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Geographically explicit global modeling of land-use change, carbon sequestration, and biomass supply

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Abstract

This study aims to determine whether carbon sequestration policies could present a significant contribution to the global portfolio of climate change mitigation options. The objective is to model the effects of policies designed to induce landowners to change land use and management patterns with a view to sequester carbon or to reduce deforestation. The approach uses the spatially explicit Dynamic Integrated Model of Forestry and Alternative Land Use (DIMA) to quantify the economic potential of global forests. The model chooses which of the land-use processes (afforestation, reforestation, deforestation, or conservation and management options) would be applied in a specific location, based on land prices, cost of forest production and harvesting, site productivity, population density, and estimates of economic growth. The approach is relevant in that it (1) couples a revised and updated version of the Special Report on Emissions Scenarios with the dynamic development of climate policy implications through integration with the Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE); (2) is spatially explicit on a 0.5° grid; and (3) is constrained by guaranteeing food security and land for urban development. As outputs, DIMA produces 100-year forecasts of land-use change, carbon sequestration, impacts of carbon incentives (e.g., avoided deforestation), biomass for bioenergy, and climate policy impacts. The

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modeling results indicate that carbon sequestration policies could contribute to a significant part of the global portfolio of efficient climate mitigation policies, dependent upon carbon prices.

Keywords: Land-use change; Carbon sequestration; Bioenergy; LULUCF; Afforestation/reforestation/deforestation; Global carbon supply; Global spatial modeling

1. Introduction

The notion of compensating for rising atmospheric carbon dioxide (CO_2) concentrations through global scale afforestation (the conversion of land unforested for 50 years prior to 1990 into forested land) was first put forward in the late 1970s [1]. Since the late 1980s, it has been suggested that sufficient lands are available to use the carbon sequestration approach to mitigate significant amounts of CO_2 emissions [2,3]. Claims have been made that forestry-based carbon sequestration is a relatively inexpensive way to address climate change [4,5]. The Intergovernmental Panel on Climate Change (IPCC) *Third Assessment Report* estimated that 12–15% of fossil-fuel emissions up to 2050 could be offset by improved management of terrestrial ecosystems globally [6]. However, this estimate is a measure of the technical potential and does not account for the opportunity costs and other barriers to implementation.

A large number of studies and surveys of carbon sequestration costs exist [7–16]. Many of the early estimates may have been biased because they focused on average and not marginal costs [17,18]. While these two recent studies more accurately capture the increasing price of converting land into forests, they do not consider alternative forestland management options, such as changing rotation lengths and changing management intensity.

The sequestration potential that is competitive economically if compared with other land-use and management options available to landowners (e.g., agriculture, pastures, etc.) may be much smaller [19]. This potential depends–among other things–on the incentives given to landowners. Shifts in cost/benefit ratios of use and management options change terrestrial biomass production and storage. However, it is not clear how much impact policies that aim to change costs and benefits would have on carbon sequestration. The costs of inducing appropriate levels of carbon sequestration by landowners will presumably be one major criterion in the political decision whether or not to pursue this policy option, and to what degree. In relation to policy frameworks to sequester carbon through changes in land use and management, the inclusion of activities related to land use, land-use change, and forestry (LULUCF) that contribute to meeting commitments under the Kyoto Protocol has been particularly contentious. The Kyoto Protocol states that parties to the agreement (the participating nations) can employ carbon sequestration as part of their portfolios of strategies to achieve their domestic CO_2 targets. In the negotiations for future commitment periods under a likely modified Kyoto Protocol, it is expected that LULUCF will play a substantial role.

To design specifications and measures for future commitment periods of the Kyoto Protocol or any other international regimes that aim to reduce the amount of greenhouse gases in the atmosphere, policy makers need more clarity. This is not only on the measurement and accounting issues that surround LULUCF measures, but also on the effects of policies designed to induce landowners to sequester carbon or to reduce emissions from land-use changes (LUCs), especially to avoid deforestation (the conversion of forested land into non-forested land).

In an effort to address these issues, this paper introduces an approach that uses the spatially explicit Dynamic Integrated Model of Forestry and Alternative Land Use (DIMA) to quantify the economic potential of global forests, explicitly modeling the interactions and feedbacks between ecosystems and anthropogenic land-use activities. The DIMA model chooses, for each time interval, which of the land-use processes (afforestation, reforestation, deforestation, or conservation and management options) would be applied in a specific location, based on land prices, cost of forest production and harvesting, site productivity, population density, and estimates of economic growth.

The DIMA model approach is unique in that it:

- couples a revised and updated version of the Special Report on Emissions Scenarios (SRES) with the dynamic development of climate policy implications (including carbon and bioenergy prices) through integration with the Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE);
- is spatially explicit, that is most of the model inputs (including spatially downscaled revised scenarios from the SRES), all decision making and the full set of outputs are processed globally on a 0.5° grid;
- is constrained by guaranteeing food security and land for urban development.

However, constraints on food security do not imply that each grid cell has enough agricultural land to secure enough food for its population. Food security is maintained by introducing an exogenous scenario-specific minimum amount of agricultural and urban land per grid cell as projected by Tubiello and Fischer [20] and used as input by DIMA. As output, DIMA produces 100-year forecasts of LUC, carbon sequestration, impacts of carbon incentives (i.e., avoided deforestation), biomass for bioenergy, and climate policy impacts.

2. Model descriptions and scenarios

2.1. DIMA model

DIMA explicitly models the interactions and feedbacks between ecosystems and human land-use activities spatially (with a 0.5° resolution). It assumes that forest management and LUC activities are implemented to maximize the profit under given biophysical and socioeconomic constraints.

For each grid cell, the model estimates forest growth using the global vegetation model TsuBiMo [21]. The process-based TsuBiMo model provides global scale net primary productivity (NPP) data based on existing NPP measurements and global geophysical, climatic, and vegetation data. The TsuBiMo model uses a set of 700 NPP estimates to predict global scale NPP based on equations that describe the process of solar radiation uptake and the photosynthetic capacity of the predominant vegetation.

Biophysical modeling results form the basis for an economically optimal choice of forest management options (thinning, harvesting) and decisions on LUC. However, individual land-use decisions change over time with socioeconomic and physical conditions. The DIMA model chooses for each decade which of the land-use processes (afforestation, reforestation, deforestation, or conservation and management options for the managed portion of the forest) would be applied in a specific grid, based on land prices, cost of forest production and harvesting, site productivity, population density, and estimates of economic growth (input data sets are described in Appendix A). The DIMA model is linked to the MESSAGE model to retrieve dynamic carbon-bioenergy price trajectories. The economic modeling thus combines a dynamic model of individual landowner choices (per 0.5° grid cell) with an underlying model of the spatial development of economic and population growth. Detailed descriptions of the many assumptions that form the basis for constructing the DIMA model can be found in Benítez et al. [10], Obersteiner and Benitez [22], Obersteiner et al. [23], and Appendix B.

2.2. MESSAGE

The MESSAGE model is a systems engineering optimization model used for medium- to long-term energy system planning, energy policy analysis, and scenario development [24]. The model provides a framework to represent an energy system with all its interdependencies, from resource extraction, imports and exports, conversion, transport, and distribution to the provision of energy end-use services, such as light, space conditioning, industrial production processes, and transportation. Scenarios are developed by MESSAGE through minimizing the total systems costs under the constraints imposed on the energy system. Given this information and other scenario features, such as the demand for energy services, the model configures the evolution of the energy system from the base year to the end of the time horizon (in 10-year steps).

2.3. SRES

The IPCC SRES contains four scenario families, each with their own storyline and model-based quantification [8,9]. In this study, the focus is on the A2 and B1 scenarios [25].

The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in a high population growth. Economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented and slower than in other storylines.

The B1 storyline and scenario family describes a convergent world with low population growth, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

For the modeling documented in this paper, revised and updated versions, with respect to the underlying demographic and economic trends, of the IPCC SRES A2, B1 and B2 scenarios are used [26], named respectively ‘A2r’, ‘B1’, and ‘B2r’ (‘r’ indicates the revised version). Consequently, prices derived here from the MESSAGE model are not consistent with the earlier SRES A2 and B1 scenarios, but they are consistent with those developed and discussed in this special issue [25,26]. The notations A2r, B1, and B2r, as explained in this paragraph, are consistently used throughout the paper.

3. DIMA model sensitivity and validation

In this section, the results from DIMA on LUC (afforestation and deforestation) and potentials for carbon sequestration and bioenergy production are compared with results from other studies as a way to validate DIMA. Initially, the model parameters and speeds of their potential change over time are chosen from within historical ranges in such a way that close replication of the baseline development for revised SRES projections is achieved. The historical values of these parameters and the relevant speeds of change are provided by Sathaye et al. [27,28]. The validation checks the sensitivity of the model outputs (LUC dynamics, carbon sequestration, and biomass potentials) to changes in carbon price at both the global and national (i.e. United States of America, USA) scale.

3.1. Global results on deforestation, afforestation, and carbon

Two carbon sequestration models (i.e., Sathaye et al. [27] and Sohngen and Mendelsohn [29]) have been chosen to compare global and regional estimates for gains of forest area and additional carbon storage with the DIMA model estimates.

Sathaye et al. [27,28] extend the bottom-up COMprehensive Mitigation Assessment Process (COMAP) model into a dynamic partial equilibrium model (GCOMAP) to address the following questions:

- Which forestry mitigation options contribute the most to carbon sequestration or emissions avoidance?
- How much carbon stock additional to a baseline or reference scenario might be created, and how much emissions reduction might be achieved through these mitigation activities under different carbon price scenarios?
- What are the costs per ton of carbon and total cost of these options?

These questions are discussed within the framework of the dynamic partial equilibrium concept. The research addresses both afforestation and forest protection (reducing deforestation) as mitigation options within a global model across ten regions (not on a grid-by-grid basis, as opposed to DIMA). For the major regions of the world the proposed model analyzes both present carbon stock changes and regional price responses.

Sohngen and Mendelsohn [29,30] examine the optimal timing and amount of carbon sequestration as a component of the global optimal control model of mitigation of greenhouse gases. This research question is investigated within the framework of a general equilibrium model of sequestration while taking into account global timber prices and the increasing scarcity of land. Results suggest that substantial amounts of carbon could be sequestered in forests, thus reducing the price of carbon. The authors argue that the bulk of this carbon should be kept in tropical forests, with a large proportion of the carbon resulting from reduced deforestation initially. However, carbon sequestration is more costly than many estimates in the literature, which suggests that it plays only a partial role in controlling greenhouse gases, and that it is important only if the price of carbon is relatively high. The modeling presented in Sohngen and Mendelsohn [30] provides results for several major world regions.

According to Sedjo et al. [31], additional forest carbon can be generated by three means:

(1) more land can be put into timber;
(2) existing forests can be grown for longer periods by extending the harvest rotation, sometimes indefinitely;
(3) additional management can be applied to increase the rate of forest growth, and consequently the amount of carbon sequestered in a stand at any given age.

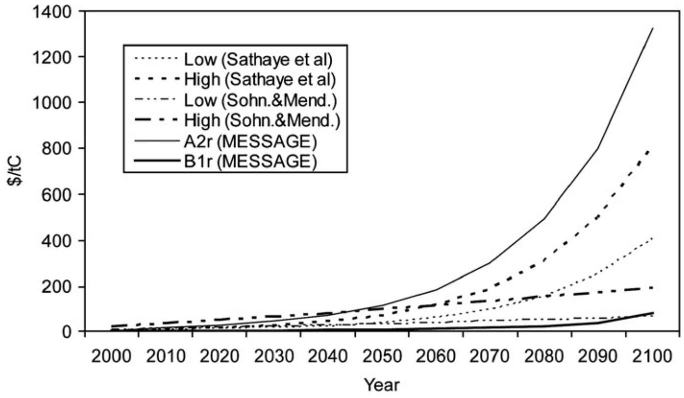

Fig. 1. Carbon price trajectories based on Sathaye et al. [27], Sohngen and Mendelsohn [29] and MESSAGE. 'Low' refers US$5/tC + 5%/year and 'High' to US$10/tC + 5%/year.

The price for carbon is the incentive for increasing forests by each of these means [31]. The DIMA modeling approach (as described in detail in Appendix B) uses carbon price (in the form of dynamic trajectories of the kind presented in Fig. 1) as the input and allows for increases in the amount of carbon in forests via the above means.

Carbon price trajectories are a key underlying factor in carbon sequestration models. Six different carbon price trajectories are presented in Fig. 1. Four of these trajectories are used to produce a comparison of DIMA outputs with modeling outputs produced by two approaches given in [28] and [30]. The two MESSAGE trajectories are produced within the framework of joint simulation with MESSAGE and are provided here only for comparison, but are not used for validation.

The global and regional results for gains in forest area and additional carbon storage in the DIMA model estimates were compared with those of Sohngen and Mendelsohn [30] (Table 1). For ease of comparison, the data from Sohngen and Mendelsohn [30] and DIMA were aggregated into four macro-regions (OECD90 and EE-Organization for Economic Cooperation and Development as of 1990 and Eastern Europe; ASIA; ALM—Africa, Latin America, Middle East; Russia, and the NIS—Newly Independent States). Sohngen and Mendelsohn [30] use the regions of the USA, Canada, South America, Centra America, Europe, Russia, China, India, Oceania, South-East Asia, Central Asia, Japan, and Africa. This set of regions could explain why this work accounts for only 3600 Mha of forest, while estimates of current worldwide total forested area are usually in the range 4000–4300 Mha, depending on the definition of forest used. Regional modeling assumptions and, most importantly, biophysical growth and socioeconomic development could account for the local differences in predictions shown in Table 1. Although a wide comparison of grid-wise land-price estimates were performed for a variety of regions, further improvement of land-price estimates may still be required (e.g., for Russia).

A further comparison was made of the global results for gains in forest area and additional carbon storage between the DIMA model estimates and Sathaye et al. [28] (Table 2). The results indicate that all three models, despite their differing modeling approaches, arrive at comparable results. Tables 1 and 2 also illustrate that the sensitivity to changes in carbon price of both model's predictions and outputs are relatively similar. It is important to clarify that the gains (in Mha forest area) presented in Tables 1 and 2, as well as the accumulated gigatons of carbon (GtC) gains in these tables, represent the increase of total

Table 1
Global and regional results for gains in forest area and additional carbon storage in the DIMA model estimates compared with those of Sohngen and Mendelsohn [30]

	Low [30] GtC 2105	High [30] GtC 2105	Low [30] Mha 2105	High [30] Mha 2105
Sohngen and Mendelsohn [30]				
OECD90 and EE	6.22	17.66	36.02	136.70
ASIA	22.99	49.49	71.89	157.10
ALM	21.61	41.40	87.82	236.24
Russia/NIS	3.88	7.09	7.99	21.68
World	54.70	115.64	203.72	551.72
DIMA				
OECD90 and EE	2.24	8.65	30.90	98.78
ASIA	20.05	46.13	65.18	125.62
ALM	19.14	38.70	73.11	224.65
Russia/NIS	4.16	8.19	5.71	14.68
World	45.60	101.67	174.91	463.73

'Low' refers to US$5/tC+5%/year and 'High' to US$10/tC+5%/year.

hectares of forest area (or GtC sequestered in the forest biomass). These add-ons are projected along the B1 storyline (with all socioeconomic parameters downscaled as presented in Grübler et al. [26]), combined with the relevant dynamic carbon price, as shown in Fig. 1.

The baseline development of B1 projects a higher increase of forest area and carbon sequestered in forests (e.g., compared with the alternative scenario B2r). This explains the lower sensitivity of these outputs (in B1 as compared with B2r) with respect to increasing carbon price. Finally, in scenario A2r the sensitivity to carbon price is even lower than in B1, since land prices are highest among the three scenarios considered (therefore to switch land use to forestry the most significant carbon incentive should be introduced).

Smaller LUC and larger amounts of carbon sequestered in DIMA compared with Sathaye et al. [28] implicate significant differences in growth assumptions (higher growth estimated by TsuBiMo as compared with the biophysical component of GCOMAP developed by Sathaye et al. [27]). Compared with a carbon price of US$5/tC+5%/year, doubling of the carbon price to US$10/tC+5% results in an additional 42% of forest land area gained in both DIMA and GCOMAP—by 2050 it adds 72% and increases by 33% the results reported for 2100.

Table 2
Comparison of global results for gains in forest area and additional carbon storage between the DIMA model estimates and those of Sathaye et al. [28]

	2050, Mha	2100, Mha	2050, GtC	2100, GtC
Sathaye et al. (low-SC.1)	190.00	662.00	13.57	70.15
DIMA (low-SC.1)	168.25	531.33	19.23	93.77
Sathaye et al. (high-SC.2)	327.00	880.00	24.92	96.50
DIMA (high-SC.2)	242.90	765.28	35.16	113.03

'Low' refers to US$5/tC+5%/year and 'High' US$10/tC+5%/year.

3.2. Carbon sequestration in the US forest sector

Carbon sequestration modeling results are compared using the supply of carbon through sequestration and related marginal costs, expressed as carbon price in the USA. Specifically for the USA, a large number of authors have published results to which DIMA results can be compared.

Fig. 2 shows an increasingly wide corridor of carbon supply trajectories projected by different authors. Nevertheless, the graph shows the overall consistency for this politically and economically important region. Over most of the range of carbon prices considered in previous forest carbon sequestration studies, DIMA cost estimates are higher than those obtained using optimization models ([32,33]) and bottom-up engineering cost methods [34]. Comparing model estimates with those from the earlier econometric study by Stavins [17], we find similar costs at low carbon sequestration levels, but significantly lower costs projected by the DIMA model at higher carbon sequestration levels. At about 600 million tons of carbon (MtC) per year, Stavins [17] projects increasingly steep price rises required to supply further carbon through sequestration, whereas the curve from the DIMA calculations at this point still shows close to linear relationships. Similar projections to those of DIMA were published in 2005 [35].

3.3. Global biomass potentials

The low emissions scenarios for the 21st century embody plantation-based bioenergy utilization in the order of hundreds of exajoules (EJ), which implies LUCs over vast areas. In our model such LUCs are predicted based on the comparison of discounted net present value (NPV) calculations of land rents under current land use. The approximation of the value of land not only in its economic, but also sociocultural and ecological, dimension is crucial to assess the potential benefits of LUC and forest management. Major adaptations of rural life, especially in developing countries, will be necessary to produce the hundreds of EJs of biomass [36]. Clearly, land prices are affected by the underlying drivers, such as population and economic wealth projections, as well as agriculture, forest, and nature conservation policies combined with climate

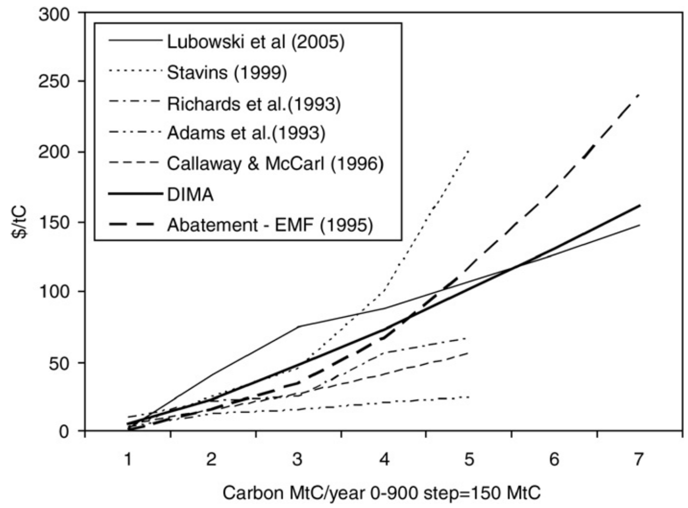

Fig. 2. Comparison of supply schedules for carbon sequestration in US forests.

policy. Apart from these drivers, human capital is needed to enable the tens of thousands of LUC projects that need to be initiated by experts from implementing regions [37]. In terms of transaction costs, the obvious economies of scale suggest that sink and biomass projects need to be planned and implemented on large scales [38]. Importantly, 'large scale' does not necessarily imply monoculture plantations.

Overall, a considerable number of studies have examined global biomass potentials. The World Energy Council (WEC) examined four 'Cases' for global energy supply to 2020, spanning energy demand from a 'low' (ecologically driven) case of 475 EJ to a 'very high' case of 722 EJ, with a 'reference' case total of 563 EJ. In the ecologically driven case, traditional biomass could contribute about 9% of the total supply, while modern biomass would supply 5% of the total, equal to 24 EJ or 561 million tons of oil equivalent (MtOE).

Shell International Petroleum Company carried out a scenario analysis of possible major new sources of energy after 2020, when renewable energies have progressed along their learning curves and become competitive with fossil fuels. After 2020, in their business-as-usual scenario, the renewables, including biomass, wind, solar, and geothermal, become the major new suppliers of energy. In their conservation scenario, in which less new energy is needed, biomass becomes the major supplier, with smaller roles for the other renewables. In the business-as-usual (Sustained Growth) scenario, total global energy use in 2060 amounts to over 1500 EJ (compared to 400 EJ today), of which biomass provides 221 EJ (14% of the total), with 179 EJ coming from plantations rather than traditional non-traded sources. Solar and wind would provide 260 and 173 EJ, respectively. In the conservation scenario, total energy use in 2060 amounts to under 940 EJ, with fossil fuels and nuclear providing 41% of the total; biomass provides 207 EJ (22% of the total), with 157 EJ from dedicated bioenergy sources.

The IPCC considered a range of options to mitigate climate change, and increased the use of biomass for energy features in all of its scenarios. In their five scenarios, biomass provides an increasing share of total energy over the next century, rising to 25–46% in 2100. In the biomass-intensive energy scenario, biomass provides 46% of total energy in 2100, and the target of stabilizing CO_2 in the atmosphere at present-day levels is approached. Annual CO_2 emissions fall from 6.2 GtC in 1990 to 5.9 GtC in 2025 and to 1.8 GtC in 2100—this results in cumulative emissions of 448 GtC between 1990 and 2100, compared to 1300 GtC in their business-as-usual case.

How much bioenergy contributes to meeting energy needs in the next century depends on many factors, all of which are difficult to foresee at this stage. Overall, the modeling results show that DIMA projections of global bioenergy potential supplied by biomass are on the conservative side of the spectrum of various assessments summarized in Fig. 3. This is partly because DIMA projections include biomass from forests or woody energy crops only, while other studies also include biomass from non-woody crops.

One can therefore conclude that the DIMA model provides plausible projections for scenario developments at a global scale, scaled up from grid-level results. As for the aggregated model results, DIMA projections (which tend to be on the conservative side) are in very good agreement with the scenario projections on forestry-related parameters in IPCC-SRES [8,9], as well as with many references cited in this section. Having validated the model sensitivity, we now apply the suggested approach to dynamic carbon-bioenergy price trajectories as projected by MESSAGE.

4. Results of the integrated modeling approach

The integrated assessment presented below aims to address issues related to climate mitigation as reflected by the revised and updated IPCC SRES [26], being the further development of scenarios

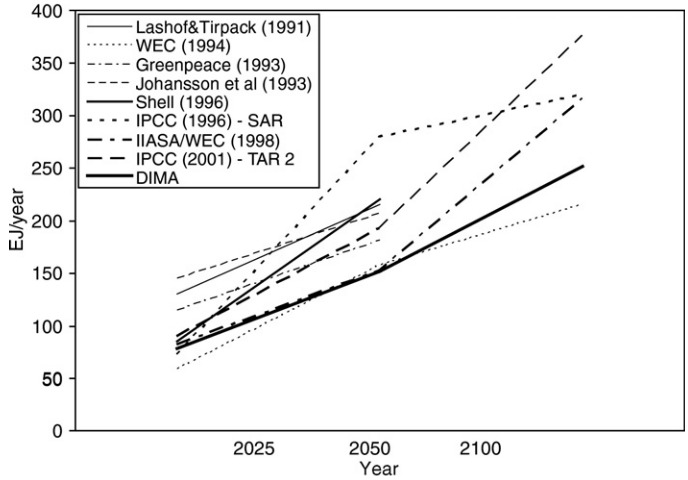

Fig. 3. Summary of various assessments of global bioenergy potentials (EJ per year) up to 2100.

introduced in IPCC 2001. The outputs to validate the model performance with respect to these scenarios are parameters related to LUC and carbon sequestration. This validation is performed with restrictions, including satisfying the respective demands for, among others, timber, bioenergy, food security and protection of land at both national and international levels. These restricting conditions are accounted for in the model results presented below.

Global price and demand trajectories for timber, carbon and bioenergy (the latter two provided by MESSAGE) are major drivers for the relevant estimates, since LUC and management regimes are predominantly driven by these factors. The sensitivity of the results to scenario storylines is assessed by downscaling different population and economic growth assumptions, consistent with the A2r and B1 scenarios. The time scale for these simulations is set to 2100—similar to that in the IPCC SRES report.

Fig. 4 provides an overview of the integrated modeling approach with the DIMA model imbedded, along with the required inputs, outputs, and information exchange with the MESSAGE model.

4.1. Land-use change

The DIMA model was calibrated against the revised and updated IPCC SRES A2r and B1, adjusting the constraints on land expansion. To mimic the dynamics of LUC in accordance with historical data, respective rates of afforestation and deforestation, as well as their potential rate of change, were constrained to the ranges observed during the period 1980–2005.

The global summary statistics for the baseline run shows that the accumulated afforestation area used in 2100 to supply bioenergy and carbon is close to 700 Mha in the B1 scenario and 500 Mha in the A2r scenario. The projected deforestation for B1 is around 200 Mha, and for A2r it is around 480 Mha. For the B1 scenario, this requires an average afforestation rate of 7 Mha per annum to balance out the deforestation and produce emission levels as described in the SRES scenario, which we tried to mimic. The current global plantation rate is 4.5 Mha per annum [39]. In total, the share of planted forest is 5% and could reach a level of about 20% in the B1 scenario in 2100.

The DIMA model replicates revised baseline SRES LUC emission scenarios and provides geographically explicit analyses of the impact of climate mitigation measures on LUC. There is large

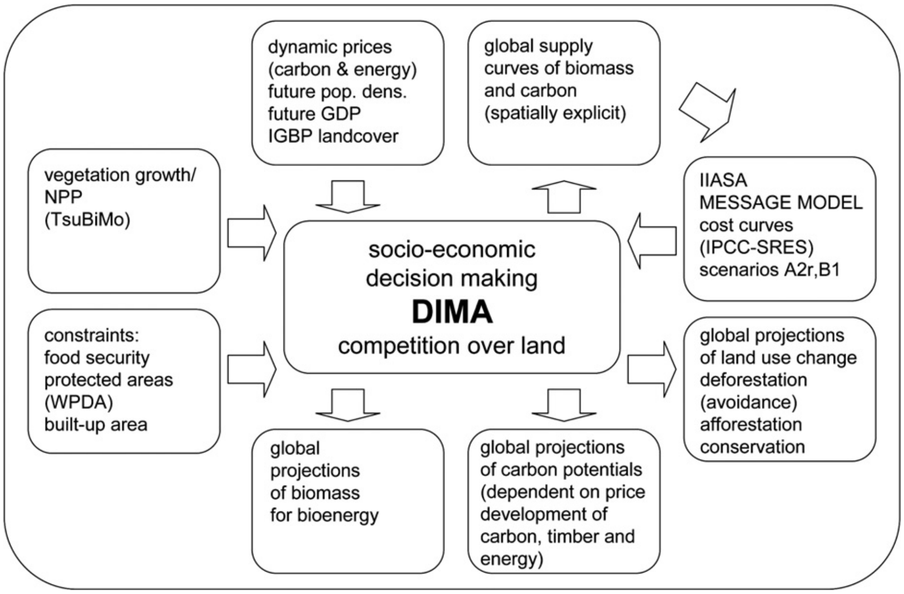

Fig. 4. Integrated modeling approach.

geographic heterogeneity in the model estimates of afforestation patterns. Afforestation mostly takes place in tropical regions. In A2r, the net tropical afforestation is projected to cover about 400 Mha by 2100, while the total global net afforestation reaches about 500 Mha. Within the tropical belt, Africa appears to be the continent with the biggest afforestation potential because of its strong relative cost competitiveness within the model.

Fig. 5 shows the trajectories for LUC as projected by DIMA. Baseline trajectories use a zero carbon price as the model input. The mitigation runs take into account dynamic price development for carbon and/or bioenergy as projected by MESSAGE for the A2r and B1 scenarios (see Fig. 1).

Compared to the afforestation patterns in the revised and updated SRES B1 scenario, afforestation in the A2r scenario would be considerably lower. Around 500 Mha would have to be afforested by 2100 to replicate the baseline development of the SRES A2r scenario using current parameterization and biophysical growth assumptions.

4.2. Carbon sequestration

If carbon sequestration incentives are set through policies, these enhance the economic benefits from afforestation and result in increased carbon sequestration measures by individual landowners. The DIMA model is able to calculate additional carbon sequestration volumes (GtC) under given carbon prices. Carbon sequestration is calculated to comprise standing biomass and long-lived timber products.

Our study focuses on the carbon implications from the joint production of carbon sequestration and biomass for bioenergy. Part of the biomass is assumed to be used for bioenergy production to substitute fossil fuel consumption. This is accounted for in the calculations of the total carbon sequestration potential at pre-set carbon prices. As the global supply curves for biomass for energy and carbon sequestration are produced together, the share of biomass for bioenergy is already deducted in the figures for carbon

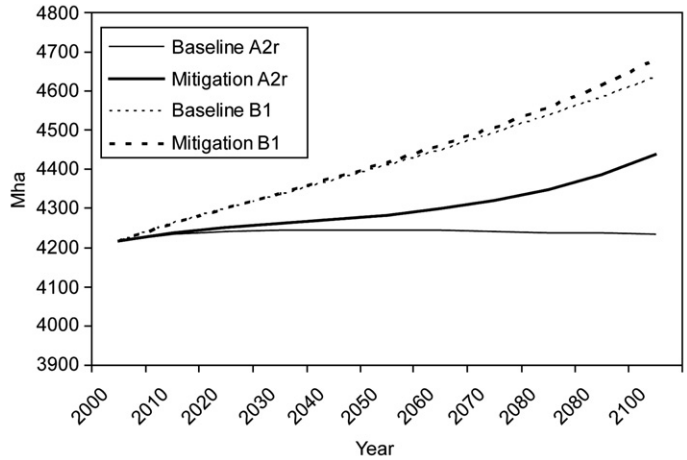

Fig. 5. Forest area dynamics for the A2r and B1 scenarios from 2000 to 2100.

sequestration. As the DIMA model calculates carbon sequestration and bioenergy production on a grid-cell basis, it is able to show the distribution spatially.

The modeling results show that introducing a carbon price makes a significant difference and changes land-use and management decisions of landowners considerably, even at rather low levels of carbon prices. The projected cumulative carbon sequestration potential that can be activated at carbon prices of US$50/tC in the revised and updated SRES B1 scenario is almost twice as high in the year 2100 than under an assumption of a carbon price of zero. A doubling of the carbon price to US$100/tC again doubles the cumulative carbon sequestration in the year 2100 to around 200 GtC. Upwards of US$200/tC, the effects of further incentives level off as the land available for conversion becomes increasingly scarce.

The DIMA model calibrated to reproduce the revised and updated SRES A2r scenario predicts that a carbon price of around US$40/tC rather quickly reduces the emissions from LUC to zero. Compared to the B1 scenario, a higher carbon price is required in A2r to arrive at the same cumulative carbon sequestration volume.

While the initial calculations provided the static carbon sequestration potentials of the forestry sector as input for an initial iteration with MESSAGE, further calculations took the dynamic price from MESSAGE as the input.

4.3. Carbon incentives

Carbon incentives, if well planned, carry a large potential for biodiversity conservation, the generation of ancillary environmental benefits and rural development [40]. Fig. 6 presents the carbon implications through avoided deforestation that results from introducing a dynamic carbon price as compared with a baseline case of zero carbon price.

The underlying assumption of avoided deforestation is a rental contract for forest biomass. In the model at the start of each decade the land user or owner is offered a new carbon contract as an incentive to refrain from deforestation. Fig. 6 illustrates the potential changes for land use in the final decade of the 21st century. At the end of the century avoided deforestation is most visible as compared to the baseline case because carbon price incentives are strongest.

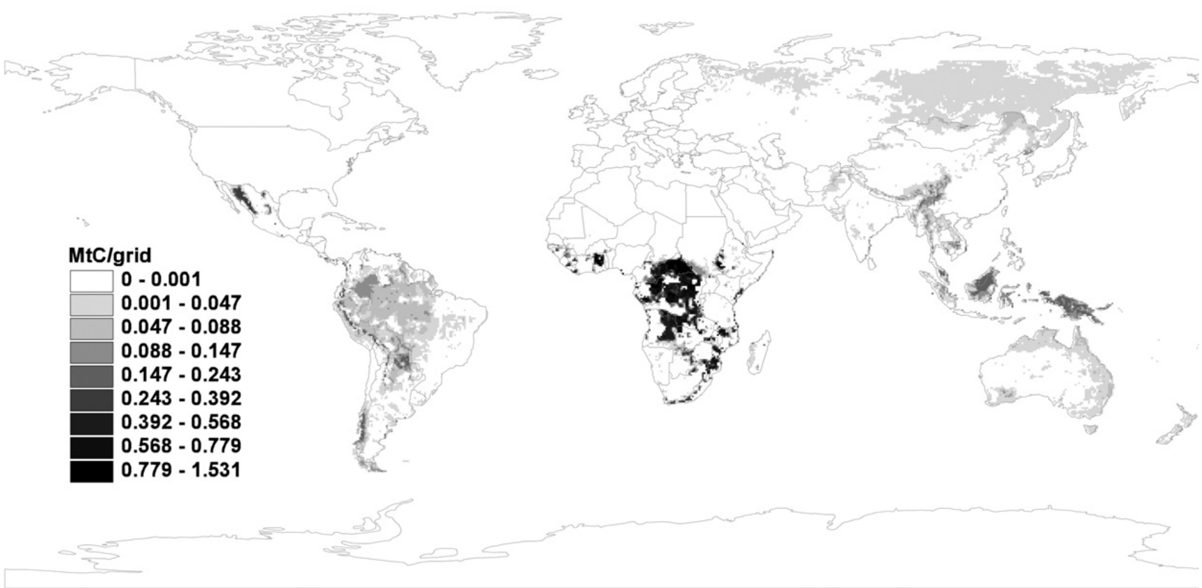

Fig. 6. Carbon implications (MtC/grid) from avoided deforestation (compared with the baseline case) using a dynamic carbon price projected by MESSAGE in 2090–2100 in A2r.

Another important implication for forest carbon budgets is that afforestation mostly happens in tropical regions, which, combined with the related flow of carbon payments, is relevant to global energy supply. This has strong implications for rural development in the developing world as substantial amounts of revenues will be generated through the supply of carbon credits and biomass.

4.4. Bioenergy

Considerable amounts of bioenergy are projected to be used in the baseline of the A2 scenario. The supply from biomass is projected to be 230 EJ per year at the end of the 21st century in the mitigated scenario, which amounts to about 55 EJ more than in the unmitigated scenario. Half of the total biomass and carbon supply comes from two regions–Africa (biomass 23.9%, carbon 26.3%) and South America (biomass 22.1%, carbon 34.3%)–where biomass productivity is high and production costs are relatively low. Total annual revenues for biomass production reach US$776.8 billion in the final decade of the century, of which 24% are because of climate policy incentives. The global flow of annual carbon payments to the forest sector in this scenario increases in absolute terms from US$17.2 million projected for 2010 to US$245 billion per year as estimated in 2100. In relative terms with respect to payments related to biomass production, the share of carbon revenues to the forest sector grows from a tiny fraction of 0.03% in 2010 to a significant share of 31% in 2100.

Region-wise, the speed of growth of financial flows associated with both carbon sequestration and bioenergy production in regions like Africa (Sub-Saharan—a macro-region as defined by IPCC and used throughout this paper) or Latin America (IPCC macro-region) is estimated to grow faster than in northern regions. While in the decade 2020–2030 the monetary flow from bioenergy production is forecast to increase in Central Planned Asia (mostly China and Vietnam, IPCC macro-region) by 14.8% and in

Western Europe (IPCC macro-region) by 28.5%, in tropical regions the growth is much faster and reaches 48.4% for Africa and 92.8% for Latin America. These two tropical regions start to control the lion's share of the carbon payments early on. Namely, in 2010 Latin America receives as much as 50.5% of all global forest-related carbon payments, and later this share continues in the range 30–45% up to 2100. In the scenarios, Africa starts in 2010 with a 30% share and remains in the 25–35% range until 2100. Shares of payments for forestry-based bioenergy production behave in a much more dynamic way. For example, Latin America starts in 2010 with just 10.0% of the total revenue, but by 2100 its share reaches 25.9%. Africa, however, starts with 23.0% of global bioenergy payments and reaches only 26.1% in 2100. Other regions the share decreases—for Centrally Planned Asia from 13.2% in 2010 to just 7% in 2100, and in South East Asia (IPCC macro-region) from 30.9% to just 9.1%. We conclude that, both in terms of carbon and biomass payments, the developing world (especially the tropical belt) will benefit from climate policies and contribute substantially to global bioenergy supply. This also has strong implications for rural development in the developing world as substantial amounts of revenues will be generated through the supply of carbon credits and biomass.

Today, approximately 70% of the total wood production is used for bioenergy supply. The model results shown in Fig. 7 fs indicates that DIMA predicts the continuation of high volumes of biomass supply to be used for bioenergy. For those areas with high biophysical biomass production because of climatic factors, such as in the tropics, bioenergy supply is especially strong.

In this run, the DIMA model uses the bioenergy (and carbon) prices from MESSAGE. Based on this information, the DIMA model predicts that, while in some areas landowners would be more motivated to retain and expand forestry practices by higher bioenergy prices, in other locations a stronger motivation is predominantly from policy related to carbon sequestration. For example, in regions like Western Europe and North America (IPCC macro-region) the carbon payments comprise just 0.9% or 4.3% of biomass payments respectively. In other regions, like Latin America, Africa, and the Former Soviet Union (IPCC macro-region), this relation reaches 13.9%, 16.7%, and 21.1%, respectively (carbon sequestration there is 15–20 times more important than biomass production compared to the Western European case, in financial terms).

4.5. Climate policy

Introduction of climate policy instruments potentially leads to considerable LUC. Namely, in the mitigation case, climate policy incentives in the form of carbon prices and higher bioenergy demand lead to an additional expansion of forest area of about 200 Mha in the A2r scenario (including 96 Mha of avoided deforestation). Computation results show that the share of globally avoided deforestation grows exponentially with the carbon price from 5% to 75% of the predicted deforestation.

In the B1 scenario climate policies lead to an additional 42 Mha as the carbon incentives are lower. There are two sources for this land expansion:

- avoided deforestation triggered by a carbon price incentive;
- additional afforestation through a joint carbon and biomass incentive.

Thus, at low carbon prices additional measures have to be taken to address the deforestation problem. However, by the end of the century carbon preservation incentives may possibly be so strong that a very large share of deforestation could be halted through climate policy measures. Similar effects can be

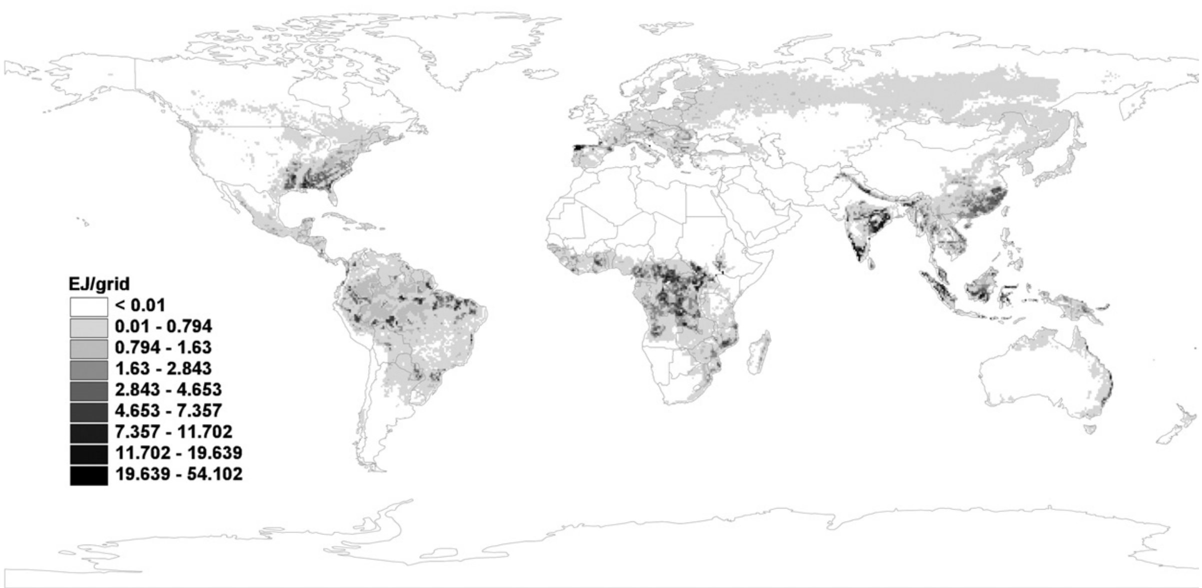

Fig. 7. Cumulative biomass production (EJ/grid) for bioenergy between 2000 and 2100 at the energy price supplied by MESSAGE based on the revised IPCC SRES A2r scenario.

expected for situations in which market prices for carbon turn out to be higher than predicted by the model because of market imperfections.

After avoided deforestation, the second source of net land expansion is afforestation. In A2r, climate policy triggers an additional afforestation of 105 Mha, which leads to a total afforestation of about 610 Mha. The path of additional afforestation is strongly influenced by the carbon incentive. The share of additional afforestation to baseline afforestation changes from 3% in 2010 to 103% in 2100. More than 70% of total afforestation occurs in the tropics through the relative competitive advantage in terms of biomass growth and costs. We found that the economic viability of afforestation crucially depends on the joint income from carbon, timber, and biomass revenues.

5. Discussion and conclusion

According to conservative estimates by IPCC [8,9], forestry has the potential to offset approximately 15% of the world's greenhouse gas (GHG) emissions, a partial solution to the overall problem of increasing GHGs. This study aims to determine whether carbon sequestration policies–such as those that promote afforestation and discourage deforestation (i.e., avoided deforestation)–could present a significant contribution to the global portfolio of GHG mitigation options, as well as their likely spatial effects on land use.

The objective of this paper was to model the effects of policies designed to induce landowners to change land use and management patterns with a view to sequester carbon or to reduce deforestation. We investigated the costs of motivating landowners to make choices in favor of forest-based carbon sequestration and/or biomass supply in a competitive setting of different land-use options. We did this by studying the likely effects of cost structures set by policies on the amount of changed land use. The management options were analyzed in a framework of joint production of biomass and carbon sequestration. Biomass was assumed to be used for bioenergy, thus substituting fossil fuel consumption, as well as for the production of wood products of various lifetimes. DIMA predicts that, while in some areas landowners would be more motivated to retain and expand forestry practices with higher bioenergy prices, in other locations stronger motivation comes predominantly from policy related to carbon sequestration.

The modeling forecasts replicated two aggregate scenarios from the IPCC SRES in their revised and updated versions (A2r and B1) for spatially explicit LUCs via downscaling. In doing so, we showed which specific assumptions and constraints are necessary in forestry and alternative land use to arrive at spatially explicit results consistent with those of the revised and updated IPCC SRES. The conclusion here is that the carbon, bioenergy, and land-use results from the revised and updated IPCC SRES scenarios are internally consistent, can be reproduced in geographic space and are consistent with conservative estimates of biological forest growth and cost estimates, assuming currently existing technology.

The results indicate that if modern biomass technologies are able to play a significant role within a wider global energy portfolio aimed at low GHG concentration targets, the global terrestrial landscapes will face unprecedented changes (the scale of these changes is quite sensitive to levels of carbon prices). This will hold true under any socioeconomic development scenario, although development for low levels of carbon prices shows significant differences between the A2r and B1 scenarios. The estimated sequestration costs of carbon sequestration are in the same range or lower than those of carbon-abatement supply functions from energy-based analyses. This suggests that forest-based carbon sequestration merits inclusion in a portfolio of cost-effective global climate-change strategies (i.e., one that equalizes the marginal costs of sequestration and abatement at a level that achieves the desired total reduction).

The modeling results indicate that carbon sequestration policies–such as those that promote afforestation and discourage deforestation (i.e., avoided deforestation)–would contribute to a significant part of the global portfolio of efficient climate mitigation policies, dependent upon carbon prices. Results from DIMA for the A2r scenario show that the share of globally avoided deforestation grows exponentially with the carbon price, from 5% to 75% of the predicted deforestation.

On a regional level, financial flows associated with both carbon sequestration and bioenergy production in regions like Africa and Latin America are estimated to grow faster than in northern regions. Within the tropical belt, Africa appears to be the continent with the largest afforestation potential because of the strong relative cost competitiveness within the model. Overall, the total carbon supply from forests (until 2100) could reach more than 200 Gt of cumulative carbon sink (equal to about 120 years of today's estimated net land-use related emissions). The vast majority of this volume comes from tropical forests, including 34% sequestered in South America and 26% in Africa.

Further development of the DIMA model and the approach described here could lead to improved accuracy via reduction of the grid size (currently 0.5°) coupled with additional refinement of the biophysical model of forest growth. The model should also be expanded to allow the integration of other GHGs and other air pollutants, as well as an uncertainty analysis and the inclusion of risks (e.g., forest fire and pests).

Acknowledgements

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Appendix A. Global data sets used

The following global spatial data sets were combined to create the resultant global data set used in this study (Table A1). Where necessary, all raster data sets were converted from their original resolution into a standard 0.5° (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 [41]. 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 [42]. 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 these estimates.

Agricultural suitability represents the fraction of each grid cell that is suitable to be used for agriculture. The methods used by Ramankutty et al. [43] to derive this data set are spatial data synthesis, analysis and numerical modeling based on temperature and soil conditions of each grid cell. The International Geosphere Biosphere Project (IGBP) data set was used in this study to represent land cover [45]. This data set utilized data from April 1992 to March 1993 and is used to identify forest area and the amount of biomass per hectare for each grid. Based on an earlier study [10], the IGBP land cover data set was found to be the most conservative (with respect to estimates of amount of standing biomass per hectare) of the recent satellite-based land-cover products available, and was used here for this reason. The net primary production (NPP) and carbon-stock data sets were derived from modeling results by Alexandrov et al. [47], who used process-based models as the drivers, with parameters derived from global databases of on-ground measurements. Future gross domestic product (GDP) and population data sets, as well as future percentages of crop area and built-up area [20], were produced based on the revised and updated scenarios from IPCC SRES [48].

Table A1 The complete set of spatial data sets used to create a database for modeling.

Data set	Units	Original resolution	Source	Type
World countries	Countries	1:1 million	[41]	Empirical
Population 1995	Persons/km^2	1 km	[42]	Statistics
Agricultural suitability	Fraction (%)	50 km	[43]	Modeled
Elevation	Meters	1 km	[44]	Empirical
IGBP land cover	17 classes	1 km	[45]	Classified
Protected areas	Polygons	1 km	[46]	Empirical
NPP	g C/m^2/year	50 km	[21,47]	Modeled
Carbon stock	tC/ha	50 km	[21,47]	Modeled
Future GDP(A2/B1 SRES)	US$/ha	50 km	[48]	Modeled
Future population (A2/B1 SRES)	Persons/km^2	50 km	[48]	Modeled
Future percentage of crop area (A2/B1 SRES)	Percent	50 km	[20]	Modeled
Future percentage of built-up area (A2/B1 SRES)	Percent	50 km	[20]	Modeled

Appendix B. Detailed structure of DIMA

The DIMA model integrates, both spatially and temporally, ecological modeling of carbon dynamics with economic modeling of land use. To our knowledge, in other models interactions in which land use affects forest ecosystems on this scale have been considered only implicitly through the use of historical land-use and land-cover databases in ecological simulations [49–52]. Antle et al. [53] have created a similar coupled model that focuses on carbon sequestration in agricultural soil. Linkages from ecology to land use are often incorporated in the sense that ecological conditions are understood to constrain economic outcomes. But many analyses ignore all linkages, and even when linkages are modeled, the dynamic interactions and feedback mechanisms between ecosystems and LUCs are largely ignored. Global dynamic integrated assessment of global forest resources using geographically explicit, coupled biophysical-economic forest sector modeling, such as the DIMA model, was introduced rather recently. The DIMA model builds on models built by Benítez and Obersteiner [54] and Benítez et al. [10]. Another regional model [55] assesses biomass resources estimates (including forestry biomass potentials) for several SRES scenarios within the framework of the IMAGE model.

B.1. Land-use change modeling

Most changes in land use are induced by the demand for cropland and grassland, which is driven by the demand for food products, the extent of biomass energy use, and policies and practices associated with forest management.

We assume that, after the necessary land area is allocated to guarantee food security and safeguard enough land for urban development [20] for a given grid, up to 80% of the remaining area is available for afforestation and reforestation (AR) activities (i.e., could eventually be afforested or reforested). The rest should then go into areas for settlements, roads, and buffer strips for, for example, riparian areas or fire. Full tree planting would require 50 years to complete full AR [22], and planting is assumed to occur at a constant rate [56].

With respect to the parameters of land price, plantation cost, stumpage price, and transport cost, 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 the official exchange rate in 2001 [57][1]. To fit the parameters of the land price function (A_i), we set minimum and maximum bounds, so that the upper bound corresponds to grids where the suitabilities 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 Eq. (5). For Brazil, the higher bound for land prices is set on US$2000/ha, which resembles sites of good quality in Latin America [58,59]. The lower bound is set to US$200/ha. Additional sources for land prices can be found at, for example, www.sinkwatch.org, and shadow values from a number of agricultural models [60] were consulted.

Plantation costs for Brazil are US$1000/ha, within the range provided by Ecosecurities [61] and Fearnside [62]. 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 estimate transportation costs, we consider that the local level of stumpage timber and/or biomass prices is linearly proportional to three

[1] The price index relative to the USA. The price index for countries that do not appear 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.

factors: the global level of the relevant price, price index (with respect to the reference country, Brazil), and the specially parameterized linear function of the normalized population density. The global level of the relevant price is introduced exogenously within the framework of MESSAGE calculations (for details of the MESSAGE modeling approach, see Messner and Strubegger [24]). To check that the coefficients were properly calibrated (within the crude assumption of linear dependency of the three listed factors) the resulting prices for the initial years were cross-checked for a number of countries with export prices reported by the FAO [63].

Consider a risk-neutral landowner facing the choice of allocating a parcel of land of uniform quality among a set of alternative uses. If net returns and the costs of converting land between different uses are approximately linear in land quantity, the size of the parcels will not affect the relative profitability of land-use options. Thus, in this case land-use decisions for a heterogeneous parcel can be treated on a per hectare basis. We posit that landowners choose to maximize the present discounted value of the stream of expected net benefits from the land, and that landowners base their expectations of future land-use profits on current and historic values of the relevant variables.

Profit-maximizing options for LUC and forest management are derived through calculating per hectare NPVs (for each grid). Based on NPP results from the TsuBiMo biophysical model [21] and socioeconomic data, the DIMA model selects areas suitable for afforestation (i.e., non-forest areas where tree-planting is viable and will not compromise food security or urban development) as well as areas that could be subjected to deforestation. For all grids the model estimates forestry-related NPVs 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.

The LUC decisions are made grid-by-grid by considering the profitability of afforestation *vis-à-vis* the current agricultural practice, that is, NPV of forestry including payments for carbon sequestration is required to be larger or equal to the NPV of agriculture. The NPV of forestry in ith grid during one rotation interval per hectare, (denoted by f_i) is estimated as:

$$f_i = -\mathrm{cp}_i + \mathrm{pw}_i \cdot V_i \cdot (1+r)^{-R_i} + B_i, \tag{1}$$

where cp_i are planting costs, pw_i is the stumpage timber price, r is the discount rate (for all considered scenarios the discount rate is currently set to be constant and equal to a 5% annual rate), R_i is the rotation interval, V_i is the timber volume, and B_i is the present value of carbon benefits (derived in Eq. (3) below) over one rotation. Carbon benefits include carbon sequestration in forest standing biomass and products net of expected (current or of the previous period) carbon storage. Approximating carbon volume storage in trees because of growth by a linear function, where ω_i measures the mean annual carbon uptake (which could be harvested later) over the rotation period R, and using pc_i for carbon price and B_i^{b} for carbon benefits per hectare in the biomass, we have:

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

The first term of Eq. (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 (through carbon-related fees that result from the provisional reduction of carbon stock). For accounting carbon benefits in products we include, (i) long-lived products that consist of timber materials like furniture and construction wood, and (ii) short-lived products that consist of quickly decomposing biomass, such as leaves, branches and timber wastes or biomass that 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 after an exponential decay function with parameterization according to Sohngen and Sedjo [64]. The parameterization is also consistent with more detailed studies [65].

Carbon benefits in products represent the long-lived fraction, β_i, of the carbon costs that occur during harvest [54]. Regarding the parameters for the decay function of forest products, we consider that 50% of the biomass that enters the forest products pool is stored in long-lived products with a half-life of 20 years, and the remaining biomass consists of short-lived products with an expected half-life of 1 year [22]. By summing up carbon benefits in biomass and products, the final expression for B_i, the total carbon benefits per hectare, is obtained via introducing in Eq. (2) an additional term related to carbon storage in products:

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

By combining Eqs. (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:

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

The NPV of agriculture is obtained indirectly assuming a two-factor Cobb–Douglas production function. To construct the dynamics until 2100 the relevant parameters are adjusted each 10 years (kth decade) based on refined projections on GDP per hectare, G_{ik}, and population density, D_{ik}. The first factor in the production function is suitability for agriculture, S_i, which indicates the aptness of the land for agricultural production given its endowments of soil and ecosystem properties. The second one is population density, D_{ik}, which represents the accessibility to markets and current infrastructure that surrounds the land (e.g., more populated areas have more roads). The NPV of agriculture for the kth decade and ith specific grid, A_{ik}, is:

$$A_{ik} = \frac{G_{ik} \cdot \upsilon_i \cdot S_i^{\alpha_i} \cdot D_{ik}^{\gamma_i}}{G_{i1}} \tag{5}$$

where the parameters α_i and γ_i determine the relative importance of S_i and D_{ik} on determining A_{ik}, and υ_i determines the general price level for land given the PPP and exchange rate for each country throughout the scenario horizon. S_i and D_{ik} are normalized between 1 and 10. Although Eq. (5) provides an approximation for the NPV of agriculture, its use allows detailed land-use statistics to be avoided. 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 (on levels of land prices) from FAO [63] to calibrate Eq. (5) and choose appropriate values of parameters α and γ. Also, when we set $A_{ik}=F_i$, we find the minimum carbon price that allows forestry to be as profitable as agriculture (in the *k*th decade).

Another parameter that influences the process of LUC choices is *forestry-related* amenity values, M_{ik}. This parameter is estimated from the relation:

$$M_{ik} = \delta_i \cdot G_{ik}^{\varepsilon_i} \cdot D_{ik}^{\nu i} \tag{6}$$

Here parameters ε_i and ν_i determine the relative importance of G_{ik} and D_{ik} on determining A_i, and δ_i determines the general level for amenity valuation for this specific grid, assumed to be proportional to the coefficient υ_i.

We derive the LUC decision-making rules for the *k*th decade and *i*th specific grid as:

1) Afforestation program starts for the *k*th decade if $F_i > A_{ik}$;
2) Deforestation starts if land is not protected and $A_{ik} > F_i + M_{ik}$;
3) Current (forestry-related) land use is conserved (neither afforestation nor deforestation occurs) if $F_i + M_{ik} \geq A_{ik} \geq F_i$

For the LUC decisions (afforestation/deforestation/conservation) we define the speed of these types of LUC, L_{ik}^m, with $m=1, 2, 3$. Then procedures A and B are followed.

(A) The value for L_{ik}^m for $k=1$ is set based on region-specific historical afforestation rates during the years 1975–2000 ($m=1$) and deforestation rates observed during 1990–2000 ($m=2$) as reported by FAO [63] and Sathaye et al. [28].

The starting values are equal for all scenarios. The values of parameters—initial (as of 2000) annual percentage of afforestation and deforestation (and the relevant allowable changes with respect to these given initial values are given in parentheses) are:

Deforestation rates: Africa 0.80 (±0.026%/year); South America 0.40 (±0.013/year); Central America 1.19 (±0.011%/year); SAS 1.03 (±0.008%/year); Rest of the world 0.6 (±0.01%). Please note that the definition of eleven IPCC SRES regions and four macro regions (abbreviated SAS, ALM, REF, OECD90 or ASIA) mentioned here and below can be found e.g. at http://www.grida.no/climate/ipcc/emission/149.htm or http://www.iiasa.ac.at/Research/POP/edu01/humancapital.html
Afforestation rates: OECD90 0.30 (±0.005%), ASIA 0.60 (±0.01%), ALM 0.15 (±0.01%), and REF 0.20 (±0.01%), and for 100 year forecasts the dynamic development of the parameters is projected in such a way that best fit of future baseline (i.e., zero carbon price) land budgets (as projected by the AIM model along the storylines of relevant SRES scenarios) is achieved.

(B) Bounds on admissible rates of changes for L_{ik}^m ($m=1, 2$) as k takes values from 1 to 10 and $m=1, 2$ are set within historical data on region-specific changes of afforestation and deforestation rates [68].

Within these given limits (two-sided estimates imposed by procedures A and B) imposed on L_{ik}^{1} and L_{ik}^{2} the model was parameterized so that its predictions are as close as possible to SRES projections for the relevant baseline cases (zero carbon price) for both A2 and B1—once the differences in scenario-specific socioeconomic parameters are taken into account according to Eq. (5).

The amount of forests in a grid at a certain point in time (H_{ikj} at the jth year ($10 \geq j \geq 1$) at the ith grid, for kth decade) is then calculated as follows:

$$H_{ikj+1} = L_{ik}^{m} \cdot H_{ikj}, \text{ where } L_{ik}^{1} > 1, 0 > L_{ik}^{2} > 1, \text{ and, finally, } L_{ik}^{3} = 1 \tag{7}$$

B.2. Carbon sequestration and biomass for bioenergy modeling

Joint carbon sequestration and biomass supply curves are derived using the IGBP land-cover data set, considering a scenario horizon of 100 years. In this study we use the population and economic growth projections implied by different IPCC SRES (revised and updated) storylines (developed and downscaled [48]) to project carbon sequestration and biomass supply implied by these scenarios.

The baseline used to estimate the projected carbon sequestration has two components:

- A grid-specific baseline that corresponding to the non-forest carbon stock [2147];
- A regional baseline that subtracts the possible AR and revegetation trends in a business-as-usual scenario.

To account for the subtraction of these factors we deduct a conservative estimate of a lump-sum 10% of the carbon sequestration for each grid. All carbon accounting for all carbon pools and for all activities (including harvesting and thinning, where applicable) are calculated with respect to this baseline.

To estimate 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 uneven stand structures in every grid, which are harvested and replanted periodically. To find the cumulative sequestered carbon, we sum carbon in biomass and products throughout stands and grids.

We assume that all the additional wood supply as compared with baseline goes into bioenergy production and/or carbon sequestration. Harvesting rotation intervals were computed as a function of the approximation of the stem volume growth (based on TsuBiMo output [21,47]) and typically varied between 9 and 120 years. The potential total biomass supply for the kth decade from the afforested land in grid i is:

$$\mathrm{BE}_{ik} = \sum_{j=1}^{10} \{\omega_i \cdot H_{ikj}\} f_i^{\mathrm{BE}} \tag{8}$$

where f_i^{BE} denotes the fraction of biomass that enters the biomass for the bioenergy pool, with the remaining amounts entering the forest industry consumption cycle.

The associated costs of biomass delivery to a biomass conversion plant are approximated by $c_i^{\mathrm{BE}} = \mathrm{pc}_i + c_h$, which is the sum of the stumpage price plus the harvesting and transportation cost c_h. The latter cost component is assumed to vary as a function of the stocking biomass, economic wealth, and population density (values c_h and c_i^{BE} were previously established [59]).

The carbon sequestration in products C_{ik} is calculated in a similar way:

$$C_{ik} = \sum_{j=1}^{10} \{\omega_i \cdot H_{ikj}\} \mu_i \tag{9}$$

where μ_i is a coefficient defined by fractions of harvested carbon going into pools of long- and short-lived products. Regarding the parameters for the decay function of forest products, we consider that 50% of the biomass that enters the forest products pool is stored in long-lived products with a half-life of 20 years and the remaining biomass that consists of short-lived products has an expected half-life of 1 year [22]. Forest sector consumption until the year 2100 depends on the socioeconomic drivers implied by the scenario storylines.

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