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Costs of Creating Carbon Offset Credits via Forestry Activities: A Meta-Regression Analysis

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Costs of Creating Carbon Offset Credits via Forestry Activities: A Meta-Regression Analysis

by

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Abstract

The main focus of efforts to mitigate climate change is on the avoidance of fossil fuel emissions. However, the Kyoto rules permit the use of forestry activities that create carbon offset credits. These could obviate the need for lifestyle-changing reductions in fossil fuel use. It is necessary for policy purposes, therefore, to determine the cost effectiveness of creating forest sink carbon credits. In this study, meta-regression analyses with 1047 observations from 68 studies are used to determine factors that affect carbon sequestration costs. Results indicate that soil carbon is not very important, but that forest plantations and use of biomass for energy make forestry activities more attractive. It also turns out that forestry activities are competitive with emissions reduction in tropical regions and, perhaps, boreal regions, but certainly not in Europe. Finally, the regression estimates are used to project the potential costs of carbon uptake for various forest management scenarios.

Keywords: climate mitigation, forest carbon offset credits, meta-regression analysis

Introduction

The main focus of efforts to mitigate climate change is on the avoidance of greenhouse gas emissions, especially CO_2 emissions associated with the burning of fossil fuels. However, the Kyoto Protocol permits various terrestrial options, particularly ones related to forest ecosystem sinks. Therefore, it is relevant to compare between terrestrial activities to sequester carbon and emissions reduction as alternative means for creating carbon offset credits – and reducing atmospheric CO_2. Such a comparison needs to be on the basis of cost effectiveness.

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 carbon offset credits. A remaining concern is 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).

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 carbon 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.

The purpose of this paper is to investigate whether the costs of creating carbon (CO_2) offset credits through forestry activities can be competitive with costs of emissions reduction. We do so by updating and greatly expanding upon 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. The original studies were reviewed for consistency, with several of the original observations eliminated as a result, and new variables were added. Finally, the latest methods for conducting meta-regression analysis are employed.

Methods: Meta-Regression Analysis

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 cost of carbon uptake studies, the effect-size indicator is usually a 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).[1] In environmental economics, most MRAs use fixed-effects models that permit some 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.

As discussed earlier, the costs of sequestering carbon and providing CO_2 offset credits 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

[1] 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).

estimates generated by a given source study:

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

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 respective variances of σ^2_e and σ^2_u (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:

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

where y_i refers to the total cost of carbon-uptake by 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).[2] 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 summary of the studies is provided in Table 1. 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 1, 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

[2] 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).

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.

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 carbon credits 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.

Even for studies providing the requisite data (and thus 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 agricultural use of land after harvest. 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-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 1 and 2.

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: (i) carbon in tree biomass (including above and below ground), (ii) soils, and (iii) wood products – 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, econometric/statistical 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.

Estimation Results

The study-level regression results are provided in Table 3, while results using individual observations are provided in Table 4. A variety of models were examined, with the results quite robust with respect to model specification. Consider first the study-level results in Table 3.

Study Averages

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 more recent estimates of carbon uptake costs 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 in Table 3 are easier to interpret. 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 offset credits 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 grows 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 4, 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 significant 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 same variable squared are very close to zero, and they are completely statistically 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 carbon sequestration costs 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 3. 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 1), who focused on both Europe and North America. In Table 5, 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 3 and 5). 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 3 that was excluded in Table 5. 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 5, 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 3, 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 3 and 5, 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 6. 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 terrestrial carbon sinks in Kyoto accounting.

Concluding Remarks

Our review of studies of costs of carbon uptake found 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. Studies failed to take into account the duration of the project, CO2 emissions at the end of the planning horizon (either rotation age or Kyoto's First Commitment Period), and potential leakages, and they frequently ignored issues of 'additionality'. 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. Meta-regression results indicate that, if carbon credits trade for \$30/tCO_2 (a not unreasonable value given experience in the European emissions trading scheme), some forestry projects to remove CO_2 from the atmosphere are worthwhile undertaking, but not all.

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 little influence. These results are important because, for example, they go a long way to explaining why the EU opposed terrestrial sinks from the outset and why there is currently greater effort to get forest sinks in tropical countries accepted under CDM.

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? Indeed, one cannot escape the fact that our review of articles not included in the meta-analysis raises some concerns about the manner in which forest activities are used to create carbon credits.

Finally, while not denying that plants and trees remove CO_2 from the atmosphere (and can do so at competitive prices), a country's reliance on forest sinks for some significant proportion of its CO_2-emissions reduction target might proof troublesome. 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 then 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 could therefore result in an onerous obligation for future generations, one which they may not be willing to accept.

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Table 1: 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 (2005)	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 1: 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 (1997)	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 (1989)	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 2: 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 3: Study-Level, Meta-Regression Analysis Results, Ordinary Least Squares, Unweighted and Weighted by Number of Observations in each Study (n=68)

Model →	Non-weighted				Weighted by number of observations			
Explanatory Variable	Est. coef.	Prob[a]	Est. coef.	Prob[a]	Est. coef.	Prob[a]	Est. coef.	Prob[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 4: All Observations, Meta-Regression Analysis Results, Ordinary Least Squares and Random Effects Models (n=1047)

Model →	OLS Regression				Random Effects			
Explanatory Variable	Est. coef.	Prob[a]	Est. coef.	Prob[a]	Est. coef.	Prob[a]	Est. coef.	Prob[a]
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 5: Limited Observations, Meta-Regression Analysis Results, Ordinary Least Squares Weighted by Number of Observations in Studies (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[a]	Est. coef.	Prob[a]	Est. coef.	Prob[a]	Est. coef.	Prob[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 6: 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.