101.270	0.091
Opportunity cost of land	200.445	0.102	198.414	0.095	217.881	0.108	198.957	0.121
Regional scope	64.104	0.322	52.484	0.318	56.050	0.048	14.864	0.305
Global scope	62.087	0.630	-37.841	0.721	-169.672	0.135	-196.522	0.137
Econometric method	-197.389	0.090	-243.139	0.051	-46.627	0.428	-60.914	0.360
F statistic	1.360	0.197	1.020	0.456	3.570	0.000	3.460	0.000
(degrees of freedom)	(19, 43)		(15, 47)		(19, 826)		(15, 830)	
R^2	0.692		0.653		0.107		0.102	
RMSE	162.070		164.680		557.420		557.650	

[a] Prob indicates the probability that the estimated coefficient is different from zero, based on robust standard errors.

Table 7: Marginal Costs of Creating Carbon Offset Credits through Forestry ($/tCO$_2$)

Scenario[a]	68 obs Weighted OLS	1047 obs OLS	63 obs Weighted OLS	846 obs OLS
Global	$28.85	$25.10	$28.96	$24.04
Planting	$0.26	-$4.93	-$22.52	-$27.03
Planting & opportunity cost of land	$29.80	$21.91	$32.15	$32.39
Planting, opportunity cost of land & fuel substitution	-$40.14	$19.88	-$4.88	$48.62
Forest management	$88.47	$35.31	$59.20	$0.22
Forest management & opportunity cost of land	$118.01	$62.15	$113.87	$59.64
Forest management, opportunity cost of land & fuel substitution	$48.07	$60.12	$76.84	$75.86
Forest conservation	$158.28	$20.16	$140.13	$1.43
Forest conservation & opportunity cost of land	$187.82	$47.00	$194.80	$60.85
Europe	$173.26	$183.64	$140.48	$162.81
Planting & opportunity cost of land	$185.44	$180.14	$158.29	$170.61
Planting, opportunity cost of land & fuel substitution	$115.50	$178.11	$121.26	$186.84
Forest management & opportunity cost of land	$273.65	$220.38	$240.01	$197.86
Forest management, opportunity cost of land & fuel substitution	$203.71	$218.35	$202.98	$214.08
Tropics (CDM Projects)	-$26.20	$4.04	-$30.04	-$1.56
Planting & opportunity cost of land	-$25.26	$0.85	-$26.84	$6.79
Planting, opportunity cost of land & fuel substitution	-$95.20	-$1.18	-$63.87	$23.02
Forest management & opportunity cost of land	$62.95	$41.09	$54.87	$34.04
Forest management, opportunity cost of land & fuel substitution	-$6.99	$39.06	$17.84	$50.26
Conservation	$103.22	-$0.90	$81.13	-$24.17
Conservation & opportunity cost of land	$132.76	$25.94	$135.80	$35.25
Boreal Region	$58.01	$8.77	$109.62	$57.06
Planting & opportunity cost of land	$70.19	$5.26	$127.43	$64.86
Planting, opportunity cost of land & fuel substitution	$0.25	$3.23	$90.40	$81.09
Forest management & opportunity cost of land	$158.40	$45.50	$209.15	$92.11
Forest management, opportunity cost of land & fuel substitution	$88.46	$43.47	$172.12	$108.33

[a] 2005 US dollars. Multiplying by 44/12 converts carbon to CO_2. The base case for each of the three regions below includes discounting of carbon and financial costs (at average values), inclusion of soil carbon, regional/national scope, optimization technique, and bottom-up method.