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How Costly are Carbon Offsets? A Meta-Analysis of Forest Carbon Sinks

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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. As a result of agreements reached at Bonn and Marrakech, carbon offsets have taken on much greater importance in meeting Kyoto targets for the first commitment period. In this study, meta-regression analysis is used to examine 981 estimates from 55 studies of the costs of creating carbon offsets using forestry. Baseline estimates of costs of sequestering carbon through forest conservation are US\$46.62–\$260.29 per tC (\$12.71–\$70.99 per t CO_2). Tree planting and agroforestry activities increase costs by more than 200%. When post-harvest storage of carbon in wood products, or substitution of biomass for fossil fuels in energy production, are taken into account, costs are lowest – some \$12.53/tC to \$68.44/tC (\$3.42–\$18.67/t CO_2). Average costs are greater, between \$116.76 and \$1406.60/tC (\$31.84–\$383.62/t CO_2), when appropriate account is taken of the opportunity costs of land. Peer review of the studies increases costs by a factor or 10 or more, depending on the model. The use of marginal cost estimates instead of average cost results in much higher costs for carbon sequestration, in the range of thousands of dollars per tC, although few studies used this method of cost assessment.

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

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1. Introduction

Climate change constitutes a long-term threat to the earth's ecosystems and possibly to the way people lead their lives. For island dwellers, for example, global warming constitutes a very real danger, and it may be a threat to agriculture, particularly subsistence farmers in developing countries. However, the full extent of potential damages remains unknown (IPCC, 1996).

Many mitigation responses to climate change have been proposed, including land use, land-use change and forestry (LULUCF) policies that increase carbon sink functions of terrestrial ecosystems (IPCC, 2000). LULUCF policies have taken on an increasingly important role as a result of negotiations on the Kyoto Protocol at COP6$_{bis}$ in Bonn (July 2001) and COP7 in Marrakech (November 2001). The agreements permit countries to substitute carbon uptake from LULUCF activities in lieu of reduced greenhouse gas emissions in meeting targets during the Protocol's first commitment period (ICTSD, 2001). Technical methodologies for estimating gas emissions and measuring carbon sequestered in sinks are in the process of being resolved, but could nonetheless remain an obstacle in monitoring of carbon offsets.

A primary motive for including sinks in the accounting process is the prospect of avoiding expensive controls on the emission of carbon dioxide and other greenhouse gases. It has been anticipated that growing trees to remove CO_2 from the atmosphere would be cheaper than developing and implementing technologies to decrease the emissions of existing industries, such as switching to alternative fuels for energy production or the use of scrubber-type cleaning technologies (Obersteiner et al., 2001; Sohngen and Alig, 2000; Chomitz, 2000). Cleaning technologies in particular may cost as much as ten times that of other means per unit of carbon stored (Dudek and Leblanc, 1990). Carbon taxes on fuels are likewise feared to be expensive instruments, perhaps costing double what it would take to reduce emissions through sinks (Callaway and McCarl, 1996).

Initial proponents were ambitious in proclaiming the possibilities that LULUCF represented. For example, a US Department of Energy official predicted that "tree-planting will allow US energy policy to go on with business as usual out to 2015" (Pearce, 1994). Early projects reported sequestering carbon through forestry at costs as low as pennies per ton of carbon (Moura-Costa and Stuart, 1998). Later, more detailed analyses revealed costs to be higher than anticipated. Rough estimates of overall costs for many ecosystems, or even for whole countries or the entire world, proved easy to obtain, but they often ignored factors that affect the rate at which trees absorb carbon, including type of species, age of stands, susceptibility to fire and disease, location, et cetera. Further, the earliest studies in many cases were not (and did not purport to be) scientific, seeking to improve public relations for sponsoring firms rather than to generate verifiable data. Some of the early studies referred to by Dixon et al. (1993), for example, considered only one party's contributions to a project's costs, ignoring contributions from different governmental bodies and environmental NGOs. The application of scientific methods and more comprehensive accounting systems naturally generated higher estimates of costs. Cost estimates are important because they are used to compare LULUCF projects and compare these to policies aimed at reducing greenhouse gas emissions.

The purpose of the current study is to review and synthesize the contributions of various studies to our knowledge of the costs of sequestering carbon in terrestrial ecosystems via forestry activities. To avoid judging the quality and/or appropriateness of various approaches to the calculation of carbon-uptake costs, we employ meta-regression analysis to distill information about factors that affect the costs of carbon sequestration via forestry projects. We begin by examining the state of the literature in section 2, and describing our approach in section 3. The meta-regression parameter estimates are provided in section 4, as are projections of the likely costs of creating carbon offsets through forest activities. In the concluding section we identify the principal factors that influence carbon sequestration costs, and call attention to some important concerns about how the Kyoto Protocol might be implemented.

2. Issues Pertaining to LULUCF Studies

There are several levels at which cost-of-carbon-sequestration studies differ. First off, the underlying environmental science can vary. Some estimates of carbon uptake take into account only the commercial component of the tree (or bole), while others include all vegetation. Still others include soil organic carbon (SOC), which can be enhanced through carbon-fixing roots and fallen and decaying branches and leaves, and deteriorated through erosion. The decision to include or exclude SOC alone can result in a vastly different estimate of carbon-uptake costs, since as much as two-thirds of the carbon stored in terrestrial ecosystems is in soils (Dudek and Leblanc, 1990, p.34). Other scientists contend that soil accounts for only 15% of carbon absorbed (Richards et al., 1993), while still others note that up to three times as much carbon is stored in soils as in vegetation (Dixon et al., 1994). Perhaps due in part to the ambiguity surrounding soil carbon and its measurement, the Kyoto Protocol remains unclear as to how soil carbon will be treated (Marland et al., 2001). Spatial variation in soil carbon storage would make broad-based testing of soil necessary for inclusion in sequestration figures (Antle and Mooney, 1999). The rate at which soil carbon is lost during harvest and the amount and rate of decomposition of debris on the site are also important considerations (Sedjo et al., 1995, p.152).

It is clear that impacts on soil should be carefully evaluated.

If a project involves growing and harvesting timber, the decay rate of the generated forest products is sometimes taken into consideration in determining how much carbon is sequestered over a given period of time. Sedjo et al. (1995) point out that "the long-term effects on atmospheric carbon [of LULUCF projects] … are highly dependent upon the assumptions of the life-cycle of the wood products" (p.154). Spinney et al. (2004) come to a similar conclusion, finding that, for loblolly pine, the amount of carbon stored can vary by as much as 70% depending on what is assumed about the life-cycle of wood products.

Various carbon sequestration policies result in different carbon uptake costs and benefits. Since deforestation accounts for more carbon emissions than fossil fuel use in developing countries such as Brazil (Fearnside, 1995), one strategy for mitigating climate change involves making sure existing forests stay intact – referred to as forest conservation. This is not costless as opportunity costs need to be taken into account, but it is likely to be less expensive than afforestation, say, or the establishment of tree plantations in place of native forest.

Other projects touted for carbon sequestration potential include reduced-impact logging (Moura-Costa et al., 1999), sustainable forest management (Ravindranath and Somashekhar, 1995), burning tree biomass in place of fossil fuels in energy production (Solberg and Hoen, 1996; van Kooten et al., 1999, 2000), and agroforestry (Dixon et al., 1994). In addition, location affects outcomes, as tropical vegetation absorbs carbon more rapidly than do temperate ecosystems (Moura-Costa et al., 1999).

Estimating carbon sequestration across ecosystems is troublesome enough, but is further complicated by the variety of ways in which cost estimates are interpreted in economic analyses. Rules for how costs should be computed and a standard statistic for expressing costs remain to be developed (IPCC, 1996, 2001). Thus, cost estimates for carbon uptake vary greatly according to the methodology employed.

In the literature, four basic methods for calculating the costs of carbon sequestration are found. Some researchers estimate average costs for sequestration, usually on large-scale projects (Sedjo and Solomon, 1989; Dudek and LeBlanc, 1990). Others estimate the costs of developing carbon sinks by identifying the land and practices that facilitate carbon uptake at a minimum cost (Moulton and Richards, 1990; Pautsch et al., 2001; Boscolo et al., 1997; Callaway and McCarl, 1996; Krcmar et al., 2004). Still others employ computer simulation models, usually based on the optimization of land uses and projections about climate and/or climate policies (Adams et al., 1999; Hoen and Solberg, 1994). Finally, some studies have employed econometric methods to determine costs of carbon sequestration (Stavins, 1999; Plantinga et al. 1999).

While computing the average amount of carbon a stand of trees would absorb per year and dividing by the initial costs of planting those trees provides a rough estimate of some of the costs, it can hardly be considered a complete accounting. Simply averaging costs over time "fails to account for the time pattern of the benefits (loss or damage reductions) arising from changes in forest carbon flux" (Adams et al., 1999). Scale of project, location, transaction costs, weighting of costs and benefits depending on when they are realized, whether or not trees are harvested and what is done with the logs, and the changing rate at which trees absorb carbon dioxide through their lifetimes affect cost estimates.

Jepma and Munasinghe (1998) give several reasons why larger scale projects are likely to be more expensive, including "diminishing uptakes as less suitable or less well managed land is forested, resulting in a lower carbon uptake per hectare", increasing public resistance to interference with present land use, and lack of operating and maintenance economies of scale (p.240). Many quantitative analyses support this contention, which is not apparent from studies that focus on average costs. Thus, for example, Stavins' (1999) calculations reveal increasing marginal costs as greater amounts of total carbon are sequestered.

Discounting is also a source of controversy in cost-benefit analyses related to LULUCF projects. Discounting implies that a unit of carbon emitted into (or removed from) the atmosphere at a future date is worth less than if that same unit were emitted (removed) today. The idea of discounting physical carbon is anathema to many, but 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). Richards (1997) demonstrates that, if physical carbon is not discounted, this assumes that damages from rising atmospheric concentrations of CO_2 are increasing at the same rate as the social rate of discount. If damages rise slower than atmospheric CO_2, a positive discount rate on physical carbon is appropriate. Since a zero discount rate on physical carbon implies that there is no difference between removing a unit of carbon from the atmosphere today, tomorrow or at some future time, this could be extrapolated to conclude that it does not matter if the carbon is ever removed from the atmosphere. Therefore, discounting carbon increases the importance of any carbon sequestration, and especially that occurring in the near future.

There are three approaches in the literature (IPCC, 1996; Richards and Stokes, 2004):

1. The "flow summation method" sums carbon sequestered regardless of when capture occurs. Total undiscounted or, more generally, discounted cost of the project is then divided by the total sum of carbon to provide a cost per ton estimate.
2. Under the "average storage method", the annualized present value of costs is divided by the mean annual carbon stored.

3. The “levelization/discounting method” discounts both costs and physical carbon sequestered depending on when they occur, although costs and carbon can be discounted at different rates.

To obtain a consistent estimate of the costs of carbon uptake, however, it is necessary to discount both project costs and physical carbon, even if at different rates of discount. To illustrate why, consider the following example.

Suppose a tree-planting project results in the reduction of CO_2-equivalent emissions of 2 tons of carbon (tC) per year in perpetuity (e.g., biomass burning to produce energy previously produced using fossil fuels). In addition, the project has a permanent sink component that results in the storage of 5 tC per year for ten years, after which time the sink component of the project reaches an equilibrium. How much carbon is stored? If an annualized method (method 2) is employed, then one must use either 2 tC or 7 tC per year. Suppose the discounted project costs amount to $1,000, or annualized costs of $40 if a 4% rate of discount is used. The costs of carbon uptake are then estimated to be either $20 per tC or $5.71/tC, with the latter figure often used to make the project appear more desirable. Under the first method, the cost would essentially be zero because $1,000 would need to be divided by the total amount of carbon absorbed, which equals infinity. Therefore, an arbitrary planning horizon needs to be chosen. If the planning horizon is 30 years, 110 tC are sequestered and the average cost is calculated to be $9.09 per tC; if a 40–year planning horizon is chosen, 130 tC are removed from the atmosphere and the cost is $7.69/tC. Thus, cost estimates are sensitive to the length of the planning horizon, which is not usually made explicit in most studies.

Cost estimates that take into account all carbon sequestered plus the timing of uptake can only be achieved under the third method. Suppose physical carbon is discounted at a lower rate (say, 2%) than that used to discount costs (4%). Then, the total discounted carbon saved via our hypothetical project amounts to 147.81 tC and the correct estimate of costs is $6.77 per tC. Reliance on annualized values is misleading in this case because costs and carbon are discounted at different rates.[1] If the same discount rate of 4% is employed for costs and carbon, the $10.62/tC cost is the same regardless of whether costs and carbon are annualized.

When planting costs are annualized, the effect is similar to the discounting of carbon. Suppose that a project sequesters 10 tC per year for 80 years and that planting costs are $2000. Using the flow summation method, the cost of carbon uptake is $2.50/tC. Assuming a discount rate of 5%, costs can be annualized by multiplying by 0.05103, resulting in a carbon-uptake cost of $10.21 (= $102.06/10 tC). This is more than four times greater than that obtained when costs are not annualized. This suggests a positive relationship between the discount rate used to discount costs and the cost of carbon uptake, much as an increase in the discount rate used to discount physical carbon leads to a higher cost (because there is now less carbon). In essence, therefore, annualizing up-front planting costs has an effect that is similar to discounting physical carbon.

The diversity in existing research makes it difficult to provide an overview of these complex methods without some form of quantitative analysis. In an attempt to develop a more comprehensively based estimate of the true costs of carbon sequestration, we use meta-regression analysis to investigate a broad spectrum of data on the costs of carbon sequestration by land use change and forestry. We examined 55 studies published between 1989 and 2004, some of which were peer reviewed while others were prepared for various government or non-governmental organizations. Inclusion of the "peer review" variable enabled us to examine

[1] If carbon is annualized using a 2% rate, costs amount to $13.53 per tC (=$40 ÷ 2.96 tC).

whether review by experts in the field affects carbon-uptake cost estimates.

3. A Meta-Regression Model of Carbon Uptake Costs

Meta-regression analysis is a statistical technique that originated in 1904 when Karl Pearson evaluated data from many studies to conclude that vaccination against intestinal fever was ineffective (Mann, 1994). Since then it has evolved into a widely accepted systematic process for analyzing data from a variety of studies on a given phenomenon to discover the factors that influence it. Where individual studies provide estimates of the relationship between variables at a given point, meta-analysis seeks to move from the results of individual studies to a more general description of the relationship between the variables (Curtis and Wang, 1998; Smith and Kaoru, 1990).

Where review articles once summarized data on a particular topic subjectively, meta-regression analysis relies on statistical analysis to report on significant trends or findings in the literature (Stanley, 2001). Since the results from a large number of studies are analyzed, meta-analysis can find a significant trend even where many individual studies might have failed to achieve significant results (Mann, 1990). In doing so, it makes large amounts of data more accessible to policymakers who might otherwise be at a loss when faced with contradictory or seemingly "insignificant" information from multiple studies (Mann, 1990, 1994). Meta-analysis is also used to explain study-to-study variation by determining the extent to which methods, design and data affect reported results (Stanley, 2001). Often times, a contributing study uses several model specifications and provides more than one estimate of the meta-variable of interest. In such a case, Stanley suggests that the average of the estimates might be used in the meta-regression analysis to avoid having one study dominate the results. Such an approach leads to the loss of information as it fails to exploit the variability in estimates flowing from different combinations of explanatory variables used in a given single study. In addition, averaging values of dependent and independent variables within a given source may lead to aggregation bias in the meta-model if non-linear specifications are employed (Stoker, 1984, 1993).

Instead, multiple observations for some or all studies call for a regression model that recognizes the common origin for a given bundle of estimates and the resulting implications for the correlation structure of error terms in the meta-model. For our application, we assume that the set of cost estimates generated by a given source study can be expressed as follows:

$$\begin{aligned} y_i &= x_i \beta + \varepsilon_i \quad \text{with} \\ \varepsilon_i &= \mu_i + e_{it} \,, \end{aligned} \qquad (1)$$

where y_i is a vector of s_i observations on sequestration costs stemming from study i, x_i is an $s_i \times k$ matrix of regressors, and ε_i is an $s_i \times 1$ vector of error terms associated with cost vector y_i. As indicated in (1), this error vector is decomposed into a study-specific constant μ_i (invariant over individual cost reports), and a vector e_{it} containing a set of s_i independent, identically distributed (iid) observation-specific errors with mean zero and common variance σ^2_e. We further stipulate the distribution of μ_i as:

$$\begin{aligned} E[\mu_i] = 0, \quad E\left[\mu_i \mu_j'\right] &= \sigma_\mu^2 \cdot I_{si} \qquad && i = j \\ &= 0 && i \neq j \end{aligned} \qquad (2)$$

where E denotes the expectation operator, and I_{si} an $s_i \times s_i$ identity matrix. Thus, each contributing study "draws" a study-specific constant term from a normal distribution with mean zero and variance σ^2_u. As indicated in (2), these deviations are uncorrelated across studies.

In addition, we assume that μ_i, e_i and x_i are uncorrelated within and across studies. In essence, (1) and (2) describe a random effects model, a common specification in panel data analysis (Greene, 2000, pp.567–78). By allowing for study-specific error terms, the model captures correlation across observations within a given study. This increases model efficiency compared to a standard cross-sectional regression with iid error terms for each observation (Moulton, 1986). The full model over all *n* studies takes the form:

$$y = X\beta + \varepsilon = X\beta + \mu + e \qquad with$$
$$\mu = \begin{bmatrix} \mu_1 \\ \mu_2 \\ \vdots \\ \mu_n \end{bmatrix} \qquad E[\mu\mu'] = \sigma_\mu^2 \cdot I_N \qquad E[ee'] = \sigma_e^2 \cdot I_N \tag{3}$$

where *y* is a vector of size $N = \sum_{i=1}^{n} s_i$ by 1, and *X* is a $N \times k$ matrix of regressors. Equation (3) can be estimated using Generalized Least Squares (GLS) or Maximum Likelihood (MLE) Methods (Greene, 2000, pp.570–72). We use both a Breusch-Pagan lagrangian multiplier test and a Hausman test for random effects.

If the hypothesis of random effects is rejected, the fixed-effects model is obtained by subtracting from equation (3) $\bar{y} = \bar{X}\beta + \mu + \bar{e}$, where $\bar{y} = \sum_n \frac{y_n}{N}$, $\bar{x} = \sum_n \frac{x_n}{N}$ and $\bar{e} = \sum_n \frac{e_n}{N}$. This gives:

$$(y_n - \bar{y}) = (X_n - \bar{X})\beta + (e_n - \bar{e}), \tag{4}$$

which can be estimated using OLS regression.

The studies we review in this paper have estimated the marginal or average costs of carbon uptake, or simply total cost. Lacking information on the potential form of the marginal and average cost curves, we assume, for simplicity, that they can be constant, linear or quadratic. In that case, the full regression model would take the following form:

$$y_i = \gamma_0 D_i + (\gamma_1 D_i + \delta_1)C_i + (\gamma_2 D_i + \delta_2)C_i^2 + (\gamma_3 D_i + \delta_3)C_i^3 + \alpha_0 + \alpha_1 x_1 + ... + \alpha_K x_K + \varepsilon_i \quad (i = 1, \ldots, N) \tag{5}$$

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, and there are *K* non-carbon regressors (see models #2 – #5 in Table 3).

Because most studies present one or more estimates of the (average or marginal) cost of sequestering carbon (on a per tonne of carbon basis), an alternative model is one that ignores the actual amount of carbon sequestered by a project (see model #1 in Table 3). Indeed, several studies provide only cost information, neglecting data on the amount of carbon sequestered. In this case, the regression equation would be:

$$y_i = \beta_0 + \beta_1 x_1 + ... + \beta_K x_K + \varphi D + \varepsilon_i \quad (i = 1, \ldots, N) \tag{6}$$

where y_i now refers to the average or marginal per unit cost of carbon uptake and ε_i is different from the term in (5) but could have the random effects structure noted in (1).

4. Estimation Results

We gathered 981 cost observations from 55 studies that provided estimates of the costs of carbon sequestration through forestry projects (Table 1). Estimates were converted to US dollars per metric ton and adjusted to a common date (2003) using the US consumer price index. The majority of studies in regions outside the United States (particularly in developing countries) provided cost estimates in US dollars, while those that employed a local currency were converted to US dollars using the effective exchange rate at that time. Exchange rates are not adjusted for purchasing power because the intent in most cases is to sell carbon credits in the international market.

After preliminary specification tests, we determined that the logarithmic form of the dependent variable (semi-logarithmic functional form) provided the best fit of the underlying data in our meta-regression model. The minimum number of observations per study was one, while the maximum was 120 (Table 1).

Studies were classified into four different types of forestry projects – forest conservation programs that prevent harvesting of trees (and subsequent release of carbon), forest management programs that enhance tree growth, tree planting programs (usually afforestation projects), and agroforestry projects where trees are planted in fields that continue to be used for crop production or grazing (see Table 2). Forest conservation was chosen as the baseline program (and included in the intercept term α_0), so the other three types were included as dummy variables in the regressions. All of the regressors are provided in Table 2.

Studies were also classified by four locations: tropics, North American Great Plains, the US cornbelt and all other regions, which included mainly studies in the US South, the US New England states, Europe and studies that covered more than one region, such as Sedjo and Solomon's (1989) study of global forestation. Given the small proportion of studies located in the cornbelt, it was combined with studies in other regions and chosen as the baseline, and thus included in the intercept term α_0.

In addition to estimating a semi-logarithmic form of model (6), the dependent variable in model (5) took two forms – total cost for an entire project and cost scaled to a per hectare basis. Quadratic and cubic semi-logarithmic functional forms were estimated for each of these models as well. Cost and carbon data were standardized to avoid ill-conditioned data. The appropriateness of including a study-specific error term was strongly rejected in each of the regressions by a Breusch-Pagan Lagrange Multiplier test for the constraint $\sigma_\mu = 0$; the null hypothesis of no intra-panel error (no random effects) cannot be rejected. The Hausman specification test for random effects comes to the same conclusion, namely, that the difference in estimated coefficient is systematic and not study specific. Therefore, a fixed-effects model was employed with the regression results reported in Table 3.

Our model fits the underlying data fairly well, as indicated by the significance of the F statistics, the significance of the majority of the coefficients, and the R^2 values for between and overall variability. As expected for a data set with large differences in panel size, R^2 within is low.[2]

Size of the study area can be used as a measure of scale, but so can the amount of carbon that is sequestered by a project. Early regression results found that area was a statistically insignificant explanatory variable, so it was excluded in the regressions because it also reduced the number of observations (see Table 2). Given the great variability in the area or coverage of various studies (and thus the amount of carbon sequestered), with some global in scale (675×10^6 ha is the largest "project" size), the most appropriate model might be the one scaled down to a single hectare, as in regression models #4 and #5. But, by scaling cost estimates down to this size, additional observations are eliminated (due to missing information). Hence, we present the results of all the models. In Table 4, in order to facilitate the discussion we also present projections of the potential costs of carbon uptake in forest ecosystems for various "scenarios" (using average values of the non-dummy regression variables). However, we exclude projections for the total cost models (#2 and #3) because projected values either approach zero or infinity. The reason is that the dummy variable triggers used to make the projections are too coarse for an estimated function where the variation in project size is so large.

[2] For a good discussion on the derivation on interpretation of goodness of fit measures in panel data models see the Stata Coporation (2003, pp.190-211).

The projected values provided in Table 4 have been converted to a year 2003 basis using the US consumer price index and are in terms of US dollars per tC. Since carbon constitutes 12/44 of the weight of a CO_2 molecule, it is necessary to multiply costs given in $ per tC by 12/44 to convert to $ per t CO_2. If CO_2 emission reductions are available at a cost of $15 per t CO_2 or less, this implies that forestry projects must sequester carbon at a cost of $55/tC or less to be competitive. For many of the scenarios illustrated in Table 4, this threshold is met.

Consider the factors common to all five models. There is remarkable consistency across models in terms of the signs and statistical significance of the common explanatory variables.

Type of Project

The type of forestry project appears to be an important factor in determining carbon sequestration costs. Our baseline consists of conservation of forests (in non-tropical and non-Great Plains regions) that delay or prevent deforestation – forest conservation projects (Table 4). As expected, projects that involve planting trees on a large scale (mainly afforestation, but also reforestation of previously logged areas perhaps with high-yielding species) or dispersed tree planting to allow for or supplement agricultural activities (cropping or grazing) lead to substantially higher costs than forest conservation projects, as indicated by the respective positive and statistically significant parameter estimates on tree planting and agroforestry in models #2 through #5. Non-carbon benefits that accrue to landowners when trees are planted as windbreaks or for shade to protect crops or animals are ignored, as such benefits are not taken into account in estimates of carbon-uptake costs.

Using Halvorsen and Palmquist's (1980) formula (e^{β}–1) to convert the coefficients of dummy variables in a semi-log equation to percent change in the dependent variable, we find that the coefficient for planting, which varies between 0.942 and 1.088, implies a 257% to 297%

increase in costs compared to conservation methods, while agroforestry averages about 261% more expensive than conservation (see also Table 4). However, none of the spillover benefits of agroforestry (e.g., soil conservation, shading, production of additional crops, protection against pests) were taken into account in the cost estimates, so more complete accounting could reveal that agroforestry is well worth the investment (e.g., Dixon et al. 1994). Still, when viewed solely as a means for carbon sequestration, indications are that agroforestry is less cost effective.

Forest management projects, which include such practices as reduced impact logging (Boscolo and Buongiorno, 1997) and digging drainage ditches in forests (Solberg and Hoen, 1996), but not tree planting, appear to result in costs similar to those of conservation projects (as the dummy variable for forest management is statistically insignificant in all but the first model). This is surprising because, even when all carbon fluxes are appropriately taken into account, it is unlikely that "additional" forest management (e.g., thinning, pruning, fertilizing) will be a cost-effective and competitive means for sequestering carbon (see Caspersen et al. 2000; van Kooten et al. 1993). Hence, we would have expected the coefficient on the forest management variable to be positive and even higher than that for the agroforestry and plantation dummy variables. Alternatively, it is possible that some commercial benefits might also be had from forest management that is not much more costly than conservation.

The Effect of Region

The effect of region is puzzling. Projects located in regions other than the tropics and North American Great Plains are taken as our baseline. Given the preponderance of low-cost forestry investments in developing countries, high growth rates and relatively low land and labor costs (Moura-Costa et al., 1999), we expected projects in the tropics to have the lowest costs. However, for the total cost models, the estimated coefficient on the tropics dummy variable is statistically significant and positive, indicating potentially higher sequestration costs in tropical regions. In the other models, this coefficient is statistically insignificant and inconsistent as to the sign of the effect. The regional dummy variable for the Great Plains is negative in all models, but is only statistically significant for the per hectare cost models. This provides some evidence to suggest that forest carbon uptake projects in the Great Plains can create carbon offsets at a lower cost than elsewhere.

Discounting and Land Costs

If the rate used to discount carbon according to when it is sequestered increases, the reported cost of carbon uptake should also increase, all other things unchanged. The reason is that, while costs remain unchanged, there is effectively less carbon. However, in models #2 through #5, the estimated coefficient on the carbon discount rate has a negative sign, opposite of what is expected, although it is only statistically significant in model #4. The coefficient on the carbon discount rate has the expected positive sign only in model #1, and is also highly statistically significant. It would seem, therefore, that whether or not carbon is discounted is less important than other factors in determining costs of carbon sequestration projects.

When a higher rate is used to discount costs, one expects carbon uptake costs to decline, *ceteris paribus*. The parameter estimates on the cost discount rate are positive in models #1 and #4, but only statistically significant in model #1. Estimates are negative in the other models and highly statistically significant for models #2 and #3, where the dependent variable is (log of) total project costs. One reason for the mixed results might be that most costs occur early on in forestry projects, although Moulton and Richards (1990) had earlier noted the insensitivity of cost estimates to discount rates on cost components. Further, as noted in section 2, there might be some confusion between discount rates for physical carbon and those of costs.

When the opportunity cost of land is taken into account, it is not surprising to find that the costs of carbon uptake are also significantly higher. This is supported by the results in Table 3, where the estimated coefficients on opportunity cost of land are positive and highly statistically significant in all models. Converting these coefficients to percent change in the dependent variable yields the result that average cost estimates will be higher by a factor of just under three to over five times in studies that take the opportunity cost of land into account compared to those that do not (see also Table 4).

Post-harvest Carbon Credits

If studies take into account what happens to carbon after trees are harvested – carbon effectively sequestered in long-lived wood products or used for energy in place of fossil fuels (thereby gaining additional carbon credits) – then the cost of creating forestry carbon credits is reduced. The estimated parameter values have the expected signs in all cases and are statistically significant for products in models #1, #4, and #5 and for fossil fuel substitution in models #4 and #5. The estimates for product sinks suggest that costs might be lowered by perhaps 75%, not insignificant cost savings. Likewise, if biomass is used to substitute for fossil fuels in energy production, costs might also be lowered by perhaps a half. These results support the arguments of Kinsman and Trexler (1993) and others who promote biomass fuels as a long-term strategy for reducing dependence on fossil fuels. However, while biomass burning is recognized under the Kyoto Protocol as a means of attaining additional carbon credits, wood product sinks currently do not qualify. Including such sinks improves the cost effectiveness of investments in terrestrial forest ecosystems to sequester carbon.

Soil Carbon Sinks

When carbon accumulation in soil sinks is taken into account, the results indicate the costs of carbon uptake are lower, as expected, but the parameter estimates are statistically insignificant in all models. This suggests that taking account of soil carbon sinks does not significantly decrease costs of carbon uptake, raising the issue about whether soil carbon should even be taken into account when estimating costs of carbon uptake from forestry activities. It also might suggest that changes in land management to create forest carbon credits do not lead to significant changes in soil carbon sinks (compared to the earlier land use).

Average versus Marginal Costs of Forest Carbon Uptake

Economists are concerned about the marginal costs of carbon uptake because decisions are made at the margin. The question is not whether to pursue a tree planting or forest conservation project on the basis of its carbon uptake benefits, but whether it is worthwhile enlarging the project – whether even more funds should be invested to enhance a project's carbon uptake or whether the project should be scaled downwards. It is the marginal cost that is the theoretically correct value to use in comparing a forest sink project with one that reducing CO_2 emissions. It is clear from all of the estimated regression models that marginal cost has a positive effect on the cost of carbon uptake, and that this effect is highly statistically significant (except for model #1). In Table 4, we use the results of the meta-regression models to provide a comparison between average and marginal costs of carbon uptake via forestry activities.

In the cost per tC regression (model #1), the marginal cost dummy variable enters as a intercept shifter only, causing the projected cost to increase by 21.8%. However, the more appropriate models are those based on the cost per hectare regressions (models #4 and #5), for reasons discussed above. Projected marginal cost estimates in Table 4 are in the thousands of dollars. This suggests that many projects need to be scaled back or, if this is not possible, that forest carbon sequestration projects are, for the most part, not able to compete with CO2 emission reduction projects.

Is the Quality of Cost Estimates Affected by Date of Study and Peer Review?

Did estimates of carbon uptake rise over time owing, say, to the availability of better data and more sound methods of analysis? For the tests within studies, the date could not be included as a regressor because it does not vary within studies. However, when testing across studies, the date of the study was negative and statistically significant at the 1% or better level of significance in all five models of the random effects regressions. This suggests that estimates of the carbon uptake costs have fallen over time, perhaps because better methods for accounting for all costs and carbon have been implemented.

Finally, one might ask whether peer-review has a systematic impact on the cost of carbon uptake estimates. The results suggest that peer-review has a positive and highly statistically significant effect on cost estimates, increasing them by a factor of 10 or more (see Table 4). This suggests that many of the reports upon which governments and non-governmental organizations base their decisions, reports available to the public but not reviewed by experts in the field, may lead to investments that would be considered unwise. Further investigation in this regard is certainly warranted.

5. Discussion

In this study, we employed meta-regression analysis to estimate a relationship between carbon uptake costs in forestry and factors that affect such calculations. We employed data from 55 different studies, many of which had multiple estimates of costs, varying according to the assumptions made by the authors or simply as a result of inherent uncertainty regarding carbon uptake and potential costs and benefits of the forest activity. By using all of the observations, we were able to avoid the loss of information that accompanies the use of study averages, as is generally done in meta-analyses (Stanley, 2001). Despite the fact that we had 981 observations, we found no statistical support for the use of a random effects specification to distinguish within-study from between-study errors, employing instead a fixed effects specification.

In the past decade, studies have provided a wide variety of estimates of the costs of carbon uptake (creating carbon offsets) through forestry activities. Since carbon offsets substitute for greenhouse gas emissions reductions, policymakers rely on such estimates in determining least-cost options for achieving internationally agreed upon emission-reduction targets. It is generally accepted that land use, land-use change and forestry projects, although limited in scope, can remove CO_2 from the atmosphere at lower cost than projects to reduce emissions. Although not attempting to validate this assertion, we did provide a useful summary of existing estimates of the costs of creating carbon offsets through forestry.

Our results do suggest that, for most regions where trees can be grown, there may be room to include carbon credits from forest sinks in meeting Kyoto-type targets. The competitiveness of terrestrial sink projects is enhanced if post-harvest uses of wood (either as a biofuel or wood products) are included. Wood product sinks are not included under current Kyoto rules. Given that following carbon past harvest is important for determining costs, the inclusion of carbon in product sinks, and the substitution of wood products for other materials, needs to be investigated further, and future climate agreements would do well to address this issue.

There are several troubling caveats that need to be mentioned with respect to the general conclusion that forest sink projects are competitive with other means of reducing atmospheric CO_2. First, if the opportunity cost of land is taken into account, average costs of forest carbon sink projects rise significantly, realistically to between $45 and more than $1300/tC (although these estimates will be reduced when product sinks are included). It is important to include the opportunity cost of land in an appropriate fashion, but this might make carbon uptake in forestry a less appealing policy option. Second, it is also troubling that our evidence suggests peer-review leads to significantly higher estimates of carbon uptake costs. Third, if the results of this study are indicative, the cost of carbon uptake in forest ecosystems is prohibitive at the margin. Yet, despite the importance that marginal costs have in directing economic policy, too few studies examined this aspect. Finally, none of the studies we examined dealt directly with the ephemeral nature of carbon sinks. In some studies this was addressed indirectly through the use of high discount rates on physical carbon or a thorough life cycle analysis of wood, but overall this aspect was not addressed in a Kyoto framework where no agreement exists beyond 2012 and countries have no formal obligation to hold carbon in sinks beyond that time.

Of course, the results presented in this study are only as good as the studies that we have summarized. Further, we do not purport to have included all of the available studies, primarily because many studies not included in this study appear as reports commissioned by governments and NGOs. Finally, each of our categories – conservation, planting, agroforestry and forest management – encompasses a wide variety of projects and methodologies, and not all nuances could be taken into account. Nonetheless, we maintain that the information provided by the meta-regression analysis provided here is a useful indicator of the potential average costs of creating carbon offsets using the forestry option.

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Table 1: Forest Carbon Sink Studies, Costs of Removing Atmospheric CO_2

Study	Observations	Mean Cost[a]	Median Cost[a]
Ab'Saber et al. (1989)[b]	9	8.37	8.27
Adams et al. (1999)	39	27.47	26.75
Adams et al. (1993)	11	68.73	41.57
Boscolo & Buongiorno (1997)	5	96.07	88.27
Boscolo, Buongiorno & Panayotou (1997)	29	46.28	22.93
Brown, Cabarle & Livernash (1997)	6	1.73	1.38
Callaway & McCarl (1996)	66	26.41	22.71
Darmstadter & Plantinga (1991)	3	11.39	11.04
Dixon et al. (1993)	7	8.19	4.46
Dixon et al. (1994)	14	26.30	15.49
Dudek & Leblanc (1990)	6	11.51	10.37
Dutschke (2000)	4	30.55	10.75
Fearnside (1995)	3	84.58	85.85
Healey et al. (2000)	5	33.89	40.90
Hoen & Solberg (1994)	16	1675.36	68.03
Houghton, Unruh & Lefebvre (1991)	18	12.20	11.65
Huang & Kronrad (2001)	37	42.14	19.73
Krcmar, van Kooten & Vertinsky (2004)	2	142.48	142.48
Lasco et al. (2002)	1	3.01	3.01
Lashof & Tirpak (1990)	9	8.70	8.45
Makundi & Okiting'ati (1995)	1	1.88	1.88
Masera, Bellon & Segura. (1995)	8	70.93	63.39
McCarl & Callaway (1995)	43	68.18	31.58
Moulton & Richards (1990)	70	25.22	24.50
Moura-Costa et al. (1999)	9	3.15	1.30
Newell & Stavins (2000)	53	154.45	57.64
Nordhaus (1991)	6	109.06	103.34
Parks & Hardie (1995)	4	245.23	226.12
Plantinga & Mauldin (2001)	45	31.71	26.56
Plantinga, Mauldin & Miller (1999)	21	63.70	61.17
Poffenberger et al (2002)	6	0.43	0.16
Poffenberger et al (2001)	3	22.36	11.13
Putz & Pinard (1993)	1	3.74	3.74
Ravindranath & Somashekhar (1995)	4	1.79	1.48
Richards, Moulton & Birdsey (1993)	4	6.54	6.54
Schroeder, Dixon & Winjum (1993)	10	17.57	6.37
Sedjo & Solomon (1989)	6	35.93	33.16
Sohngen & Haynes (1997)	2	47.20	47.20
Solberg & Hoen (1996)	19	153.31	92.48
Spinney, Prisley, and Sampson (2004)	6	19.19	14.07
Stavins (1999)	4	120.24	105.50
Stennes (2000)	8	31.03	20.86
Stuart & Moura-Costa (1998)	2	1.97	1.97

Table 1: continued

Study	Observations	Mean Cost[a]	Median Cost[a]
Swisher (1991)	28	10.76	6.68
TERI (1997)	27	15.24	6.16
Totten (1999)	12	4.53	3.53
van Kooten and Bulte (2000)[c]	30	741.52	468.71
van Kooten & Hauer (2001)	29	81.18	28.06
van Kooten, Arthur & Wilson (1992)	24	60.09	33.40
van Kooten et al. (1999, 2000)	120	36.17	36.92
van Vliet et al. (2003)	3	2.31	2.41
Volz, Kriebitzsch & Schneider (1991)	11	205.86	163.47
Winjum, Dixon & Schroeder (1993)	16	13.61	9.55
Xu (1995)	20	4.84	3.37
Zelek and Shively (2003)	36	22.94	22.15
Entire Sample	**981**		
Mean of Study Averages[d]	17.84	81.66	40.34
Median of Study Averages[d]	9.00	24.72	19.53

[a] \$US/tC (2003 dollars)

[b] quoted in Andrasko et al. (1991)

[c] Recalculation of values originally provided by Slangen et al. (1997).

[d] See Table 2 for means and medians of all individual observations.

Table 2: Explanatory Variables, Means and Ranges (n=981)

Variable	Obs	Mean	Std. Dev.	Minimum	Maximum
Total project cost (10^9 2003 US$)[a]	822	31.47	271.23	0	5152.0
Cost of carbon uptake ($/tC)	981	94.13	545.15	0.04	13466.65[c]
Cost per hectare ($/ha)	822	2420.15	6136.22	0.37	93242.91[c]
Years after 1989 study published	981	7.6636	3.8712	0	15
Carbon uptake by project (Mt)	817	1152.2	7794.0	0.0001	87000
Study area (10^6 hectares)[a]	759	21.855	63.661	0	675
Carbon per hectare (tC/ha)	714	58.49	88.35	0.15	501.24
Discount rate on carbon	981	0.0127	0.0240	0	0.10
Discount rates on costs (%)	981	0.0526	0.0406	0	0.1725
Regional dummy variables					
Tropics (=1, 0 otherwise)	981	0.2650	0.4416	0	1
Great Plains (=1, 0 otherwise)	981	0.1478	0.3551	0	1
US cornbelt (=1, 0 otherwise)	981	0.0204	0.1414	0	1
Other region (=1, 0 otherwise)	981	0.5668	0.4958	0	1
Forest activity dummy variables	(1=item included, 0 = otherwise)				
Planting of forest[b]	981	0.7635	0.4251	0	1
Agroforestry project	981	0.0632	0.2434	0	1
Forest conservation project	981	0.0683	0.2524	0	1
Forest management project	981	0.2232	0.4166	0	1
Items included dummy variables	(1=item included, 0 = otherwise)				
Carbon in products	981	0.4251	0.4946	0	1
Soil carbon	981	0.7054	0.4561	0	1
Wood used for fuel	981	0.0846	0.2784	0	1
Opportunity cost of land	981	0.7370	0.4405	0	1
Was study refereed? (1=Y, 0=N)	981	0.7788	0.4153	0	1

[a] The large values for cost and area are due to Sedjo and Solomon (1989), who provide estimates of costs of carbon uptake on a global scale. This accounts for the high averages and minimum values that appear to be zero but are an order of magnitude in the thousands.
[b] Mean of the planting dummy is 0.7635, indicating that 76.35% of the observations involve sequestration through afforestation or reforestation.
[c] These are large values because they are marginal measures.

Table 3: Fixed-Effects GLS Meta-Regression Results: Estimated Coefficients, Level of Statistical Significance and Test Statistics for Various Models

Dependent Variable →	$ per tC	Total cost (mil. $)		Cost per hectare ($)	
		Quadratic	Cubic	Quadratic	Cubic
Explanatory Variable	#1	#2	#3	#4	#5
Marginal cost dummy	0.197	1.501***	2.313***	7.423***	9.622***
Carbon (Mt)		4.566***	7.778***	0.803***	1.473***
MC dummy on Carbon		5.282***	-12.970***	18.429***	47.830***
Carbon-squared		-0.290***	-1.378***	-0.138***	-0.760***
MC dummy on Carbon-squared		-51.142***	-132.837***	9.121*	98.922*
Carbon-cubed			0.070***		0.112***
MC dummy on Carbon-cubed			502.369***		77.678*
Tree planting dummy	0.116	1.088***	0.942***	1.077***	0.977***
Agroforestry dummy	0.206	0.820**	0.750**	1.149***	1.059***
Forest management dummy	-0.703***	-0.622*	-0.592*	-0.043	-0.154
Tropics region dummy	-0.064	0.886**	0.625*	0.170	0.094
Great Plains region dummy	-0.273	-0.439	-0.393	-0.455***	-0.410**
Carbon discount rate	17.464***	-3.269	-2.654	-6.389***	-0.961
Rate used to discount costs	6.402***	-29.512***	-29.068***	4.295	3.857
Fossil fuel substitution dummy	-0.379	-0.062	0.069	-0.641*	-0.792***
Soil carbon sink dummy	-0.503	-1.071	-1.051	-0.456	-0.573
Product carbon sink dummy	-1.041***	-0.603	-0.591	-1.324***	-1.444***
Opp. cost of land dummy	1.191***	1.042**	1.105***	1.699***	1.587***
Study refereed dummy	3.094***	1.207	1.140	3.246***	3.351***
Constant	0.184	9.134***	-194.038***	2.125***	2.524***
R^2 within	0.1287	0.1650	0.2221	0.3668	0.3883
R^2 between	0.1657	0.0618	0.0644	0.0818	0.0497
R^2 overall	0.1504	0.0031	0.0042	0.1423	0.1338
Goodness of fit F statistic	10.37***	8.49***	10.94***	22.25***	21.75***
(df)	(13,913)df	(17,730)df	(19,728)df	(17,653)df	(19,651)df
σ_u	1.8301	359.5258	23915.913	3.2628	5.7690
σ_e	0.9118	1.4665	1.417	0.9325	0.9179
ρ (fraction of variance due to u_i)	0.8011	1.0000	1.000	0.9245	0.9753
Number of observations	981	791	791	713	713
Number of studies	55	44	44	43	43
Average observations per study	17.8	18.0	18.0	16.6	16.6
F test that all u_i=0	10.67***	23.18***	18.57***	14.73***	13.98***
(df)	(54,913)df	(43,730)df	(43,728)df	(42,653)df	(42,651)df

*** significant at 5% level or better; ** significant at 10% level or better; * significant at 20% level or better

Table 4: Predicted Cost per tC of Creating Carbon Offsets through Forestry Activities, US$ 2003 Values, Predictions from Three Scenarios and Three Models

Model →	Average costs (not reviewed)			Average costs (peer reviewed)			Marginal costs (peer reviewed)		
Scenario	#1	#4	#5	#1	#4	#5	#1	#4	#5
Baseline (Other/Conservation)	2.11	8.45	9.12	46.62	217.01	260.29	56.78	15,700.48	75,205.37
Other									
Planting	2.37	24.80	24.23	52.36	637.10	691.44	63.76	46,094.38	199,781.17
Agroforestry	2.60	26.65	26.31	57.29	684.67	750.53	69.76	49,535.57	216,853.63
Forest Management	1.05	8.09	7.82	23.08	207.87	223.14	28.11	15,039.67	64,471.46
Other with conservation									
Soil Sink	1.28	5.35	5.14	28.19	137.54	146.76	34.33	9,951.18	42,403.15
Fuel Substitution	1.45	4.45	4.13	31.92	114.31	117.89	38.87	8,270.47	34,063.37
Product Sink	0.75	2.25	2.15	16.46	57.74	61.42	20.05	4,177.41	17,747.11
Opportunity Cost of Land	6.95	46.20	44.60	153.41	1186.70	1272.55	186.82	85,857.68	367,683.54
Tropics									
Conservation	1.98	10.01	10.02	43.73	257.22	285.94	53.26	18,609.85	82,617.59
Planting	2.23	29.40	26.62	49.11	755.16	759.59	59.81	54,635.89	219,471.55
Agroforestry	2.44	31.59	28.90	53.74	811.54	824.50	65.44	58,714.75	238,226.67
Forest Management	0.98	9.59	8.59	21.65	246.39	245.13	26.37	17,826.59	70,825.75
Tropics with conservation									
Soil Sink	1.20	6.35	5.65	26.45	163.03	161.22	32.21	11,795.18	46,582.39
Fuel Substitution	1.36	5.27	4.54	29.94	135.49	129.51	36.46	9,803.03	37,420.65
Product Sink	0.70	2.66	2.37	15.44	68.44	67.48	18.81	4,951.50	19,496.26
Opportunity Cost of Land	6.52	54.76	49.00	143.90	1406.60	1397.97	175.23	101,767.52	403,922.33

Table 4: Continued

Model → Scenario	Average costs (not reviewed) #1	#4	#5	Average costs (peer reviewed) #1	#4	#5	Marginal costs (peer reviewed) #1	#4	#5
Great Plains									
Conservation	1.61	5.36	6.05	35.49	137.68	172.74	43.21	9,961.14	49,910.06
Planting	1.81	15.74	16.08	39.85	404.21	458.88	48.53	29,244.49	132,584.82
Agroforestry	1.98	16.91	17.46	43.60	434.38	498.09	53.10	31,427.74	143,914.97
Forest Management	0.80	5.13	5.19	17.57	131.89	148.08	21.39	9,541.88	42,786.50
Great Plains with conservation									
Soil Sink	0.97	3.40	3.41	21.46	87.26	97.40	26.13	6,313.51	28,140.86
Fuel Substitution	1.10	2.82	2.74	24.29	72.52	78.24	29.58	5,247.18	22,606.16
Product Sink	0.57	1.43	1.43	12.53	36.63	40.76	15.26	2,650.35	11,777.87
Opportunity Cost of Land	5.29	29.31	29.60	116.76	752.90	844.53	142.18	54,472.23	244,013.27