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Interim Report **IR-04-022**

Global Supply for Carbon Sequestration: Identifying Least-Cost Afforestation Sites Under Country Risk Considerations

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Contents

Abstract

We have provided a framework for identifying least-cost sites for carbon sequestration and deriving carbon sequestration cost curves at a global level in a scenario of limited information. The method is based on determining sequestration costs for geographical explicit units (50km grid cells), based on GIS parameters on land-use and ecosystem properties, and aggregated economic data. Special attention is given to country risk considerations and the sensitivity to special datasets. Our model results suggest that within 20 years and considering a carbon price of $50/tC, afforestation could offset one year of global carbon emissions in the energy sector. However, if we account for country risk considerations — associated with political, economic and financial risks — the carbon supply is reduced to about 60%. With respect to the geography of supply, illustrated by grid-scale maps, we find that most least-cost projects are located in Africa, South America and Asia, assuming a 5% discount rate without risk. Once risk is factored into the equation, these countries become more expensive to operate in.

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Michael Obersteiner is a Research Scholar in IIASA's Forestry Project where he is the principle investigator and scientific coordinator of the INSEA project. Dr. Obersteiner joined the Forestry Project in 1993 as a Guest Research Assistant. Since 2002 he has been dealing with multiple research topics, including information technology and structural change of the global forest sector and carbon analysis complying with the Kyoto Protocol. Dr. Obersteiner received his Ph.D. from the Institute of Forestry, at the University of Agriculture and Forestry in Vienna, Austria. In addition, he graduated as a Diploma Economist (M. phil. in Economics) in the Joint Ph.D. Program in Economics, from both Columbia University (New York, USA) and the Institute for Advanced Studies in Vienna, Austria. Before coming to IIASA, Dr. Obersteiner was a visiting scientist at the Institute for Economics and Industrial Organization, the Siberian Branch of the Russian Academy of Sciences in Novosibirsk, Russia working on forest industry modeling. Prior to this he was a Fullbright Research Assistant at the College of Forest Resources at the University of Washington in Seattle, Washington, working in the area of eco-physiological responses of plant stress. In addition to his research at IIASA, Dr. Obersteiner is a Research Economist with the Department of Economics and Finance at the Institute for Advanced Studies (IHS) in Vienna, Austria. Dr. Obersteiner has been a consultant to a number of national and international organizations, including *inter alia* the European Commission, OECD, and national governments. He is author of over 80 scientific papers and consultancy reports in the above mentioned fields.

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Pablo Benítez, Ian McCallum, Michael Obersteiner and Yoshiki Yamagata

1 Introduction

Global warming as a consequence of human-induced emissions of greenhouse gases (GHG) is a growing concern. Latest predictions of the International Panel of Climate Change (IPCC) suggest that by 2100 the globally averaged surface air temperature will increase by 1.4–5.8°C and the average sea level will rise to between 8 and 88 cm, leading to major disturbances for human settlements and natural ecosystems (IPCC, 2001). This warming would vary between regions causing diverse impacts on agriculture, forestry, human health and biodiversity. Tropical regions would be more affected by a decrease in agricultural production, while temperate regions would face the expansion of vector-born diseases like malaria and dengue fever, and would confront higher temperatures and more frequent heat waves during summer (IPCC, 2001). Globally, increases in the occurrence of extreme weather events will lead to higher insurance premiums and might result on certain risks being reclassified as uninsurable. Natural systems like coral reefs, mangroves, tropical and boreal forests, polar and alpine ecosystems, and prairie wetlands are at the risk of irreversible damages and the loss of vulnerable species. Facing these threats and the costs of adaptation to be borne by future generations, mitigation measures have been proposed within international agreements like the Kyoto Protocol (UNFCCC, 1998). As a general classification, mitigation is divided into two groups: (1) the reduction of GHG emissions in the energy sector and industrial process, and (2) the enhancement of carbon sinks. Integrated assessments in the energy sector have estimated carbon mitigation cost curves (Gritsevskyi and Schrattenholzer, 2003; Sijm *et al*., 2000). To a lesser extent, these have been done in the sink sector. As an imperative need for finding least-cost mitigation alternatives, we aim to estimate carbon sequestration cost curves at a global level and determine sites where these costs are at a minimum.

Global assessments of the potential of sinks for carbon mitigation started in the 1990s. Trexler and Haugen (1995) have estimated the potential for carbon sequestration in the tropics and Nilsson and Schopfhauser (1995) estimated the global afforestation potential. These early studies found out how much carbon could be sequestered in forests, but omit cost estimations of such activities. Economic studies providing sequestration costs exist from case studies of particular countries like the USA (Stavins, 1999), China (Xu, 1995), Brazil (Fearnside, 1995), India (Ravindranath and Somashekhar, 1995), Mexico (de Jong *et al*., 2000) and Argentina (Sedjo, 1999).

However, economic studies providing carbon supply curves at a global level are limited, where the research of Sohngen *et al*. (1999), and Sohngen and Mendelsohn (2003) seem to be pioneers. By using optimal control and timber supply models, they evaluated the interaction of timber markets and carbon fluxes. Given the complexity of the analysis, they used high aggregation levels for representing relevant world regions. Contrasting to these studies and as a new research contribution, we estimate global supply curves by using information at a disaggregated level, and scrutinizing the potential afforestation area so that sequestration costs are estimated at geographically explicit grid-cells of about 50 × 50 km. We select applicable land classes, and exclude highly productive land, areas of high population density, areas of high elevation and areas where there is no net carbon uptake. By doing so, we evaluate how the heterogeneity in land attributes (e.g., net primary productivity and suitability for agriculture) and the heterogeneity of prices (e.g., land and timber prices), influence sequestration costs and determine carbon-supply patterns; and identify least-cost locations for carbon sequestration. Being aware of the effect of country considerations associated to political, financial and economic risks, we evaluate its influence on the global supply of carbon. In addition, we perform a sensitivity analysis of the land cover classes by utilizing multiple datasets for comparison.

2 The Model

A myriad of economic land-use change models have been developed to derive supply-curves of carbon sequestration measures. Some are based on simple cost-benefit analysis (Sathaye *et al*., 2001), while others involve more comprehensive analyses like econometric models (Plantinga *et al*., 1999; Stavins, 1999), general equilibrium approaches (Callaway and McCarl, 1996), timber supply models (Sohngen *et al*., 1999), and land-use optimization models (Parks and Hardie, 1995). In our context, we propose a flexible approach that tries to make use of the latest spatial data products and geographic information systems (GIS). The analysis starts by selecting grids (geographically explicit 50 km cells) that are suitable for afforestation, i.e., non-forest areas where tree-planting is viable and will not compromise food security of the region. We then estimate sequestration costs for each grid based on estimates for net primary productivity (NPP), plantation costs, expected timber and land prices, and carbon storage in products. Finally, we obtain the cumulative sequestration cost-curve by aggregating grid-level results, taking into account that afforestation activities occur only in grids where the carbon price exceeds sequestration costs. Besides obtaining the cost-curve, the method allows identifying the geographic distribution of carbon costs and growth potentials throughout a region.

The sequestration decisions are made grid-by-grid by considering the profitability of afforestation vis-à-vis the current agricultural practice, i.e., the net present value of forestry including payments for carbon sequestration is required to be larger or equal to the net present value of agriculture. The net present value of forestry (f), in grid “i”, during one rotation interval is estimated as:

$$f_i = -cp_i + pw_i \cdot V_i \cdot (1+r)^{-R_i} + B_i \ , \qquad (1)$$

where cp_i are planting costs, pw_i is the stumpage timber price, r is the discount rate, R_i is the rotation interval, V_i is the timber volume and B_i is the present value of carbon benefits over one rotation. Carbon benefits include carbon sequestration in standing biomass and products net of expected carbon storage to the baseline agricultural practice. Approximating tree-growth by a linear function, where ω_i measures the yearly carbon uptake, and using pc_i for carbon price and $B^b{}_i$ for carbon benefits in the biomass, we have:

$$B^b{}_i = pc_i \sum_{t=1}^{R_i} \omega_i \left(1+r\right)^{-t} \quad - \quad pc_i \cdot \omega_i \cdot R_i (1+r)^{-R_i} \quad . \tag{2}$$

The first term of equation (2) corresponds to the present value of carbon benefits during the growing stage of the forest and the second term describes the carbon costs that occur during harvest. For accounting carbon benefits in products we include, (i) long-lived products consisting of timber materials like furniture and construction wood, (ii) short-lived products like leaves, branches and timber wastes that decomposes or is thermally converted inside or outside the forest after harvest has taken place. Carbon stored in products is released to the atmosphere following an exponential decay function (Sohngen and Sedjo, 2000). As shown in Benítez and Obersteiner (2003), carbon benefits in products represent a fraction β_i of the carbon costs that occur during harvest. The factor β_i depends on the fraction of short and long term products, their rates of decay and the discount rate.

By summing up carbon benefits in biomass and products and subtracting a fixed fraction, b_i, for the baseline, we obtain the final expression for total carbon benefits:

$$B_i \ = pc_i \cdot \omega_i (1-b_i) \left\{ r^{-1} \left[1-(1+r)^{-R_i} \right] - R_i (1-\beta_i)(1+r)^{-R_i} \right\} \ . \tag{3}$$

By using equations (1) and (3) we estimate the net present value of forestry for one rotation interval (f_i) and from this we obtain the net present value for multiple rotations (F_i). Given constant prices and fixed rotation intervals we have:

$$F_i = f_i \left[1-(1+r)^{-R_i} \right]^{-1} \ . \tag{4}$$

The net present value of agriculture is obtained indirectly with a two-factor Cobb-Douglas production function. The first factor is suitability for agriculture, S_i, and indicates the aptness of the land for agricultural production given its endowments of soil and ecosystem properties. The second is population density, D_i, and represents the accessibility to markets and current infrastructure surrounding the land (more populated areas have more roads). Thus, the net present value of agriculture, A_i, is:

$$A_i = \upsilon_i \cdot S_i^{\alpha_i} \cdot D_i^{\gamma_i} \ , \tag{5}$$

where the parameters α_i and γ_i determine the relative importance of S_i and D_i on determining A_i, and υ_i determines the general price level for land given the purchasing power parity and exchange rate for each country. S_i and D_i are normalized between 1 and 10. Although equation (5) provides just an approximation for the net present value of agriculture, its use allows the avoidance of relying on detailed land-use statistics and prevents its underestimation in case that land is not well-managed. For practical reasons, we denote A_i as the land price knowing that in the absence of risks and uncertainties, and having competitive markets, A_i will reflect the value that an agricultural landowner will be willing to accept in exchange of his land. When we set $A_i = F_i$, we find the minimum carbon price (what we define as the carbon costs) that allows forestry to be as profitable as agriculture:

$$pc_i = \frac{A_i\left[1-\left(1+r\right)^{-R_i}\right] + cp_i - pw_i \cdot V_i(1+r)^{-R_i}}{\omega_i(1-b_i)\left\{r^{-1}\left[1-(1+r)^{-R_i}\right]-R_i(1-\beta_i)(1+r)^{-R_i}\right\}} \quad . \tag{6}$$

Equation (6) allows the estimation of the carbon costs for each grid on the basis of parameters available from GIS databases and existing economic data available from public statistics and publications. Note that there might be grids where forestry without payments for carbon sequestration, provide higher revenues than agriculture. This situation will show a negative sign for pc_i.

For estimating the cumulative carbon sequestration at a given time, we consider that trees are replanted just after harvest and that planting is delayed, meaning that each year just a fraction of every grid is converted into forests until the whole grid is fully forested. This leads to having uneven stands in every grid, which are harvested and replanted periodically. For finding the cumulative sequestered carbon, we sum carbon in biomass and products throughout stands and grids (refer to Benítez and Obersteiner, 2003, for a detailed description of this estimation).

2.1 Considering Country Risk

In the preceding section we assumed that investors are careless about country risk, meaning that they would be indifferent on planting trees in Canada or Sierra Leone under equal sequestration costs. However, for implementing afforestation projects for timber production and carbon sequestration purposes, it is clear that every investor will take into consideration country particularities like institutions, government credibility, corruption, economic stability, inflation, wars and terrorism. By a simple screening of some of these aspects, it is accepted that, by far, Canada is a better country for investing in carbon sequestration projects than Sierra Leone. In this study, we attempt to account how country considerations associated to political, financial and economic risks influence the global cost of sequestration.

There are diverse ways for accounting risk in investment projects. A commonly applied method is the use of risk-adjusted discount rates or required returns. For employing this technique in our study, the discount rate used for estimating carbon costs (equation 6) needs to be adjusted to risk. Generally, the capital asset pricing model (CAPM) serves for estimating risk-adjusted discount rates. The CAPM considers market efficiency where the differences between the market return and the risk-free rate are a measure of the price paid for market risk. The fundamental equation of the CAPM is:

$$r = r_f + \beta\,(r_m - r_f)\,, \tag{7}$$

where r is the required return for an asset, r_f is the risk-free rate of return, r_m is the market rate of return and β (beta) measures the contribution to risk of the investment relative to the market. Extensions of the CAPM have been applied globally (see Bekaert and Harvey, 1995) where expected returns are influenced by both world and country factors. While these CAPM extensions lead the estimation of required returns for different countries, it has limited applicability for worldwide analyses given the absence of equity markets in most developing countries. Considering this factor, Erb et al. (1996a) used an alternative formulation for estimating expected returns in a large number of developing countries, under the assumption that expected returns are a function of risk ratings:

$$r_i=\gamma_0+ \gamma_1 \cdot ln(RR_i)+\varepsilon_i \, , \qquad (8)$$

where r_i is the expected return in country i, RR_i is the risk rating of country i, γ_0, γ_1 are parameters of the return function, and ε_i is the error term. The log-linear model has been proposed in order to capture potential non-linearities when country risk is high. Since risk rating agencies provide data for more than 70% of the world's countries, this method is applicable worldwide. In practice, the estimation of expected returns is done as follows, (i) select a country risk index that reflects major risk concerns, (ii) find a list of countries where expected returns of the investment in question are available, (iii) by means of regression analysis, estimate the parameters γ_0, γ_1 with the available expected returns and the correspondent risk indexes, and (iv) use equation (8) for predicting expected returns for other countries.

3 Data

3.1 Global Datasets

The following spatial datasets were combined to create the resultant global dataset used in this study (Table 1). All raster datasets were converted from their original resolution to a standard 0.5 degree grid using appropriate methods, and include an actual area field. A link was maintained in the dataset in order to map the results of the model.

Four global land cover datasets were used in this comparison (see Table 2), namely (1) International Geosphere Biosphere Project (IGBP); (2) University of Maryland (UMD); (3) Global Land Cover 2000 (GLC2000); and (4) MODerate resolution Imaging Spectroradiometer (MODIS). Equivalent IGBP classes were assigned to the UMD, GLC2000 and MODIS databases in order to allow comparison.

Table 1: The complete set of spatial datasets used to create a resultant database for modeling.

Dataset	Original Resolution	Units	Source
World Countries	0.5 degree	Countries/Continents	ESRI (1998)
Population 1995	2.5 minutes	Persons/km2	CIESIN (2000)
Agricultural Suitability	0.5 degree	Fraction of cell (%)	Ramankutty *et al*. (2001)
Elevation	30ArcSeconds	Meters	GTOPO30 (1996)
IGBP Land Cover	30ArcSeconds	17 IGBP classes	USGS (2003)
UMD Land Cover	30ArcSeconds	IGBP classes	Hansen *et al*. (2000)
GLC2000 Land Cover	30ArcSeconds	IGBP classes	JRC (2003)
MODIS Land Cover	30ArcSeconds	IGBP classes	MODIS (2002)
NPP	0.5 degree	gC/m2/year	Alexandrov *et a*l. (1999); Alexandrov *et al*. (2002)
Carbon Stock (non-forest)	0.5 degree	tC/ha	Alexandrov *et al*. (1999); Alexandrov *et al*. (2002)
Carbon Stock (5 year old)	0.5 degree	tC/ha	Alexandrov *et al*. (1999); Alexandrov *et al*. (2002)
Carbon Stock (30 year old)	0.5 degree	tC/ha	Alexandrov *et al*. (1999); Alexandrov *et al*. (2002)

Table 2: The main characteristics of the four land cover products compared in this study.

Characteristics	IGBP	UMD	GLC2000	MODIS
Sensor	AVHRR	AVHRR	SPOT4 Veg	MODIS
Time of Data Collection	April 92–March 93	April 92–March 93	1 Nov. 1999–31 Dec. 2000	10/15/00–10/15/01
Input Data	12 Monthly NDVI composites	41 Metrics derived from NDVI and bands 1–5	Daily mosaics of 4 spectral channels and NDVI	12, 32-day composites of 8 input parameters
Classification Technique	Unsupervised clustering	Supervised classification tree	Generally unsupervised classification	Supervised decision-tree classifier, neural networks
Classification Scheme	IGBP (17 classes)	Simplified IGBP (14 classes)	FAO LCCS (IGBP correspondence)	IGBP
Validation	High resolution satellite images	Used other digital datasets	Statistical Sampling (in progress)	Confusion matrices, confidence values

3.2 Land Available for Afforestation

The land available for afforestation consists mainly of non-forest land where agricultural production is low or unprofitable, since afforestation projects can hardly compete on productive agricultural lands with traditional forms of land use. In addition, the UNFCCC and the Kyoto Protocol prescribe that land-use change for carbon benefits should not endanger food security. Given these prescriptions, we selected five land cover classes: *grasslands, open shrublands, closed shrublands, savannas and crops*[1] (see Figure 1). From these classes, we exclude (i) highly productive land where the indicator of suitability for agricultural is above 50% (this indicator ranges from 0 to 100%); (ii) grids where the population density is over 200 hab/km^2; (iii) grids with elevation more than 3500 m; and (iv) grids where there is no net carbon uptake.

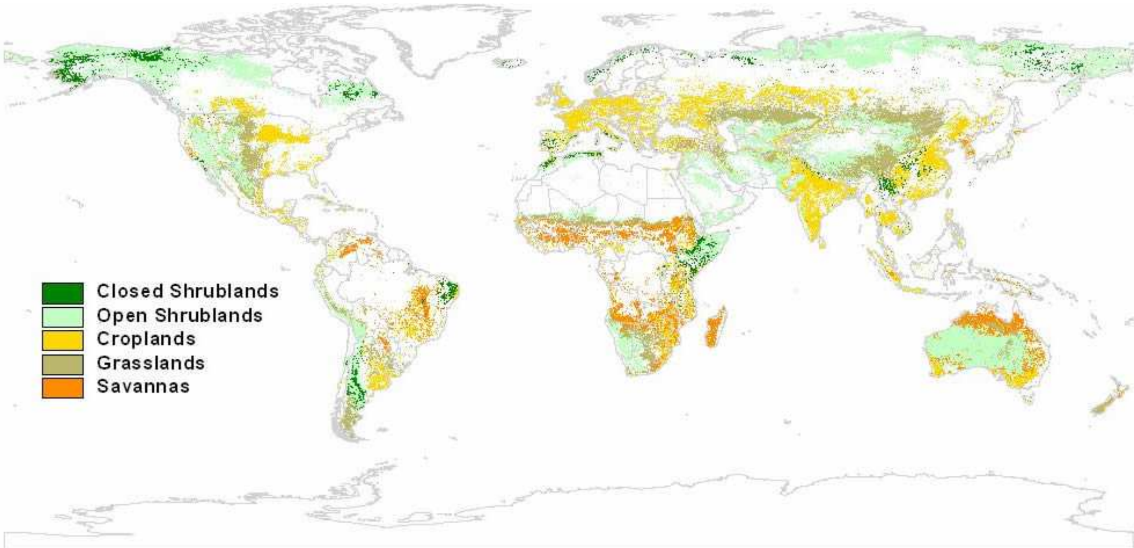

Figure 1: IGBP land cover dataset showing the five classes used in this study.

3.3 Economic and Tree Growth Parameters

Timber productivity is proportional to biomass accumulation in the above-ground forest and a conversion factor of 2 m^3/tC is used. Rotation intervals are considered constant and equal to 30 years. Rotation intervals — time between planting and harvesting — are exogenous in the model. Being conservative, we use a value of 30 years for all grids (but note that the rotation interval in the tropics could be as short as 10 years for some species and longer in the boreal forest). The baseline factor is assumed to be 10%. The baseline has two components: (i) a site-specific baseline corresponding to the non-forest carbon stock (Alexandrov *et al.*, 1999; Alexandrov *et al.*, 2002); and (ii) a regional baseline which subtracts possible afforestation and revegetation trends in a business-as-usual scenario. For this we deduct 10% of the carbon sequestration for each grid.

[1] Grasslands: lands with herbaceous type of cover; tree and shrub cover: 0–10%. Open Shrublands: lands with woody vegetation less than two meters tall; shrub cover: 10–60%. Savannas: lands with herbaceous and other understory systems; forest cover: 10–30%. Closed Shrublands: lands with woody vegetation less than two meters tall; shrub cover: more than 60%. Croplands: land covered with temporary crops (Hansen *et al.*, 2000).

Regarding the parameters for the decay function of forest products, we consider that 50% of the forest biomass is stored in long-lived products with a half-life time of 20 years and the remaining biomass that consists of short-lived products has a half-life time of one year. We assume that 80% of each grid could be afforested, tree-planting requires 50 years for completion, and that planting occurs at a constant rate as in Trexler and Haugen (1995).

Regarding economic parameters, we take Brazil as the country of reference. For other countries, we correct prices with the price index which is the ratio between the purchasing power parity (PPP) conversion factor to official exchange rate in 2001 (World Bank, 2003)[2]. Plantation costs for Brazil are \$800/ha that is within the range provided by Ecosecurities (2002) and Fearnside (1995). For fitting the parameters of the land price function (A_i), we set minimum and maximum bounds, so that the upper bound corresponds to grids where suitability for agriculture and population density are the highest, and the lower bound corresponds to grids where these indicators are the lowest. We assign equal weights for both indicators, so that $\alpha_i = \gamma_i$ in equation (5). For Brazil, the higher bound for land prices is set on \$2000/ha which resembles sites of good quality in Latin America (de Jong *et al.*, 2000; Benítez *et al.*, 2001). The lower bound is set to \$200/ha. Stumpage timber prices across grids are estimated with a similar procedure as for the land price. In the absence of a detailed infrastructure map that allows a precise estimation of transportation costs, we consider that stumpage timber prices are dependent on population density. Taking into account that transportation costs are major determinants of stumpage timber prices, we expect that in areas of high population density, transportation costs will be low since distances to markets are small and infrastructure availability is high. The higher bound for timber price in Brazil is \$35/m^3, based on an export price of \$50/m^3 (FAO, 2002) and harvesting and transportation costs of \$15/m^3. The lower bound for timber price is \$5/m^3 and the values in-between are adjusted linearly with population density. Given the rough approximation for land and timber prices, we conducted an in-depth sensitivity analysis in order to calibrate the model in an interactive mode.

3.4 Country Risk Data

A number of risk indicators have emerged, which are available for a large number of countries including (Erb *et al.*, 1996b), (i) Institutional Investors: provides country credit ratings (CCR) based on surveys from bankers located worldwide; (ii) Moody's: provides ratings describing the creditworthiness of corporate bonds; (iii) Standard and Poor's (S&P): use a similar rating system as Moody's, but creates finer rating; and (iv) International Country Risk Grading (ICRG): provides ratings for political, financial and economic risk factors and also calculates a composite index. Some of the factors included in the political risk rating of ICRG are political leadership, economic planning failures, external conflict, corruption, military and religion in politics, civil war, terrorism and quality of the bureaucracy. Financial risk includes loan default, repudiation of contracts by government, losses from exchange controls and

[2] Price index relative to the US. Price index for countries not appearing in the reference were assigned as follows: low income countries, 0.2; lower middle income countries, 0.5; and upper middle income countries, 0.7.

expropriation of private investments. Finally, some of the economic risks factors are inflation, debt service and international liquidity. ICRG uses a scale from 0 (worse) to 100 (best).

Given the available risk rating systems, we select the ICRG as it is not limited only to credit risk but compiles political, economic and financial aspects that determine the overall concern for investing in a specific country. From the ICRG database, we use the 5-year composite index forecast and the correspondent average of worst and best case scenarios for each country.

As a proxy for required returns for carbon sequestration projects, we use available data on discount rates used for this type of project in relevant scientific publications. As shown in Table 3, researchers in developing countries use much higher discount rates than in industrialized countries, reflecting the higher risk perception for these countries.

Table 3: Discount rates for carbon sequestration projects in key countries.

Country	**Discount rate**[a]	**Reference**	**ICRG rating 5-year forecast**[b]
USA	5%	Stavins (1999)	78.5
Canada	4%	van Kooten *et al*. (2002)	79.8
Argentina	10%	Sedjo (1999)	66.3
Brazil	12%	Fearnside (1995)	67.8
Costa Rica	7%	Nieuwenhuyse *et a*l. (2000)	74.5
India	17%	Ravindranath and Somashekhar (1995)	65.3
Indonesia	20%	Cacho *et al*. (2002)	57.5
Mexico	10%	Masera *et al*. (1995)	66.8

[a] Some authors perform their analysis using several discount rates. For these cases we selected the one corresponding to the benchmark scenario.
[b] The average between worse and best scenario (PRS, 2004).

Based on these data, we estimate the parameters of equation (8) by regression analysis, and extrapolate the required return estimation towards other countries. When the estimated return for the less risky countries is below 3%, we assign a value of 3% to such country in order to avoid having a rate below a risk-free rate[3]. Although the primal data contemplates a small sample of countries, the estimated returns for the others seems reasonable. For example, for the stable economy of Australia we estimated a rate of 3.6%. For China, we have a moderate rate of 7.5%. Chile, as a newly industrialized country, has a rate of 7.4%. Countries under conflict, like Somalia and Liberia, have rates of 33%, reflecting their unattractiveness for private investment. Appendix 1 shows the risk-adjusted rates for all the countries of the study. Note that for some countries there is no data on the ICRG risk index, so we assigned values correspondent to similar countries or from the income group.

[3] US treasury bills are often used as a reference for risk-free rates. For early 2004, 3-month treasury bills yield about 1%. The average for the last five years is 3.6% (FFC, 2004).

4 Results

In our first analysis, we use a unique discount rate of 5% that is often considered for carbon mitigation assessments in the energy sector. We derive carbon-supply curves for the four different land cover datasets, considering a sequestration period of 20 years. From Figure 2, we find zero-cost options for carbon sequestration at the left-side of the curve (the carbon price appears to be negative), where timber benefits would provide sufficient incentive to convert non-forest use of land into plantations for timber production. If we take, as a reference, a carbon price of \$50/tC we expect up to 6900 MtC sequestered in 20 years using the IGBP database. This is roughly equivalent to one year of carbon emissions in the energy sector (IPCC, 2000). Comparing the four global datasets, we find that IGBP provides the most conservative estimate of the supply-curve, while UMD gives a much higher estimation. GLC and MODIS provide similar estimates. Differences resulting on database selection could be up to 45% on the cumulative sequestration (at a carbon price of \$50/tC). This finding emphasizes the need to utilize multiple datasets in this work in an attempt to show the possible magnitude that different input datasets for the same parameters can have on results.

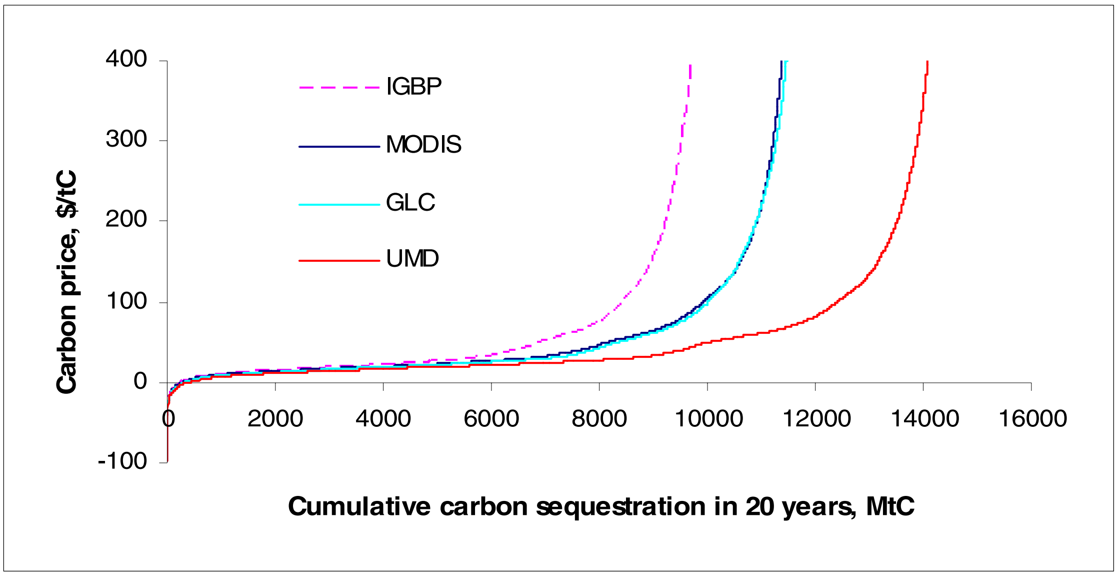

Figure 2: Carbon supply for different global land cover datasets and a uniform discount rate of 5%.

When we evaluate the impact of risk-adjusting discount rates for each country using the IGBP land cover dataset, we find a significant effect particularly at low carbon prices (Figure 3). For example, with a price of \$50/tC the cumulative sequestration level is 59% less when country risk is considered, and with \$100/tC this difference is 20%. These results stress the importance of including country risk in global assessments in order to prevent an over-estimation of the carbon mitigation potential.

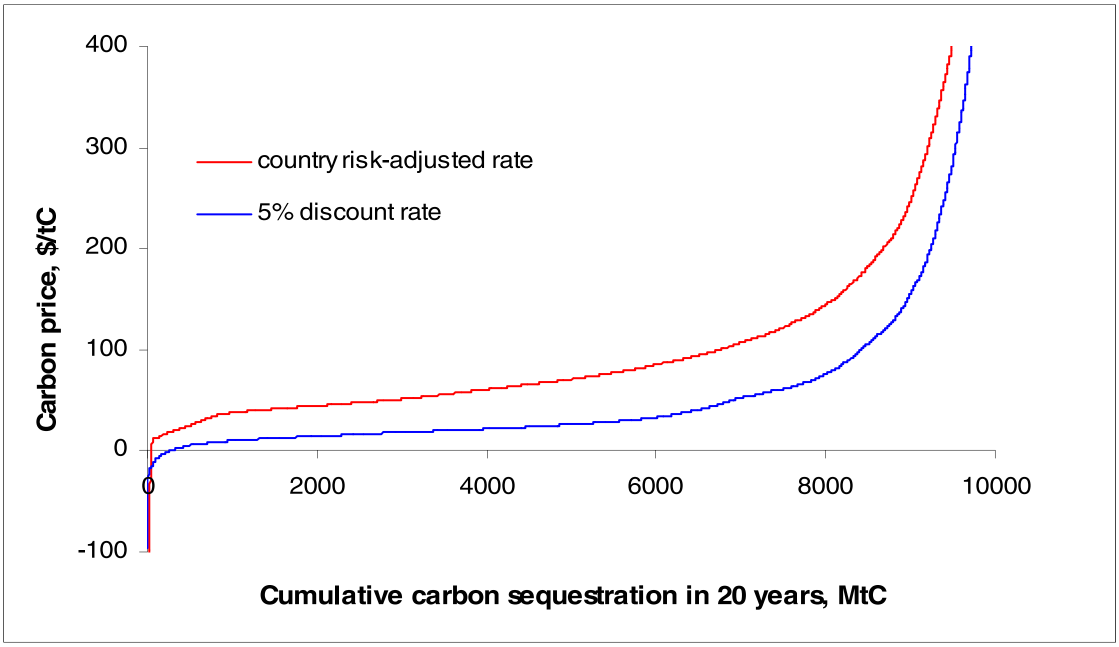

Figure 3: Effect of country-risk considerations on carbon-supply (IGBP dataset).

Furthermore, owing to the use of disaggregated datasets in this analysis, we are able to analyze the results from a spatial viewpoint. Figure 4 represents the cumulative carbon sequestration in 20 years under a carbon price of $100/tC. Based on this graph, Africa, Asia and South America appear obvious choices for carbon sequestration. This is also visible in the maps provided in Appendix 2. When we include risk into the analysis, the relationships are maintained but the cumulative sequestration of most regions is diminished significantly. We should be aware that the reduction of the carbon supply in Europe is caused by risks associated to countries like Russia, Romania, Belarus and Ukraine, and the reduction in the carbon supply in North America is caused by risks associated to Mexico.

4.1 Sensitivity Analysis

There are innumerable uncertainties in the assessment of carbon sequestration with respect to parameter choice and input data. Sensitivity analysis has shown that important factors are land price, timber price and the rate of carbon uptake. In Table 4, we provide a summary of the sensitivity analysis with respect to these factors in three selected points of the 20-year cost curve, using the IGBP dataset and a uniform discount rate of 5%.

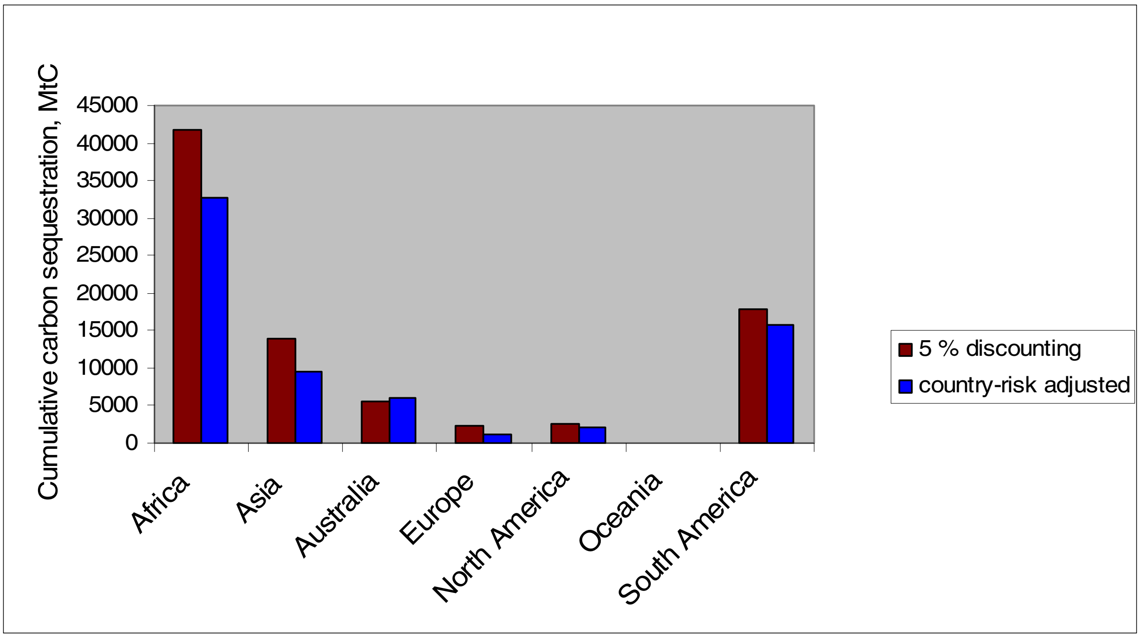

Figure 4: Comparison of carbon supply per continent for a 20-year period and a carbon price of $100/tC.

Table 4: Sensitivity analysis of global supply-curve (IGBP dataset, 5% discounting).

	Cumulative carbon sequestration, 20-year period (IGBP dataset)		
	Carbon price: US$50/tC	**Carbon price: US$100/tC**	**Carbon price: US$200/tC**
1. Land price			
50% lower for each grid	7759	8746	9372
Main scenario	6889	8420	9242
50% higher for each grid	6358	8119	9067
2. Timber price			
50% lower for each grid	6528	8214	9159
Main scenario	6889	8420	9242
50% higher for each grid	7425	8605	9292
3. Carbon uptake			
25% lower for each grid	4466	5879	6686
Main scenario	6889	8420	9242
25% higher for each grid	9723	11027	11779

There are three main points to stress from the sensitivity analysis, (i) carbon uptake is the most sensitive parameter, but increasing research efforts on this aspect are reducing current uncertainty levels, (ii) land prices have a lower impact on the supply curve, but it is difficult to have accurate estimates since ultimately, land prices depend on particular preferences, attitudes of landowners and land market policies, and (iii) carbon prices have a strong influence on the sensitivity where the higher the carbon price is, the lower the sensitivity and more robust the sequestration results are.

5 Conclusions

We have provided a framework for identifying least-cost sites for carbon sequestration and deriving carbon sequestration cost curves at a global level. The method is based on determining sequestration costs for geographical explicit units (grids), based on GIS parameters on land-use and ecosystem properties, and aggregated economic data. Major advantages of the method are: (i) provides an standard approach applicable worldwide where results from different world regions could be compared; (ii) there is no need to entirely depend on local statistics that are often scarce in developing countries, but major parameters are estimated indirectly from publicly available databases; (iii) estimation of sequestration costs accounts for the entire life-cycle of the sequestered carbon, including carbon uptake during growing phase, carbon emissions during harvest, and residual carbon storage in short and long lived-products. The explicit treatment of the full life-cycle helps to alleviate problems on carbon accounting that have become a major concern for CDM[4]-sink projects; (iv) it is a practical tool for testing the sensitivity on global parameters related to ecosystems (e.g., land-use databases) and economics (e.g., country risk).

Our model results suggests that under reasonable assumptions on the land and timber price and excluding country risk considerations, the global supply of carbon at a price of $50/tC during a 20 year period would be 6900 MtC, roughly equivalent to one year of carbon emissions in the energy sector. This is valid when the IGBP database is used. Using other databases lead to sequestration potential up to 45% higher. The fact that country risk is a major investor's concern, we have estimated required returns for forestry investments based on CAPM theory. In the absence of equity markets in most developing countries, required returns for forestry investments where determined as a function of the composite ICRG index that aggregates political, financial and economic risk for each country. By taking into account country risk considerations, the supply for carbon sequestration is reduced significantly: 59% given a carbon price of $50/tC. With respect to the geography of supply, as illustrated by our grid-scale maps, we find that the majority of least-cost projects are located in Africa, South America and Asia, assuming a discount rate of 5% and no risk. However these findings appear to be very sensitive to risk, and one needs to look at these further.

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Appendix 1: Risk-adjusted Discount Rates

Country	ICRG rating 5-year forecast[a]	Risk-adjusted discount rate	Country	ICRG rating 5- year forecast[a]	Risk-adjusted discount rate
Afghanistan[b]	57.7	19.4%	Lithuania	72.5	8.4%
Algeria	62.5	15.6%	Macedonia[c]	52.5	24.0%
Angola	54.75	22.0%	Madagascar	65.5	13.3%
Argentina	66.25	12.7%	Malawi	59.25	18.1%
Armenia	63.5	14.8%	Malaysia	64.5	14.0%
Australia	80	3.6%	Mali	62.5	15.6%
Austria	85.5	3.0%	Mauritania[b]	57.7	19.4%
Azerbaijan	60.5	17.1%	Mexico	66.75	12.4%
Belarus	56.25	20.7%	Mongolia	61.75	16.1%
Benin[b]	57.7	19.4%	Montenegro	52.5	24.0%
Bhutan[b]	57.7	19.4%	Morocco	67.5	11.8%
Bolivia	68.75	10.9%	Mozambique	55	21.7%
Bosnia/Herzegovina[c]	52.5	24.0%	Myanmar	52.75	23.8%
Botswana	80.75	3.2%	Namibia	73.5	7.7%
Brazil	67.75	11.7%	Nepal[b]	57.7	19.4%
Brunei	78.75	4.4%	Netherlands	84.5	3.0%
Bulgaria	73.25	7.9%	New Zealand	78.75	4.4%
Burkina Faso	62.75	15.4%	Nicaragua	51.75	24.7%
Burundi[b]	57.7	19.4%	Niger	60.25	17.3%
Cambodia[b]	57.7	19.4%	Nigeria	57.25	19.8%
Cameroon	61.5	16.3%	Norway	86.5	3.0%
Canada	79.75	3.8%	Pakistan	55.25	21.5%
Central African Rep.[b]	57.7	19.4%	Panama	70.25	9.9%
Chad[b]	57.7	19.4%	Papua New Guinea	62.25	15.7%
Chile	74	7.4%	Paraguay	55.75	21.1%
China, P.R.	73.75	7.5%	Peru	63.75	14.6%
Colombia	59.75	17.7%	Poland	75.25	6.6%
Congo D.R. (Zaire)	51.5	24.9%	Portugal	79	4.2%
Congo, Republic	54.5	22.2%	Romania	59.5	17.9%
Cote d'Ivoire	63	15.2%	Russian Federation	55	21.7%
Czech Republic	76.5	5.8%	Saudi Arabia	69	10.8%
Denmark	84	3.0%	Senegal	59.25	18.1%
Ecuador	59.5	17.9%	Serbia	52.5	24.0%
Eritrea[b]	57.7	19.4%	Sierra Leone	44.75	31.7%
Ethiopia	59.75	17.7%	Slovenia	77.25	5.3%
Finland	82.75	3.0%	Somalia	43.75	32.8%
France	82	3.0%	South Africa	64	14.4%
Gabon	65.75	13.1%	Spain	82.25	3.0%
Georgia[d]	55	21.7%	Sudan	52.5	24.0%
Germany	82.5	3.0%	Suriname	65.75	13.1%
Ghana	61.75	16.1%	Swaziland[e]	64	14.4%
Guinea	58	19.2%	Sweden	80.75	3.2%
Guyana	64.25	14.2%	Switzerland	86.5	3.0%
Iceland	79.5	3.9%	Syria	64.25	14.2%
India	65.25	13.5%	Tajikistan[d]	55	21.7%
Indonesia	57.5	19.6%	Tanzania	59.5	17.9%
Iran	68.25	11.3%	Thailand	66.75	12.4%
Iraq	57	20.0%	Togo	61	16.7%
Ireland	82.25	3.0%	Tunisia	66.75	12.4%
Israel	66.75	12.4%	Turkey	66.75	12.4%
Italy	77.25	5.3%	Turkmenistan[d]	55	21.7%
Japan	84.75	3.0%	Uganda	60.75	16.9%
Jordan	72	8.7%	Ukraine	58.5	18.8%

Country	ICRG rating 5-year forecast[a]	Risk-adjusted discount rate	Country	ICRG rating 5- year forecast[a]	Risk-adjusted discount rate
Kazakstan	64	14.4%	United Kingdom	79	4.2%
Kenya	61.25	16.5%	United States	78.5	4.5%
Korea, D.P.R.	44	32.5%	Uzbekistan[d]	55	21.7%
Kyrgyzstan[d]	55	21.7%	Venezuela	63.75	14.6%
Laos[b]	57.7	19.4%	Vietnam	60.25	17.3%
Latvia	70.25	9.9%	Yemen, Republic	64.5	14.0%
Lesotho[b]	57.7	19.4%	Zambia	58	19.2%
Liberia	44	32.5%	Zimbabwe	56	20.9%
Libya	62.25	15.7%			

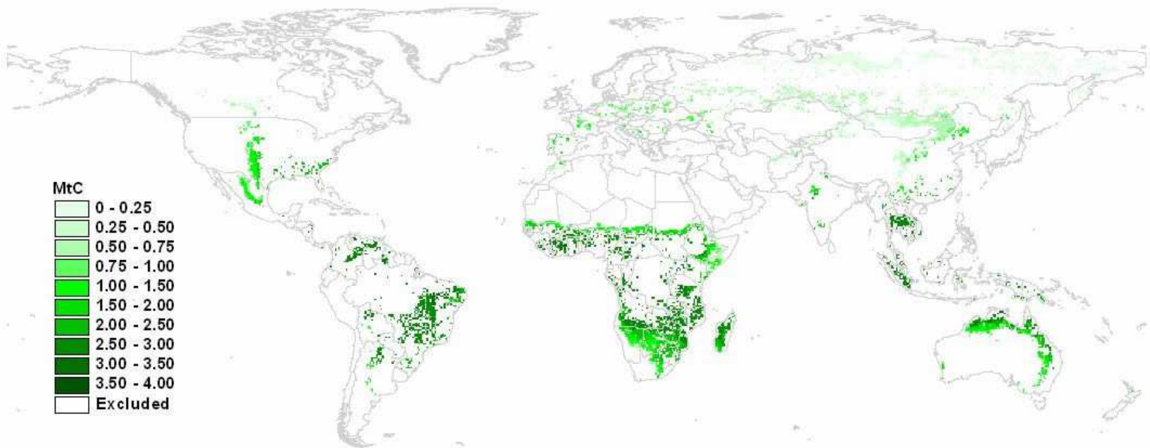
[a] The average index between worse and best scenario (PRS, 2004).
[b] Average ICRG index for low income countries.
[c] Data for Serbia.
[d] Data for the Russian Federation.
[e] Data for South Africa.

Appendix 2: Plates

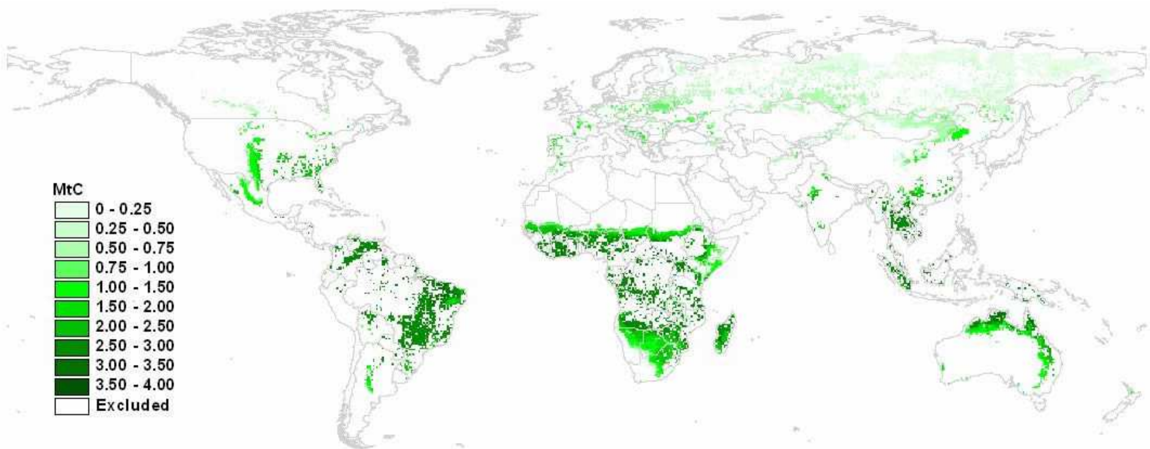
1 Land Available for Plantations and Sequestration Potential in 20 Years.

The following five plates show the amount of carbon sequestered in 20 years for grid cells with a price less than 200 US$/tC based on different land cover datasets. The bulk of the carbon sequestration appears in the Southern Hemisphere.

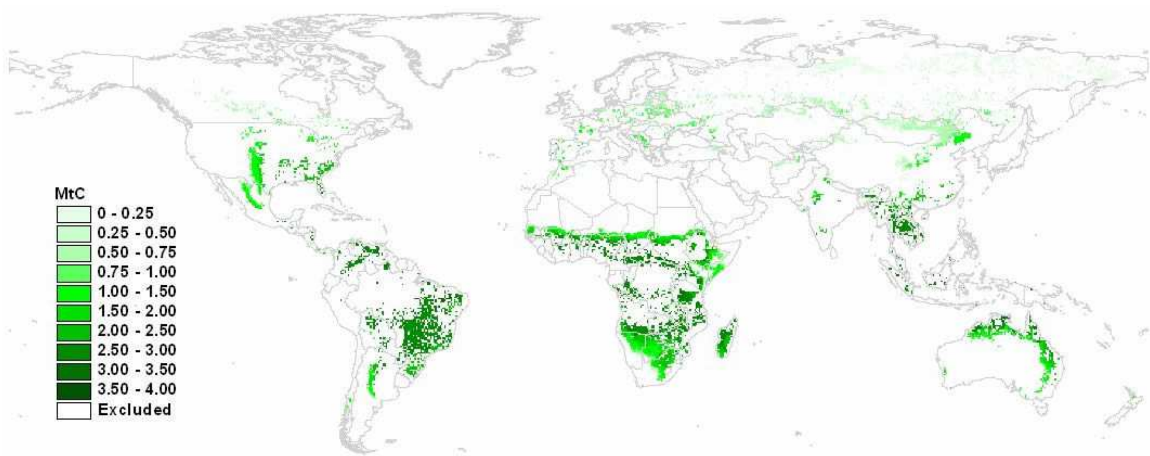
1.1 IGBP



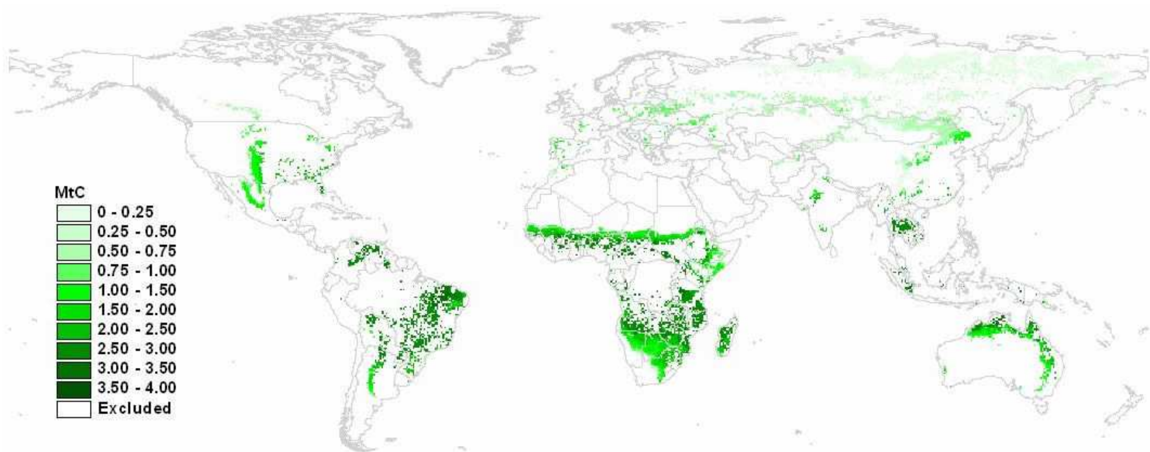
1.2 UMD



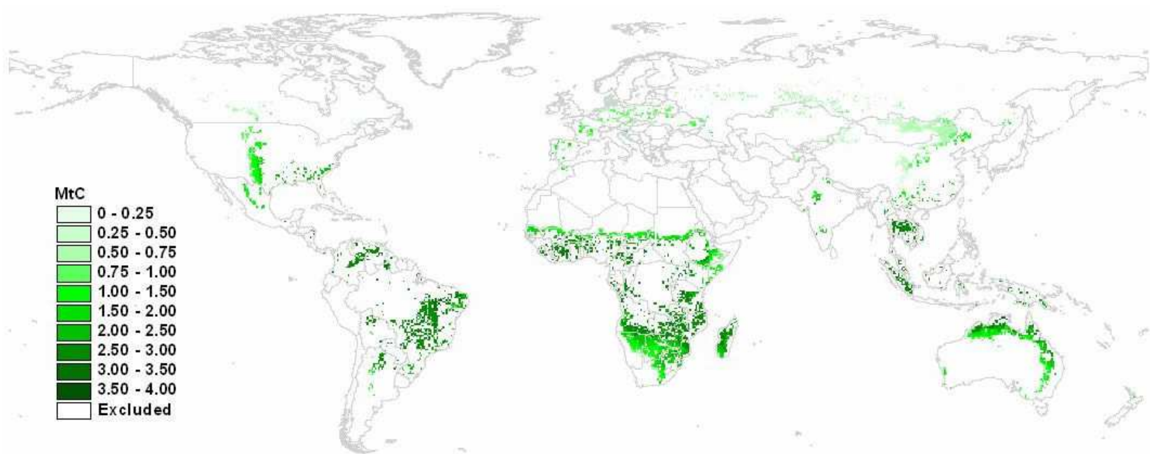
1.3 GLC2000



1.4 MODIS



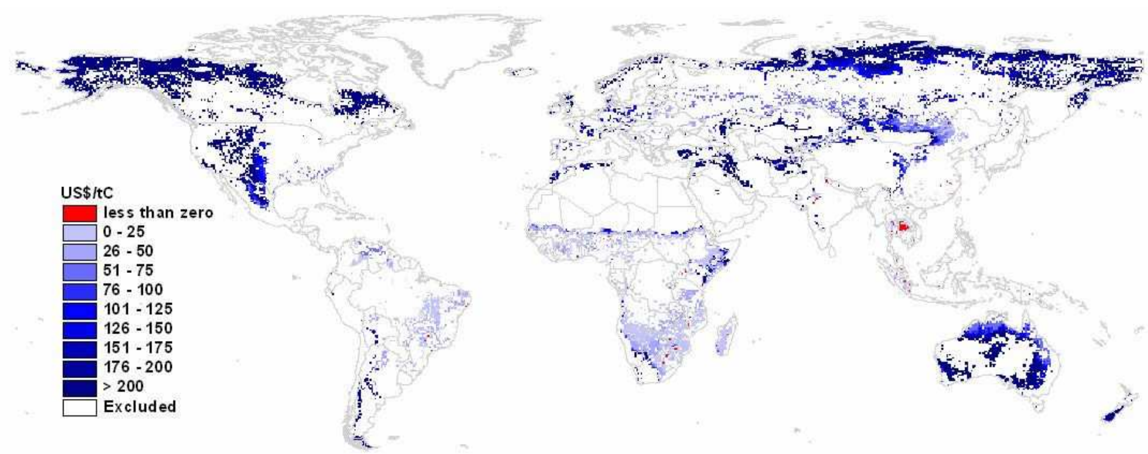
1.5 IGBP (risk-adjusted)



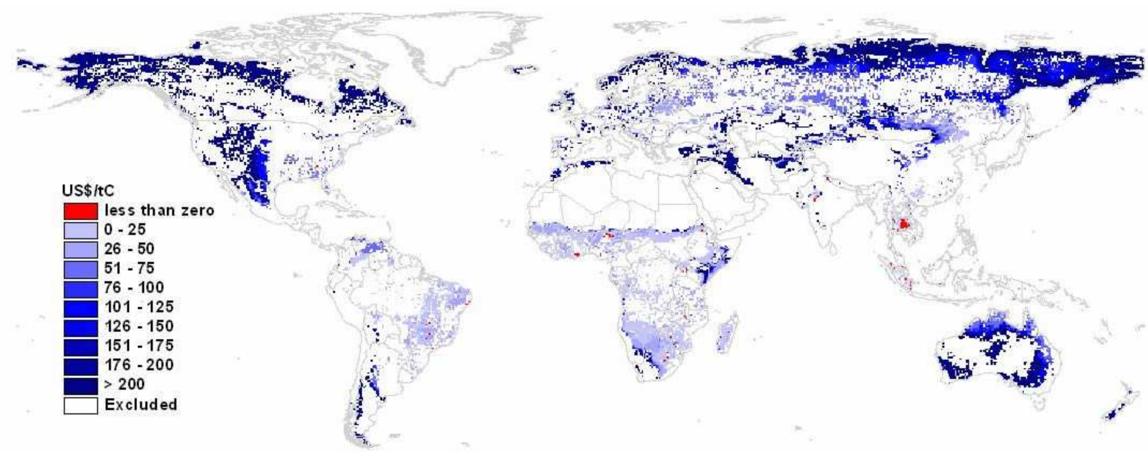
2 Carbon Cost

The following five plates show the price in US$/tC up to a maximum of 1000 US$/tC based on different land cover datasets. The area in red identifies regions where forestry without payments for carbon sequestration provides higher revenues than agriculture. Under the risk scenario, this area shifts over to Europe.

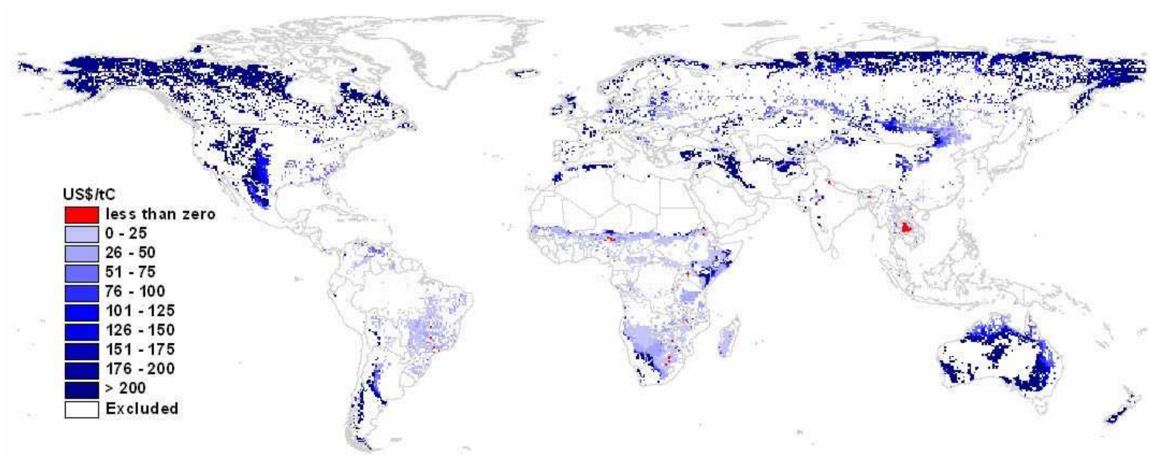
2.1 IGBP



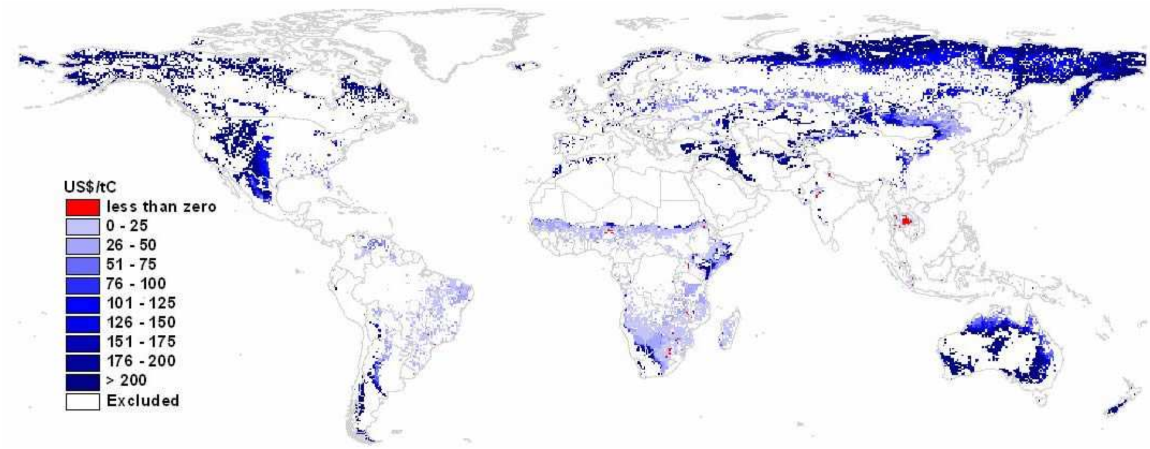
2.2 UMD



2.3 GLC2000



2.4 MODIS



2.5 IGBP (risk-adjusted)