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GLOBAL SUPPLY OF BIOMASS FOR ENERGY AND CARBON SEQUESTRATION FROM AFFORESTATION/REFORESTATION ACTIVITIES

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Abstract. In this paper we provide an analytical framework to estimate the joint production of biomass and carbon sequestration from afforestation and reforestation activities. The analysis is based on geographical explicit information on a half-degree resolution. For each grid-cell the model estimates forest growth using a global vegetation model and chooses forest management rules. Land prices, cost of forest production and harvesting are determined as a function of grid specific site productivity, population density and estimates of economic wealth. The sensitivity of the results due to scenario storylines is assessed using different population and economic growth assumptions, which are consistent with B1 and A2 of the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios (IPCC-SRES) marker scenarios. Considerable differences in the economic supply schedules are found. However, technical potentials seem to converge given constancy in other underlying assumptions of the model.

Keywords: bioenergy, afforestation/reforestation, carbon sequestration, global supply, geography

1. Introduction

In almost all of the Intergovernmental Panel on Climate Change (IPCC) emission scenario models that aim at stabilizing of atmospheric carbon concentrations at less than double of current level, biomass-based energy systems take a prominent share of the total energy portfolio (IPCC 2001a). Climate mitigation targets, as defined by the objectives of the United Nations Framework Convention on Climate Change (UNFCCC), shall contribute to allow natural ecosystems to adapt autonomously to climate change, guarantee food security and sustainable economic development. What we do not know is whether a large-scale implementation of biomass projects all over the world might threaten the very objectives of the framework convention. A socially and environmentally benign implementation of competitive bioenergy systems is a major challenge for sustainable human development, particularly in the developing world.

In its principles, the UNFCCC demands that climate mitigation options should be comprehensive, cover all relevant sources, sinks and reservoirs of greenhouse gases (GHG) – thus allowing for managing terrestrial ecosystems for mitigation benefits. Bioenergy resources comprise of residues and wastes, dedicated energy crops and natural vegetation (Kartha and Larson 2000). Resources from afforestation or reforestation (AR) activities, which are analyzed in this paper, can be categorized in all three categories. If AR uses autochthon plant material in combination with semi-natural forest management practices the resource will be 'natural' vegetation, if AR uses high yield – in many cases exotic species – we may categorize this activity as an energy plantation and, finally, if residues, e.g., leaves and branches, are used for energy conversion purposes then the resource is residues. Production of woody biomass from afforestation yields joint production of biomass for energy use (or use for timber) and sink enhancement – there is a linkage between the growing stock (biomass in afforested lands) and the flow (use for bioenergy). Assessments of this joint nature of production are rare since most studies either focus on biomass supply or on the sink side. In this paper we will focus on the economic joint production potential of biomass from afforestation activities and its associated carbon sink. AR activities have been identified as an effective land-use change measure to sequester carbon and to deliver biomass for energy (Obersteiner et al. 2001, 2002; Schlamadinger et al. 2001a,b; Levandrowski et al. 2004; Schneider and McCarl 2003). There are excellent reviews available on economic potentials for sequestration (e.g., Richards and Stokes 2004) and biomass resources (e.g., Berndes et al. 2003; Hoogwijk 2004). However, a global analysis of the implications of the joint production of AR activities has not yet been assessed.

Contrasting to these studies and as a new research contribution, we estimate global supply curves of both biomass for energy and its joint product carbon sequestration *in situ* by using information at a disaggregated level, and scrutinizing the potential afforestation area so that sequestration costs are estimated at geographically explicit half degree grid-cells. We select applicable land classes and exclude 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/biomass prices) influence sequestration costs and determine carbon-supply patterns and identify least-cost locations for carbon sequestration. Furthermore, we evaluate the sensitivity of the model to the basic scenario drivers for a B1 and A2 scenario.

2. The Model

Geographically explicit, coupled biophysical-economic forest sector modeling is a rather recent phenomenon in integrated assessment of continental scale land resources. Obersteiner (1998, 1999) has developed a forest sector specific model, which is geographically explicit, fully dynamic, endogenous price driven and allows for the assessment of a variety of interaction modes of economic agents. Such types of models allow for the assessment of real life phenomena, however, they are computationally intensive, expert driven, thus to some degree opaque, and are difficult to solve due to non-linearity and complexity. The purpose of the model discussed in this paper is to also combine biophysical models of biomass growth, but with simple economic rational of decision making. This approach is computationally frugal, guarantees a higher degree of transparency and allows immediate linkage with other integrated assessment models. The model directly builds on models built by Benitez and Obersteiner (2003) and Benitez et al. (2004). Excellent recent work by Hoogwijk (2004) constructed a strikingly similar model for scenario assessment of biomass resources within the framework of the IMAGE model.

The model prioritizes land areas according to their biophysical and economic suitability for AR activities. We estimate net present values (NPV) by subtracting production cost estimates from carbon and biomass revenues for each grid. The estimates are based on estimates and assumptions on *inter alia* biological growth, plantation costs, expected timber and land prices, and carbon storage in products. We obtain the cumulative sequestration cost-curve and biomass supply curve by aggregating and sorting grid-level results, taking into account that AR activities occur only in grids with positive NPVs. Besides obtaining the cost-curve, the method allows the identification of the geographic distribution of carbon costs and biological growth potentials. The methodology, for the case of carbon sequestration decisions, is described in Benitez et al. (2004). In this section we derive the decision making rule to sequester carbon through AR activities with the option to utilize renewable biomass for energy purposes. From the model we derive static supply schedules which were used by the IIASA MESSAGE model.

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

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

where cp_i are planting costs, pw_i is the stumpage timber price, r is the discount rate, R_i is the rotation interval estimated by expert judgment, 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, which was supplied by a biophysical forest growth models TsuBiMo (Alexandrov et al. 1999), by a linear function, where ω_i measures the yearly carbon uptake, and using pc_i for carbon price and B_i^b for carbon benefits in the biomass, we have:

$$B_i^b = pc_i \sum_{t=1}^{R_i} \omega_i (1+r)^{-t} - pc_i \cdot \omega_i \cdot R_i (1+r)^{-R_i}. \tag{2}$$

The first term of Equation (2) corresponds to the NPV of carbon benefits during the growing stage of the forest and the second term describes the carbon costs, which occur during forest production. For accounting carbon benefits in products we include, (i) long-lived products consisting of timber materials like furniture and construction wood, (ii) a short-lived products pool consisting of quickly decomposing biomass *in situ* such as leaves, branches and timber wastes or biomass which is thermally converted inside (e.g., slash burning) or outside the forest after harvest has taken place (e.g., black liquor combustion). Thermal conversion in this case is considered not to be an additional activity and is assumed carbon neutral within the 10-year time step of simulation. Carbon stored in products is released to the atmosphere following an exponential decay function with parametrization according to Sohngen and Sedjo (2000). The parameterization is also consistent with more detailed aggregate studies like Obersteiner (1999a). Carbon benefits in products represent the long-lived fraction, β_i, of the carbon costs that occur during harvest.

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:

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

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

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

The NPV of agriculture is obtained indirectly assuming 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 (e.g., more populated areas have more roads). The NPV of agriculture, A_i, is defined by:

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

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 throughout the scenario horizon. S_i and D_i are normalized between 1 and 10. Although Equation (5) provides just an approximation for the NPV of agriculture, its use allows avoiding detailed land-use statistics. This land price formulation, thus, implicitly mimics the scenario dependence of competition over land resources. 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. Land price calculations allow linkage to agricultural models by using shadow values from such models. At the same time, we use current data from land transactions to calibrate Equation (5). 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:

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

Equation (6) allows the estimation of the carbon costs for each grid on the basis of parameters available from Geographic Information Systems (GIS) databases and existing economic data available from public statistics and publications (see, e.g., Benitez and Obersteiner 2003). Note that there might be grids where forestry without payments for carbon sequestration, provide higher revenues than agriculture. In this situation carbon values are allowed to be negative and yet AR activities will take place due to the high values of timber or biomass.

For estimating the cumulative carbon sequestration at a given time, we consider that trees are replanted after harvest and that planting is delayed, meaning that each year a fraction of every grid is converted into forests until the whole grid is fully forested. This leads to uneven stand structures in every grid, which are harvested and replanted periodically according to the rotation cycle. For finding the cumulative sequestered carbon, we calculate the sum of carbon in biomass and products throughout all grids.

The potential biomass supply over the entire scenario period T from the afforested land in grid i is,

$$\mathrm{BE}_i = \{\omega_i^{\mathrm{st}} \cdot R_i \cdot \eta_i \cdot A_i\} f_i^{\mathrm{BE}} \tag{7}$$

where $\eta_i = \mathrm{floor}(\frac{T}{R_i})$ is the number of rotations within the scenario period T. f_i^{BE} denotes the fraction of biomass entering the biomass for bioenergy pool with the remaining amounts entering the forest sector consumption cycle. Note that within forest sector consumption we distinguish between a short- and long-term pool as outlined above. ω_i^{st} denotes the biomass stored in carbon pools that are accessible for biomass use, e.g., stemwood. The associated costs of biomass delivery to a biomass conversion plant are approximated by $c_i^{\mathrm{BE}} = pc_i + c_h$, this is the sum of the stumpage price plus the harvesting and transportation cost c_h. The latter cost component varies between 5–95US$/tC and is assumed to vary as a function of the stocking biomass, economic wealth and population density. For the calibration of the cost function we rely on cost estimations from engineering type of models according to Obersteiner (1999b) and Lundmark (2003) as well as information gained from the literature accommodating for less capital-intensive harvesting technologies employed in developing countries.

TABLE I
The complete set of spatial datasets used to create a resultant database for modeling

Dataset	Units	Original resolution	Source	Type
World Countries	Countries	1:1 Million	ESRI (1998)	Measured
Population 1995	Persons/km^2	1 km	CIESIN (2000)	Measured
Agricultural suitability	Fraction (%)	50 km	Ramankutty et al. (2001)	Modeled
Elevation	Meters	(1 km)	GTOPO30 (1996)	Measured
IGBP Land Cover	17 classes	(1 km)	USGS (2003)	Measured
NPP	gC/m^2/year	(50 km)	Alexandrov et al. (1999, 2002)	Modeled
Carbon Stock (non-forest/5/30 yr)	tC/ha	(50 km)	Alexandrov et al. (1999, 2002)	Modeled
Future GDP (A2/B1 SRES)	US$/ha	(50 km)	Gruebler et al. (2005)	Modeled
Future Population (A2/B1 SRES)	Persons/km^2	(50 km)	Gruebler et al. (2005)	Modeled

3. Data

3.1. Global Datasets

The following global spatial datasets were combined to create the resultant global dataset used in this study (Table I). Where necessary, all raster datasets were converted from their original resolution to a standard 0.5 degree (approximately 50 km) grid using appropriate methods.

Country boundaries as of 1998 were provided by the Environmental Systems Research Institute (ESRI) and were converted into raster format. The population as of 1995 was provided by the Center for International Earth Science Information Network (CIESIN) and within each cell the number of persons per/km^2 was identified (CIESIN 2000). The grid approach used a simple proportional allocation of administrative unit population totals over grid-cells. Sources of error include: the accuracy of the interpolation method, the timeliness of the census estimates, the number of estimates (one or two), and the accuracy of those estimates.

Agricultural suitability represents the fraction of each grid-cell that is suitable to be used for agriculture. It is based on the temperature and soil conditions of each grid cell. The methods used to derive this dataset are spatial data synthesis, analysis and numerical modeling (Ramankutty et al. 2001).

Elevation was provided by the GTOPO30 dataset, with each gridcell containing the elevation in meters above mean sea level (GTOPO30 1996). A variety of data sources were used to derive this global product, with the majority of the area represented by data having between 30 and 160 meters vertical accuracy.

The International Geosphere Biosphere Project (IGBP) dataset was used in this study to represent land cover (USGS 2003). This dataset utilized data from April 1992 to March 1993 and identified 17 land cover/land-use classes. Based on an earlier study by Benitez et al. (2004), the IGBP land cover dataset was found to be the most conservative of the recent satellite-based land cover products available, and was used here for that reason.

The net primary production (NPP) and carbon stock datasets were derived from modeling results (Alexandrov et al. 1999). Process-based models served as the drivers, with parameters derived from global databases of on-ground measurements.

Future gross domestic product (GDP) and population datasets were produced based on the IPCC Special Report on Emissions Scenarios (Gruebler et al. 2005). In particular, the A2 and B1 scenarios were used. The A2 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. The B1 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. The work involved a downscaling procedure that took results from the macro region and assigned them to continents, and finally to the 0.5 degree grid.

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 from the IGBP land cover dataset: closed shrublands, open shrublands, croplands, grasslands, and savannas (see Table II Figure 1). From these classes, we exclude (i) highly productive land where the indicator of suitability for agriculture is above 50% (this indicator ranges from 0 to 100%); (ii) grids where the population density is over 200 persons/km^2; (iii) grids with an elevation of more than 3500 meters; and (iv) grids where there is no net carbon uptake as predicted by the forest growth model. By selecting only land with agricultural suitability below 50% we ensure that only marginal crop and pasture lands are considered in our analysis. Calculations in the model for net present value of forest and agricultural land can further reduce the suitable area.

3.3. Economic and tree growth parameters

Timber productivity is proportional to biomass accumulation in the above-ground forest using allometric relationships. Rotation intervals were computed as a function of the approximation of the stem volume growth and varied between 9–120 years for plantations which delivered biomass for energy and were equal T

TABLE II

Description of the initial IGBP non-forest land cover types used in this study

Class	Definition
Closed shrublands	Lands with woody vegetation less than two meters tall and with shrub canopy cover >60%. The shrub foliage can be either evergreen or deciduous.
Open shrublands	Lands with woody vegetation less than two meters tall and with shrub canopy cover between 10–60%. The shrub foliage can be either evergreen or deciduous.
Croplands	Lands covered with temporary crops followed by harvest and a bare soil period (e.g., single and multiple cropping systems). Note that perennial woody crops will be classified as the appropriate forest or shrub land cover type.
Grasslands	Lands with herbaceous types of cover. Tree and shrub cover is less than 10%.
Savannas	Lands with herbaceous and other understorey systems, and with forest canopy between 10–30%. The forest cover height exceeds two meters.

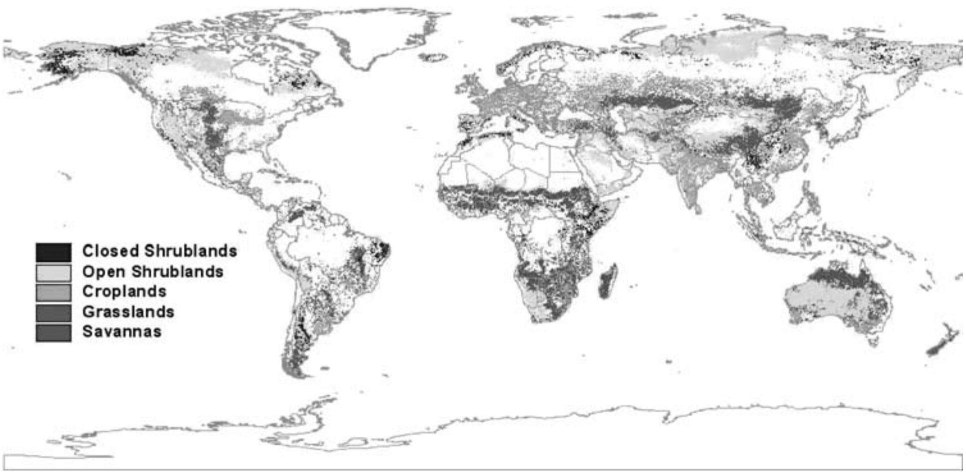


Figure 1. IGBP land cover dataset showing the five classes used in this study.

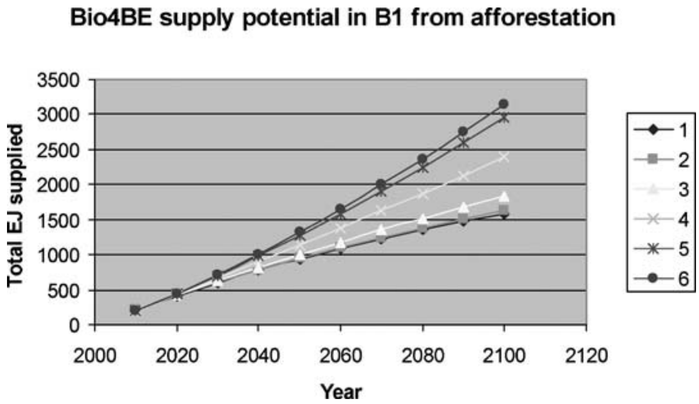
for afforestation areas which were afforested for the carbon sink value only, i.e., in cases where harvesting and transportation costs were prohibitive for biomass harvest and delivery. The baseline has two components: (i) a site-specific baseline corresponding to the non-forest carbon stock (Alexandrov et al. 1999, 2002); and (ii) a regional baseline which subtracts possible AR and revegetation trends in a business-as-usual scenario. To account for this factor we deduct a conservative estimate of a lump-sum 10% of the carbon sequestration for each grid.

Regarding the parameters for the decay function of forest products, we consider that 50% of the biomass entering the forest products pool 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 an expected half-life time of one year. We assume that 80% of each grid could be afforested and reforested with the rest going into areas for settlements, roads and bufferstrips for, e.g., riparian areas or fire, full tree-planting would require 50 years for completion of full AR, and that planting occurs at a constant rate as in Trexler and Haugen (1995). Forest sector consumption until the year 2100 depends on socio-economic drivers implied by the scenario storylines. All the additional wood supply goes into bioenergy production/carbon sequestration.

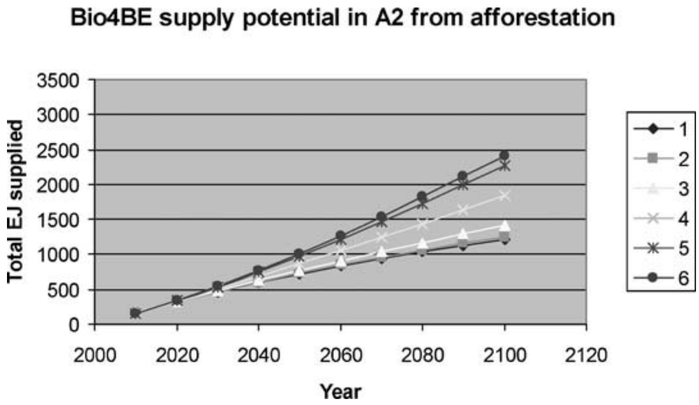
With respect to economic parameters, we take Brazil as the country of reference. For other countries, we correct prices with the price index, which is the ratio between the purchasing power parity (PPP) conversion factor to official exchange rate in 2001 (World Bank 2003).[1] Plantation costs for Brazil are US \$1000/ha, 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 US\$ 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 US\$ 200/ha. Additional sources for land prices relevant to AR can be found under e.g. www.sinkwatch.org, and shadow values from a number of agricultural models (e.g., De Cara and Jayet. 2000) were consulted. 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/biomass prices are, as mentioned above, dependent on the stocking density, S and D. The resulting prices for the initial years were cross-checked for a number of countries with export prices reported by the FAO (2002).

4. Results

We derived joint carbon sequestration and biomass supply curves using the IGBP land cover dataset, considering a scenario horizon of 100 years. Sensitivity runs of carbon sequestration potentials using a number of different land cover products are presented in Benitez et al. (2004) along with sensitivity analysis of the model to changes in land prices, timber prices and carbon uptake rates. In addition, country risk was assessed in that study. In this study we limit sensitivity analysis of our biomass supply and carbon sequestration model to the assessment of different population and economic growth assumptions. Qualitatively, the sensitivities for biomass supply are similar to those for carbon sequestration.



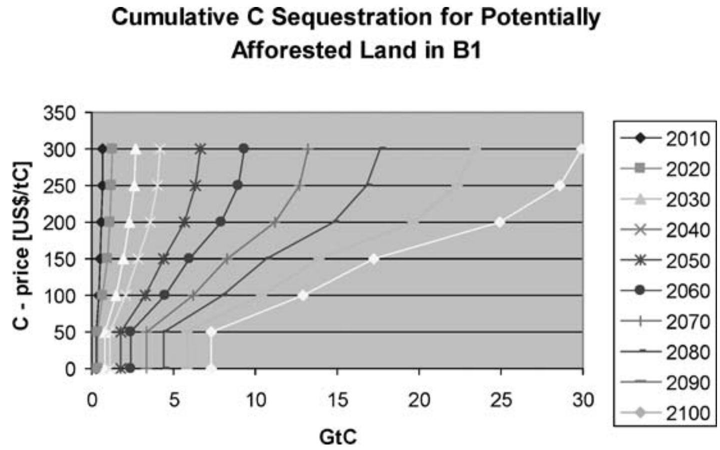
(a)



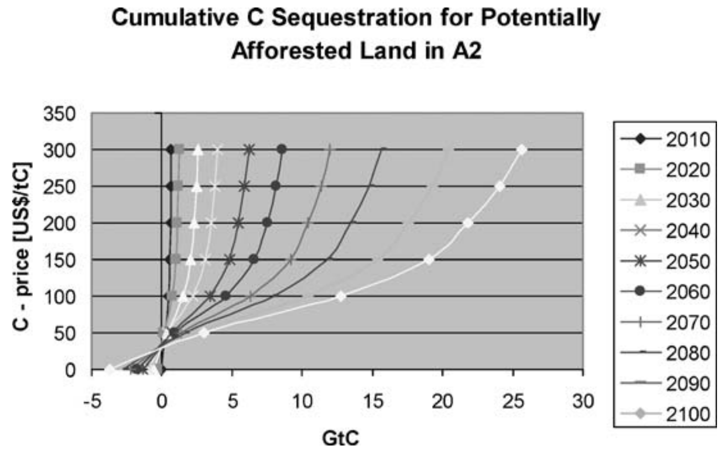
(b)

Figure 2. (a) Biomass for bioenergy supply potential for 2000–2100 in SRES scenario B1 for static energy prices from 1US$/EJ to 6US$/EJ. (b) Biomass for bioenergy supply potential for 2000–2100 in SRES scenario A2 for static energy prices from 1US$/EJ to 6US$/EJ.

Figures 2a,b show the results of global biomass supply using the static version of the supply model, i.e., marginal prices for energy are time invariant. Note that the incentive price is expressed in terms of an energy price (US$ in 2000), but it could equally stand for any other monetary incentive to plant forest biomass. In the modeling it was assumed that each decade in the period 2000–2100 the down-scaled data for either B1 or A2 SRES (IPCC Special Report on Emission Scenarios) projections of GDP and population density are utilized (see Gruebler et al. 2005; IPCC 2001b). At the end of each decade, for grids that are not yet afforested, the updated economic incentives are applied and some of these grids start to become afforested (since from that moment on it is profitable to plant trees for both carbon storage and biofuel production). Model results suggest that qualitatively the behavior of supply curves in both scenarios is similar. The major



(a)



(b)

Figure 3. (a) Supply schedule of carbon sinks as a function of carbon prices between 0 and 300US$/tC in 2000–2100 for SRES scenario B1. (b) Supply schedule of carbon sinks as a function of carbon prices between 0 and 300US$/tC in 2000–2100 for SRES scenario A2.

difference for bioenergy supply is in the total supply until 2100 (the difference between B1 and A2 increases over time and reaches approximately plus 30% for 2100 for each relevant energy price level). The potentials show lower sensitivity at low 1–3 US$/Exajoule (EJ) and high (5–6 US$/EJ) ends of the suggested energy price range.

Figures 3a,b indicate the carbon sequestration potentials for carbon prices lower than 300 US$/tC for two SRES scenarios (B1 and A2). The model output suggests that for the baseline case (zero carbon prices) for lands potentially involved in afforestation programs, they become a substantial sink in B1, but are a source in A2.

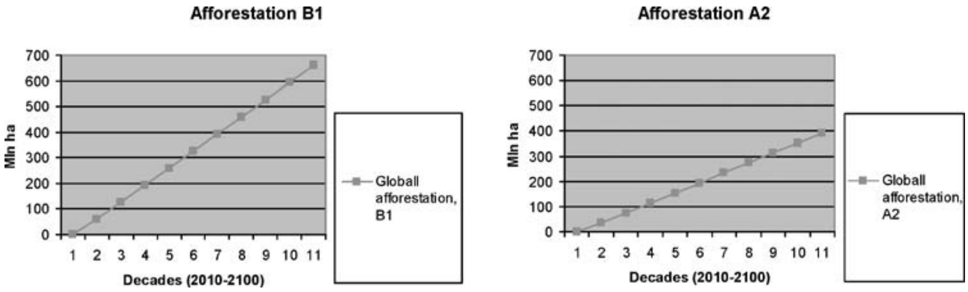


Figure 4. Comparison of total afforested areas in B1 and A2 in million ha over ten decades until 2100.

This is in agreement with projections on SRES scenarios made based on MESSAGE model calculations (IPCC 2001b). Around the middle carbon price range (100–150 US$/tC) two scenarios produce similar projections for carbon sequestration. On the other hand, for higher prices (200–300 US$/tC) B1's output is higher and the difference reaches approximately 17%. This indicates multiplicative effects of socio-economic parameters, which vary along with the choice of scenario, combined with different carbon price levels.

One can compare the magnitudes of the supply schedules of biomass supply (Figure 2) and the relevant sink (Figures 3a, b) using a conversion coefficient of 20 to convert EJ into GtC (for conversion coefficient between GtC and EJ see FAO (1999)).

This comparison reveals a difference of a factor about five. In the long term, the contribution from fossil fuel substitution as part of afforestation activities to reduce atmospheric carbon concentrations is much larger than respective carbon sink potential. It is, however, also important to mention that in the short term the sink effect dominates.

Figure 4 illustrates the difference in projected afforested areas between scenarios B1 and A2 till 2100. Socio-economic projections for the B1 scenario (about 660 Million ha) suggest an almost 70% larger area compared to that of A2 (about 390 Million ha) for the baseline scenario (IPCC 2001b). Aggregate land requirement behaves as an almost linear function of time. This is in part due to the model assumption that at each individual grid, once it becomes economically viable to start with AR activities, the speed of afforestation is assumed to be bounded.

While the aggregated projections are summarized in Figures 4–6 provide a geographically explicit distribution of the afforested areas. These figures present the percentage (out of the total suitable and available area for each grid) of potentially afforested areas.

In this paper we do not present results on the sensitivity of model results with respect to model parameters. However, it is important to mention the conclusions from previous work (Benitez et al. 2004) that (i) carbon uptake is the most sensitive

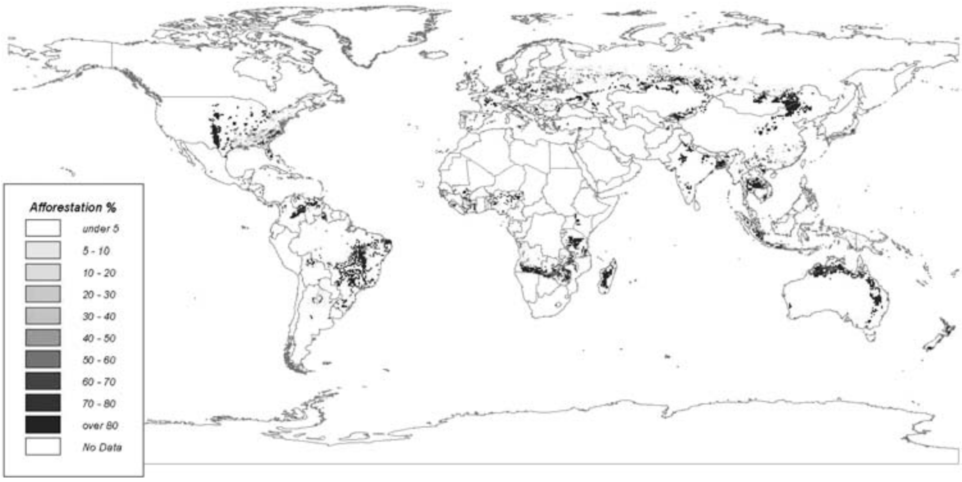


Figure 5. Afforestation in scenario B1.

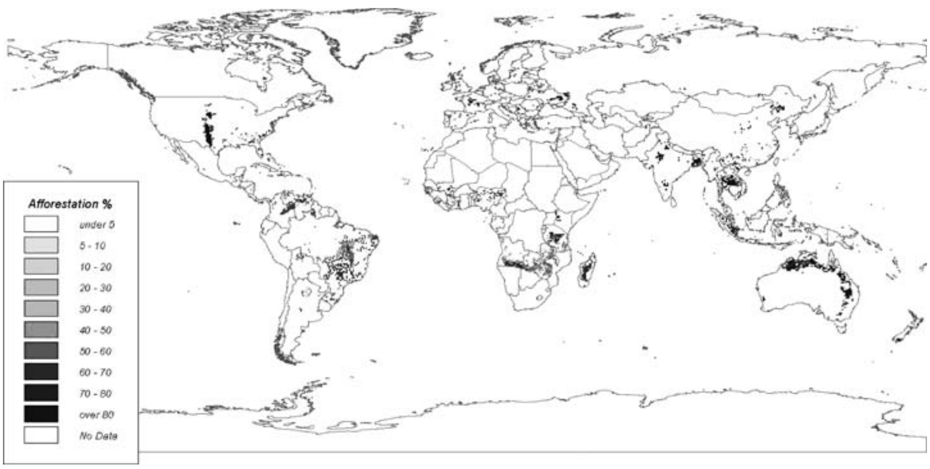


Figure 6. Afforestation in scenario A2.

parameter, (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 and timber prices have a strong influence on the sensitivity. The sensitivity decreases as the price signal strengthens and thus the robustness of the results.

In this paper we developed supply schedules using a static model, i.e., we assume time invariant prices as a carbon/bioenergy production incentive. This assumption is common practice in economic analysis in order to generate quantity price charts of supply. However, it is known that shadow prices in stabilization scenarios are sharply increasing over time. This time invariance has strong implications for the supply pattern of biomass and sink benefits (Obersteiner et al. 2003) as the incentive signal is usually strong at the end of the stabilization period and weak and volatile at the beginning. Thus, a dynamic analysis would most likely generate a smaller economic potential.

5. Discussion

In this paper we have constructed a relatively simple model to quantify the economic potential for AR activities. In the model the activity is triggered by a market price for carbon, and a biomass for bioenergy or a timber price. We did not consider issues related to the implementation potential of AR activities, which might yield higher or smaller sequestration and energy potentials compared to the pure economic potential. Most crucial for the competitiveness of AR activities for biomass supply and carbon sequestration are the biological growth patterns, land and production prices, accounting schemes and other ‘carrots’ and ‘sticks’.

One can distinguish between a number of incentive categories (carrots) for AR activities: (i) direct government assistance/program; (ii) preferential tax treatment; (iii) industry partnerships and third party leasing arrangements; (iv) market-based trading; (v) non-traditional compensation mechanisms; (vi) research and development subsidies; and (vii) legal prescription. Most of these incentive schemes can, in principle, readily be incorporated in our modeling framework. “Sticks” for implementation come in the form of institutional barriers and environmental constraints. Obersteiner et al. (2001) and Schlamadinger et al. (2001a,b) have proposed ways to include certification instruments for sustainable forest management in competitive markets for carbon credits. They conclude that certification schemes for sustainable forest management should be mandatory for biomass-based trading schemes under the UNFCCC. However, the malaise with the realities of certification today suggests that both social and environmental values cannot be guaranteed by this market-based instrument (see, e.g., Carrere and Fonseca 2003).

Therefore, the results presented in this paper take on a conservative approach in the sense that, for example, we do not assume large-scale productivity effects of future tree improvement programs by holding the parameters of the biological growth constant over time. In addition, our estimation of current growth is modest and we applied forest growth assumptions that would occur under idealized forest management with naturally occurring forest species. This assumption mimics a mixture of forest management of ‘natural’ forest plantations and less intensively managed plantation species. In this way we tried to approximate a ‘realistic’ mosaic of AR patterns, which also respect the mitigation of possible environmental externalities from large scale monocultures leading to a loss of biodiversity, requiring pest control and intensive fertilization and associated N_2O emissions. Thus, a natural adaptation value is indirectly incorporated in the analysis presented in this paper.

It has to be noted, however, that a purely economic response to an uncertain climate change signal would most likely imply shortening the rotation period combined with an artificial change of species. In this sense our economic mitigation potential is not consistent with purely economic reasoning on the adaptation side. Issues of social and cultural adaptation were not yet dealt with directly in the analysis. This adaptation process might be captured by additional assumptions, beyond those that can be associated with biological growth of forests, including the percent cover of AR area within each grid-cell, biomass yield adjustments for agro-forestry cases, the speed of AR, and transaction cost items.

The low emissions scenarios for the 21st century embody plantation-based bioenergy utilization of the order of hundreds of Exajoules (EJ) during this century. This implies land-use changes of large amounts of land. In our model such land-use changes are predicted based on the comparison of discounted NPV calculations of land rents under current land use and AR. The approximation of the value of land in its economic, but also sociocultural and ecological dimension is crucial for the assessment of AR projects. Major adaptations of rural life, especially in developing countries, will be necessary to produce the hundreds of EJ of biomass (Rosillo-Calle 2000). Clearly, land prices are affected by the very underlying drivers such as population and economic wealth projections as well as agriculture, forest and nature conservation policies and other policies like climate policy. Apart from these drivers and policies, human capital is needed to enable the tens of thousands of land-use change projects that are needed to be initiated by experts from implementing regions (Haque et al. 1999). The experts need to be trained in the necessary skills to implement projects at the community level, motivating the communities that live on the land to enter this new market, as well as identifying appropriate technologies, securing finance, and demonstrating carbon and other ancillary benefits or damages. All of these activities associated with AR in the model could be added up in a cost category of transaction costs or, as in our case, form part of the land price. In terms of transaction costs, there are obvious economies of scale suggesting that sink and biomass projects need to be planned and implemented on large scales (Dieter and Elsasser 2004). It is important to mention that large scale does not necessarily mean large-scale monoculture plantation projects.

For the cost approximation of silvicultural production as well as logging operations we have used data gained from engineering models for harvesting, forwarding and trucking described in Obersteiner (1999) and Lundmark (2003). We have refrained from including assumptions on technological learning (i.e., cost reductions) for harvesting and transportation in the scenario presented. Technological learning through increased mechanization of logging operations has definitely occurred in the past and this trend might prevail as assumed through discounting. In principle there are two ways to incorporate technological learning directly into the model. First, one could assume a fixed learning schedule, which would be equivalent to discounting (e.g., constant learning rate) or alternatively, being consistent with technological learning literature, make the learning rates a function of past installed capacity and research and development expenditures. The latter would be implemented in a dynamic formulation of the model with a link to a global energy model.

The choice of the accounting scheme for the benefits from afforestation can substantially change the economic evaluation of afforestation projects. In the case of sequestration incentives, the effect of changes in land-use change practices on the atmospheric concentrations of GHGs depends on the length of time for which carbon is sequestered. Cropland converted to forest will sequester additional carbon for 3–100 years, but most of the additional carbon will be released when the timber is harvested. A unit of carbon sequestered in biomass is equivalent to a unit of GHG emissions reduction if the carbon remains sequestered permanently. This requires maintaining the carbon sequestration activity permanently – either with a one-time permanent commitment or with a series of contracts extending through time. Traditional economic research on the economics of carbon sequestration in agriculture and forestry are based on the assumption of permanence and therefore over-estimate the additional carbon sequestered. More recent research considers a system in which producers receive proportionally smaller 'rental' payments to store additional carbon for a finite contract period. Payments cease at the end of the contract period when carbon storage will be discontinued. Rental contracts provide more flexibility for fossil fuel power plant owners on when to invest in emission reducing technologies. In our scenarios, we have implemented such rental contracts for carbon sequestration incentives, which are incurred before the biomass for energy stage.

6. Conclusions

In this paper we have presented a model, which approximates technical and economic potentials of biomass supply for bioenergy and its jointly produced terrestrial sink from AR activities. Geographically explicit analysis allows identification of least-cost sites for AR given the set of assumptions employed. Aggregate cost curves at a global or regional level can be derived directly from the gridded information. 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) it provides a 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. Local information, such as data from AR projects, can be used for validation purposes; and (iii) it is a practical tool for testing the sensitivity on global parameters related to biological production, technology and economic development.

The results indicate that if modern biomass technologies will play a significant role within a wider global energy portfolio that aims at low GHG concentration targets the global terrestrial landscapes will face unprecedented changes due to AR activities. This will hold true under any socioeconomic development scenario. These changes will be featured by a number of key phenomena. First, we will see a rapid expansion of AR activities mainly triggered and focused on satisfying increasing demand for biomass. The expansion will be more concentrated in the tropical belt due to higher biological growth, cheaper production resources and relatively small costs for long distance transportation. Barriers to trade could ease the pressure on tropical biomass production at the loss of efficiency. Second, competition for land and land values will lead to intensification of agricultural production on the remaining food producing areas. Conservation of biodiversity, amenity and conservation values of entire landscapes will become a major challenge, but not a mission impossible. Third, large scale implementation of AR activities might also lead to increased pressure on rural communities to relocate and/or adapt to new environments. A more informed assessment of future cultural and social costs of AR activities still requires more investigation.

Note

1. The price index relative to the US. The price index for countries not appearing in the reference was assigned as follows: low income countries 0.2; lower middle income countries 0.5; and upper middle income countries 0.7.

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