GREENHOUSE GAS–AIR POLLUTION INTERACTIONS AND SYNERGIES

GAINS

GHG MITIGATION POTENTIALS AND COSTS FROM LAND-USE, LAND-USE CHANGE AND FORESTRY (LULUCF) IN ANNEX I COUNTRIES

METHODOLOGY

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This report documents the basic methodology of IIASA's GAINS model that has been used for comparing mitigation efforts across Annex I Parties.

The following additional information sources are available at http://gains.iiasa.ac.at/Annex1.html:

- An interactive **GAINS GHG mitigation efforts calculator** that allows online-comparison of mitigation efforts across Annex I Parties. Free access is provided at http://gains.iiasa.ac.at/MEC.
- Access to all input data employed for the calculations for all countries via the on-line version of the GAINS model at http://gains.iiasa.ac.at/Annex1.html.

The following report documents the basic methodology of IIASA's GAINS model that has been used for comparing mitigation efforts across Annex I Parties:

- Potentials and costs for greenhouse gas mitigation in Annex I countries. M. Amann et al., 2008

Other reports document details of the methodology for specific sectors:

- GHG mitigation potentials and costs from energy use and industrial sources in Annex I countries. J. Cofala, P. Purohit, P.Rafaj. Z. Klimont, 2008
- GHG mitigation potentials and costs in the transport sector of Annex I countries. J. Borken-Kleefeld *et al.,* 2008
- Potentials and costs for mitigation of non-CO_2 greenhouse gases in Annex I countries. L. Höglund-Isaksson et al., 2008

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Executive summary

Mitigation efforts and investments over the next two to three decades will have a large impact on opportunities to achieve lower stabilisation levels of greenhouse gas emissions. It will be a formidable challenge to negotiating Parties to arrive at a generally accepted scheme for sharing efforts among Annex I countries that achieves the necessary emission reductions.

In this report the International Institute for Applied Systems Analysis (IIASA) presents an approach that aims at a coherent international comparison of greenhouse gas mitigation efforts in the LULUCF sector among Annex I Parties in 2020. The GAINS methodology considers (i) conservation, to prevent emissions from existing carbon pools, (ii) sequestration, to increase stocks in existing pools, and (iii) substitution, to substitute energy-intensive products or products on fossil fuel basis with products based on regrowing resources.

To estimate mitigation potentials and costs a framework of models was applied. Land use change related options such as afforestation and avoided deforestation are estimated using a global land use model and a spatially explicit forestry model. The model cluster covers all land-use types and thus allows for fully integrated analysis of competitive interactions between different land uses and land use change types. Combining the different models allows for geographically explicit analysis of afforestation and avoided deforestation policies in a global context. A similar model setup is used to supply costs and potentials of bioenergy measures. A more detailed European scale model calculates both mitigation potentials and costs of mitigation options at farm level. This model is applied to deliver CO_2 mitigation cost curves for agriculture, mainly different tillage options.

It is found that for some Annex I countries significant mitigation potentials could be estimated for forest management. However, these estimates are rather sensitive towards critical assumptions, e.g., about the baseline development. For afforestation and deforestation, comparably small potentials are estimated for Annex I countries.

About the authors

The work was carried out by IIASA scientists working at IIASA's Forestry programme (coordinated by Hannes Böttcher). Team members include Hannes Böttcher, Kentaro Aoki, Stephane De Cara, Mykola Gusti, Petr Havlik, Georg Kindermann, Uwe Schneider and Michael Obersteiner.

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Table of contents

1 Introduction

Changes in terrestrial carbon stocks have significantly contributed to the increase of greenhouse gases (GHGs) in the atmosphere (Houghton and Hackler, 2001). Approximately 40 percent of the human-induced emissions of GHGs that occurred during the last 20 decades were caused by land-use change (DeFries *et al.*, 1999). The overall carbon losses of the biosphere due to land-use and land-use change (LULUCF) are considered to amount up to 170 Gt of carbon having caused atmospheric CO_2 concentration levels to rise by 40-70 ppm (House *et al.*, 2002).

The special role of terrestrial ecosystems in the global carbon cycle that differs significantly from other components is related to the properties of carbon pools in forest ecosystems. Comparably high carbon stocks were accumulated over centuries after the last glaciation, amounting currently to about 1640 Gt of carbon (Sabine *et al.*, 2004). Management of terrestrial ecosystem carbon stocks can introduce and enhance sinks of CO_2 from the atmosphere through different measures as a service of atmospheric carbon mitigation. Three strategies to curb the increase of CO_2 in the atmosphere are available (Freibauer, 2002; IPCC, 2001) within LULUCF:

- Conservation, to prevent emissions from existing carbon pools. This measure has an immediate benefit for the atmosphere. Its theoretical potential equals the current existing carbon stock in terrestrial ecosystems that could potentially be released. Conservation is important in regions with high C stocks per unit area. An example is forest conservation from deforestation.
- Sequestration, to increase stocks in existing pools. The effect of sequestration can be characterized by a slow build up, e.g., following tree growth and accumulation of carbon in litter and soil. The potential of activities aiming at this effect is the carbon gain of the biosphere assuming a complete restoration up to its natural carrying capacity. Sequestration applies to areas where C stocks have been depleted. Examples are reduced tillage in agriculture or longer rotations in forestry.
- Substitution, to substitute energy-intensive products or products on fossil fuel basis with products based on regrowing resources. The effect as a mitigation measure is somewhat similar to benefits from conservation, and accumulates over time with each harvest and product use. The technical potential can be as high as the emissions from fossil fuel that can potentially be substituted, but it always has to be seen against a theoretical reference scenario with use of fossil fuels. The effect of fossil fuel substitution depends on whether the substitution actually reduces fossil fuel use or just limits its increase. Substitution relies on harvest and therefore opposes conservation and sequestration objectives in forests. Examples of substitution are bioenergy options based on sustainable land management.

Affected pools can be biomass (above and belowground), litter, dead wood, soil organic matter, products and fossil fuel carbon substituted by products and the use of biomass for energy production. Single management activities can either increase or decrease these pools.

Short-term effects of management on the terrestrial carbon budget are relatively easy to measure in the above-ground biomass. A major challenge, however, is to quantify the long-term effects of historical forest use on soil carbon stocks and to separate them from the effects of recent forest management. While some practices like inter-rotational site preparation can have a very substantial effect on soil C in tropical plantations (Paul *et al.*, 2002), effects of silvicultural practices are comparably small considering the high small-scale variability of soil carbon stocks (Mund and Schulze, 2006; Smith and Conen, 2004).

Management options that are relevant in forestry, agriculture and bioenergy include:

- Afforestation and reforestation,
- avoided deforestation and forest degradation,
- forest management through longer rotations, changed thinning regime, enhanced growth (e.g., fertilization), species change (more important as adaptation measure), fire management, pest management, treatment of harvest residues,
- harvested wood products, which increase the share of longer living wood products,
- restoration of degraded vegetation,
- cropland management, through no or low tillage, diversified rotations, winter cover crops, change soil inputs, treatment of harvest residues,
- grassland management, by improved grazing practices, conversion of marginal agricultural land to grassland,
- wetlands and organic soils,
- bioenergy production for fossil fuel substitution.

Management effects differ between stand and landscape levels or ecosystem and forest sector perspectives. The overall net-effect of management is expressed by changes in atmospheric carbon stocks. But terrestrial ecosystems are also vulnerable to climate change, and carbon stocks accumulated over decades bear a certain potential of CO_2 efflux through various types of disturbances (Körner, 2003).

In this analysis for forestry options, only aboveground carbon is considered; agricultural management options include effects on soil carbon; bioenergy options take into account emissions and removals from feedstock production and conversion technologies.

This analysis focuses on mitigation options in forestry, agriculture and bioenergy. The specific options in LULUCF covered in this analysis are listed in Table 1.1. As can be observed from Figure 1.1, LULUCF options are of different importance in Annex I countries. While emissions from deforestation that could be potentially avoided are only significant in some countries, removals through agriculture ad forest management are an option for many.

Table 1.1: LULUCF mitigation options considered.

CO_2	
Land use change	• Afforestation of agricultural land • Avoided deforestation
Forestry	• Prolongation of rotation periods in existing forests
Agriculture	• Reduced tillage
Bioenergy	• Ethanol • Biodiesel • Fuel for combustion, cofiring

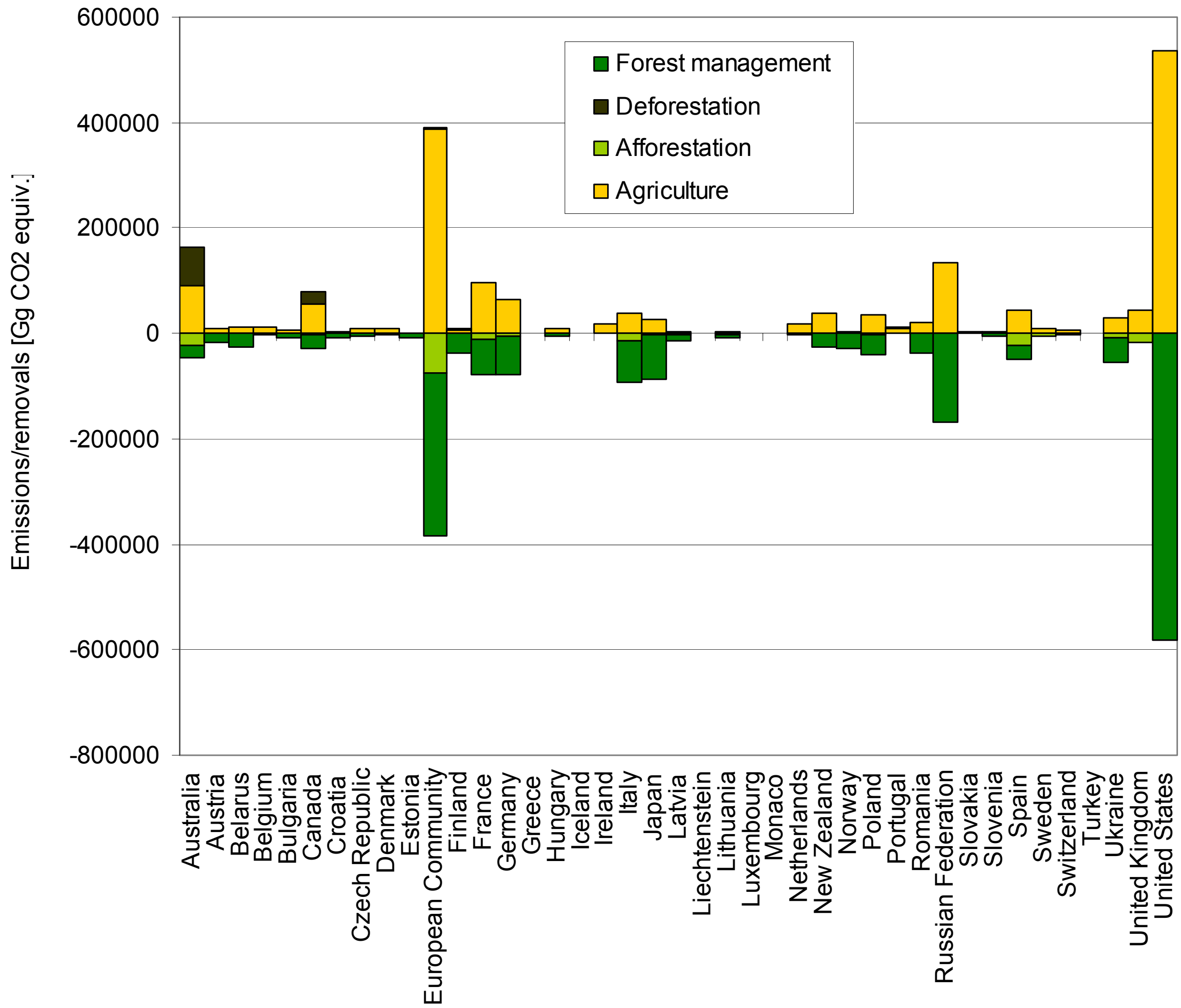

Figure 1.1: Reported emissions and removals from Agriculture, Afforestation, Deforestation and Forest management in 2005 (UNFCCC database).

To estimate mitigation potentials within the LULUCF sector a framework of models was applied (cf. Figure 1.2). Land use change related options such as afforestation and avoided deforestation are estimated using a global land use model (GLOBIOM) and a spatially explicit forestry model (G4M). The model cluster covers all land-use types and thus allows for fully integrated analysis of competitive interactions between different land uses and land use change types. Combining the different models allows for geographically explicit analysis of afforestation and avoided deforestation policies in a global context. The model G4M also provides mitigation potentials and costs of options in management of existing forests. A similar model setup is used to supply costs and potentials of bioenergy measures. Here the optimisation model EUFASOM is linked to the biophysical agricultural model EPIC. The agricultural model supplies EUFASOM with geographically explicit biomass potentials for various energy crops and bioenergy plantations. The more detailed European scale model AROPA-GHG calculates both mitigation potentials and costs of mitigation options at farm level. This model is applied to deliver CO_2 mitigation cost curves for agriculture, mainly different tillage options.

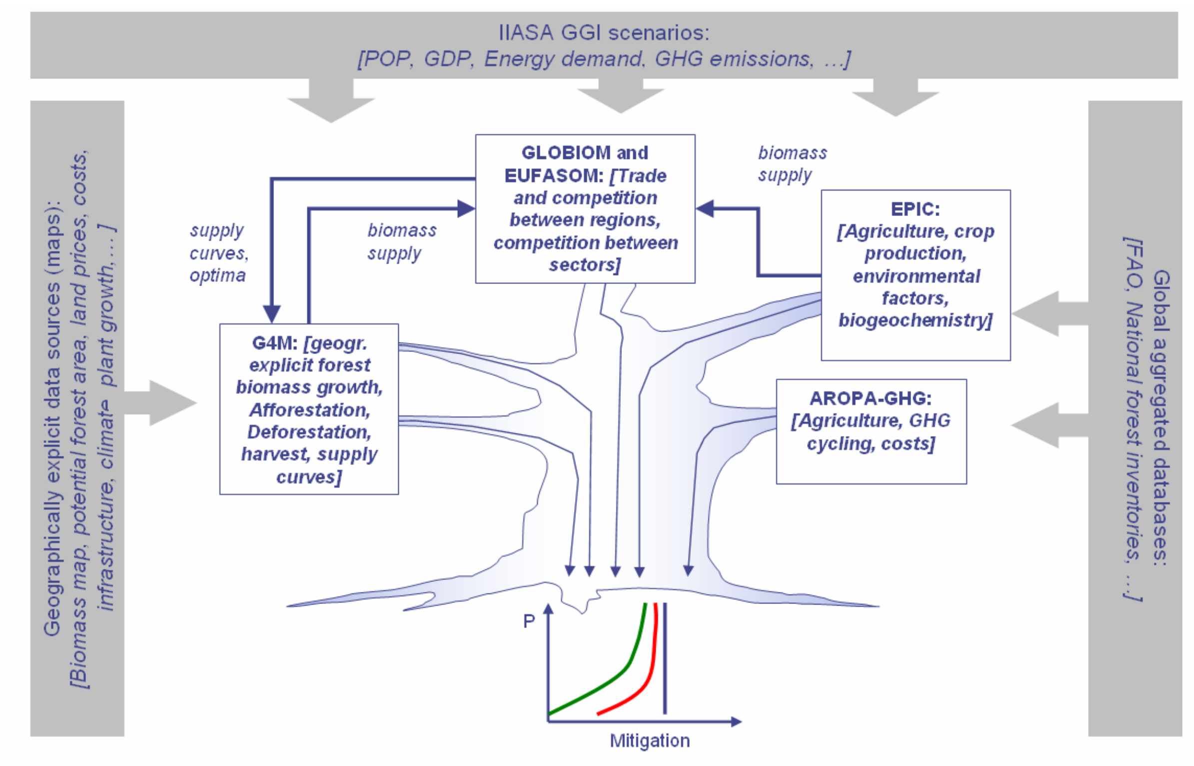

Figure 1.2: IIASA FOR land use modelling cluster.

2 Afforestation, Reforestation and Deforestation

The idea of storing CO_2 by planting trees was developed already in the 1970s (Dyson, 1977) and proposed again during the 1992 Earth Summit in Rio de Janeiro (Marland and Marland, 1992). It was estimated that 345 Mio ha of new forest plantations and agroforestry measures could be established, sequestering up to 1.5 Gt C yr^{-1}, equivalent to ~30 percent of anthropogenic carbon emissions. More recent estimates suggest that in general 12-15 percent of fossil-fuel emissions until 2050 could be offset by improved management of terrestrial ecosystems globally (Sathaye and Bouille, 2001).

Globally, the latest Forest Resource Assessment of the United Nations Food and Agriculture Organization FAO (FAO, 2005) estimates the current rate of afforestation, landscape restoration and natural expansion of forests at 5.7 million hectare/yr, which is contrasted by a loss of 13 million hectare/yr through deforestation.

2.1 Brief description of abatement measures

2.1.1 AFFORESTATION

The area of forest plantations increased by 2.8 million ha per year between 2000 and 2005, mostly in Asia (FAO, 2005). According to the Millennium Ecosystem Assessment scenarios (MEA, 2005), the forest area in industrialized regions will further increase between 2000 and 2050 by about 60 to 230 million hectares. These areas of new forests are characterized by a very juvenile age structure (e.g., in European forests it is old coppices or post-war plantations) that still show increasing increment growth rates. The sustained accumulation of carbon in these forests also results from harvest rates that are lower than the increment because of not adapting harvesting to increasing productivity (Ciais *et al.*, 2008).

The carbon sequestration potential of afforestation depends on many different factors such as previous land-use, soil type or tree species (Guo and Gifford, 2002; Jandl *et al.*, 2007). Afforestation typically leads to increases in biomass and dead organic matter carbon pools and, to a lesser extent, in soil carbon pools (Paul *et al.*, 2003). However, on sites with high initial soil carbon stocks (e.g., grassland ecosystems) soil carbon stocks can decline through biomass removal and site preparation prior to afforestation (Davis and Condron, 2002; Thuille and Schulze, 2006). Carbon sequestration is larger on sites that were depleted in soil carbon, e.g., due to unsustainable agricultural practice (De Koning *et al.*, 2005; Jandl *et al.*, 2007).

2.1.2 DEFORESTATION

Deforestation and degradation of forest is globally resulting in emissions of 8.0 Pg CO_2 in 1995 (Houghton and Hackler, 2003). Net emissions from land-use change in the tropics are estimated at 4.0 ± 1.1 Pg CO_2 per year (Achard *et al.*, 2004). This estimate includes emissions from biomass and soil carbon after deforestation, emissions from forest degradation, fire emissions and sinks from regrowth.

Deforestation in developed countries is comparably low (see Figure 1.1). While in the tropics governed or ungoverned cropland expansion is a key driver of deforestation, forest conversion in Annex I countries is in most cases a result of infrastructure and settlement expansion. In many Annex I countries efficient policies and laws are in place that have reduced deforestation rates significantly.

2.2 Modelling approach

The quantitative analysis of mitigation supply through afforestation and avoided deforestation is carried out in a global total land-use context. The cluster of global models combines geographically explicit biophysical models with economic modelling. The model cluster covers all land-use types and thus allows for a fully integrated analysis of competitive interactions between different land uses and land use change types. Combining the different models allows for geographically explicit analysis of afforestation and avoided deforestation policies in a global context. The geographically explicit analysis of policy options is carried out using the G4M (former DIMA) model (Kindermann *et al.*, 2008; Kindermann *et al.*, 2006; Rokityanskiy *et al.*, 2007). G4M is driven by exogenous market price assumptions for land and commodities without taking market feedbacks into account. The partial equilibrium model GLOBIOM generates endogenous prices. GLOBIOM has a global geographic coverage and accounts for all land uses and thus allows for land use policy analysis in a wider land use and global change context. When the two models are coupled, the G4M model serves a double purpose. First it informs GLOBIOM on basic biophysical forest growth information and engineering costing of various forest management options. Second, results from GLOBIOM, such as endogenous commodity and land prices and trade, are used as exogenous drivers for the geographically explicit modelling using G4M. In the latter, G4M becomes a "sophisticated" downscaling algorithm for GLOBIOM results.

In the following sections the two models are described. In the description of G4M we provide a detailed description of the improved carbon accounting and calibration methods departing from Kindermann *et al.*, 2006. Changes in the calibration methodology have necessarily created considerable differences in baseline emissions and costs compared to those published in Kindermann *et al.*, 2006. Baselines in Kindermann *et al.*, 2006 have been determined mainly by future GDP and population development assuming low institutional barriers for expansion of the agricultural and forestry sectors, whereas the latter is mainly driven by the continuation of historical emissions and the continuation of institutional barriers of agricultural and forestry sector development. The version of G4M that has been employed for the assessment presented in this report was calibrated against global emissions estimates provided by the IPCC, while the one in Kindermann *et al.*, 2006 was calibrated against global analyses derived from remote sensing data.

2.2.1 DESCRIPTION OF G4M

The Global Forestry Model (G4M) is a geographically explicit agent-based model to assess land use change decision making. A series of papers by Benítez *et al.*, 2004, Benítez and Obersteiner, 2006, Rokityanskiy *et al.*, 2007 and Kindermann *et al.*, 2006 document the evolution of the model starting from modelling afforestation in Latin America to global forestry scenario analysis covering avoided deforestation, afforestation and forest management decision making. The basic deforestation module of the G4M model is described in Kindermann *et al.*, 2006. This model was extended by more thorough representation of emissions from belowground biomass, dead trees, litter and organic soil carbon (SOC), which is described in detail in Gusti et al. (2008). In G4M, land use change decisions are calculated geographically explicitly for 0.5x0.5° grid cells, which approximately correspond to a 50x50 km grid taking sub-grid information into account as described in Kindermann *et al.*, 2006.

Information entering the model is available on different levels of aggregation. While some model parameters are global (e.g., decay rates of long/short living products, carbon price, etc.), some are region specific (e.g., relative stumpage wood price and net present values of agriculture), some are country specific (e.g., corruption factor, risk-adjusted discount rate, forest planting costs, GDP, hurdle, afforestation and deforestation rate adjustment coefficients) and others are grid specific (e.g., population density, agricultural suitability, NPP, forest biomass, litter and coarse woody debris, potential vegetation, protected areas, etc.). A number of exogenous model parameters change over time following the B2 IPCC scenario story line (e.g., population density, GDP (GGI Scenario Database, 2007), area of agricultural extend assuming full food security, and development of build-up land (Tubiello and Fischer, 2007), etc.).

Previous versions of the model were calibrated globally and tested by comparing global results with FAO deforestation data, global deforestation emissions and results of other models (e.g., Kindermann *et al.*, 2006; Rokityanskiy *et al.*, 2007). In the current version of the model we calibrate model parameters (i.e., country-specific hurdle rates, deforestation and afforestation rate correction coefficients) in such a way that the rate of change of country net (i.e., afforested minus deforested) forest area and total afforestation and deforestation rates match respective FAO data (FAO, 2006) for the period 2000-2005.

Land use change decisions are modeled on the basis of comparing net present value of forestry vis-à-vis the net present value of land use from agriculture. The net present value of forestry for multiple rotations R_i and country specific risk-adjusted discount factor (Benítez *et al.*, 2004) r_c is defined with the following equation:

$$F_i = f_i \cdot \left[1-(1+r_c)^{-R_i}\right]^{-1} \quad (1)$$

Where f_i is the net present value of forestry for one rotation defined as the sum of stumpage wood price pw_i, multiplied by harvested wood volume V_i, value of stored carbon B_i, minus planting costs cp_i.

$$f_i = -cp_i + pw_i \cdot v_i + B_i \quad (2)$$

Net present value of agriculture is modeled using Cobb-Douglas production function arguments which are standardised agriculture suitability $SAgS_i$ (Ramakutty et al 2002) and standardised population density SPd_i.

$$A_i = v_{i,2000} \cdot SAgS_{i,2000}^{\alpha} \cdot SPd_{i,2000}^{\alpha} \cdot AGB_{reg} \tag{3}$$

Parameters α and v_i define the price level of land. Deforestation is modeled to take place in a grid, if the net present value of agricultural production together with benefits from selling wood after the clear-cut of the forest is greater than net present value of forestry (sustainable production of wood during multiple rotation periods and also considering economic measures giving additional value to stored carbon). G4M applied for afforestation and avoided deforestation considers carbon pools of above-ground and belowground biomass, dead trees, litter and soil organic carbon (SOC). The net present value of agriculture is modeled with an agricultural land price in a form of Cobb–Douglas production function, in which agricultural suitability and population density are independent variables (Benítez *et al.*, 2004). In the model deforestation is prohibited in conservation and nature protection areas.

Afforestation takes place in a grid, in which there is land that can be afforested (i.e., not under buildings and roads or secured for agriculture), the environmental conditions are suitable for forestry and the net present value of forestry multiplied by a hurdle coefficient is greater than the net present value of agriculture. Economic policies, e.g. carbon tax in case of deforestation or payments for carbon accumulated additionally in forest ecosystem in case of a/re-fforestation, add value to the maintenance of keeping the forest carbon stock. The hurdle coefficient is derived from applying a calibration method to match base year predictions to FAO and IPCC values. The hurdle rate can be interpreted as an endogenously determined transaction cost factor to LUC. The other two parameters which are endogenously determined in the calibration phase are the country specific adjustment factors for deforestation and afforestation rates. The deforestation rate (amount of forest land that can be converted to agricultural land during one year), and afforestation rate (amount of agricultural land on which forest can be planted during one year) represent more differences in capacity to implement land use changes e.g. technical, infrastructural and financial capabilities of deforesting or establishing new forests. Thus, deforestation and afforestation rates are modeled to be also a function of gross domestic product (GDP), population density and agricultural suitability.

Emissions from deforestation include emissions from burning of slash, dead wood and coarse roots, and from decomposition of wood products, litter and soil organic matter. To assess carbon losses from deforestation we track all carbon pools over time. Likewise, the evolution of carbon pools resulting from afforestation are tracked over time for all respective carbon pools. When modelling the impacts of climate policies all of the carbon pools are credited or debited. Thus, all the emissions when multiplied by the carbon price enter the net present value comparison for land use change decision making.

2.2.2 DESCRIPTION OF GLOBIOM

GLOBIOM is a global recursive dynamic partial equilibrium model integrating the agricultural, bioenergy and forestry sectors with the aim to provide policy analysis on global issues concerning land use competition between the major land-based production sectors. Concept and structure of GLOBIOM are similar to the US Agricultural Sector and Mitigation of Greenhouse Gas (ASMGHG) model (Schneider *et al.*, 2007). The global agricultural and forest market equilibrium is computed by choosing land use and processing activities to maximize the sum of producer and consumer surplus (see objective function below) subject to resource, technological, and policy restrictions, as described by McCarl and Spreen (1980). The market is represented by implicit product supply functions based on detailed, geographically explicit, Leontief production functions, and product demand functions. Explicit resource supply functions are used only for water supply. Figure 2.1 provides a detailed description of GLOBIOM, where not only the individual product chains but also the land use change options are represented.

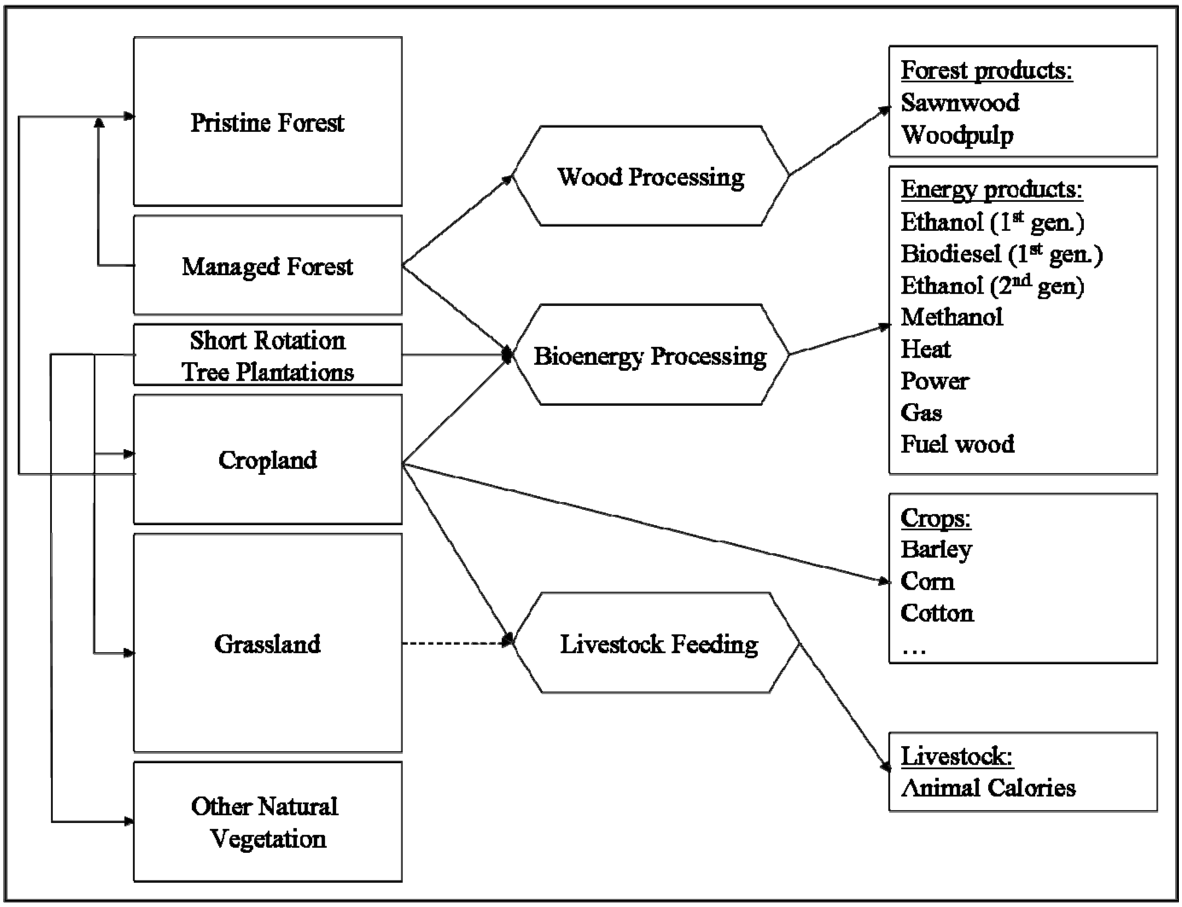

Figure 2.1: GLOBIOM land use and product structure.

Land resources and their characteristics are the fundamental elements of our modelling approach. In order to enable global bio-physical process modelling of agricultural and forest production, a comprehensive database has been built (Skalsky *et al.*, 2008), which contains geo-spatial data on soil, climate/weather, topography, land cover/use, and crop management (e.g. fertilization, irrigation). The data were compiled from various sources (NASA, JRC, FAO, USDA, IFRPI, etc.) and significantly vary with respect to spatial, temporal, and attribute resolutions, thematic relevance, accuracy, and reliability. Therefore, data were harmonized into several common spatial resolution layers including 5 and 30 arcmin as well as country layers. Subsequently, Homogeneous Response Units (HRU) have been delineated by geographically clustering according only those parameters of landscape, which are almost constant over time and are, thus, independent of land use. At the global scale, we have included five altitude classes, seven slope classes, and five soil classes. In a second step, the HRU layer is merged with a 0.5° × 0.5° grid and with country boundaries, to delineate Simulation Units (SimU) which contain other relevant information such as global climate data, land category/use data, irrigation data, etc. For each SimU a number of land management options are simulated using the bio-physical process model EPIC (Environmental Policy Integrated Climate Model; Izaurralde *et al.*, 2006; Williams, 1995). These simulations are the basis for estimation of land use/management parameters in all other supporting models.

Primary forest production from traditional managed forests is characterized also at the level of SimUs. The most important parameters for the model are mean annual increment, maximum share of sawlogs in the mean annual increment, and harvesting cost. These parameters are shared with the G4M model.

As represented graphically in Figure 2.1 the model allows for endogenous change in land use within the land resources. Expansion into other land use types is not allowed, and thus the total land area remains fixed over the whole simulation horizon. When carrying out simulations over several periods, changes made in one period, are consistently transferred into the next period, introducing recursive dynamics into the model. Land use change options are on the one hand limited through general restrictions on conversion from one land use to the other; e.g. cropland expansion into other natural vegetation is not allowed anywhere. On the other hand, land suitability criteria linked to production potentials exclude selectively land use conversion to a particular land use type in a particular SimU. Land use suitability is taken into account either indirectly through estimated crop and forest productivity, or directly by not only calculating the production potentials but also by explicitly delineating suitable areas. This detailed direct suitability analysis has been carried out for short rotation tree plantations. The following equations are used to describe the processes discussed above.

Objective function:

$$
\begin{aligned}
Max \cdot WELF_i = & \sum_{r,y}\left[\int \varphi_{r,t,y}^{demd}\left(D_{r,t,y}\right)\mathrm{d}(\cdot)\right] - \sum_{r}\left[\int \varphi_{r,t}^{splw}\left(W_{r,t}\right)\mathrm{d}(\cdot)\right] \\
& - \sum_{r,l,\tilde{l}}\left[\int \varphi_{r,l,\tilde{l},t}^{lucc}\left(\sum_{c,o,p,q} Q_{r,t,c,o,p,q,l,\tilde{l}}\right)\mathrm{d}(\cdot)\right] \\
& - \sum_{r,c,o,p,q,l,s,m}\left(\tau_{c,o,p,q,l,s,m}^{land} \cdot A_{r,t,c,o,p,q,l,s,m}\right) \\
& - \sum_{r}\left(\tau_{r}^{live} \cdot B_{r,t}\right) - \sum_{r,m}\left(\tau_{r,m}^{proc} \cdot P_{r,t,m}\right) \\
& - \sum_{r,\tilde{r},y}\left[\int \varphi_{r,\tilde{r},t,y}^{trad}\left(T_{r,\tilde{r},t,y}\right)\mathrm{d}(\cdot)\right] \\
& - \sum_{r,e}\left(\tau_{t,e}^{emit} \cdot E_{r,t,e}\right)
\end{aligned}
\tag{4}
$$

where D represents demand quantities, W defines irrigation water consumption, Q the area of land use change, A stands for land under different management, B defines livestock production, P is the processed quantity of primary input, T for trade and E greenhouse gas emissions. Indices account for properties of each simulation unit like economic region, time period, country, land cover type etc. The functions φ^{demd}, φ^{splw}, φ^{trad}, φ^{lucc} describe demand, water supply and trade costs (as a constant elasticity function), and land use change costs (as a linear function). Prices and international trade flows are endogenously determined for respective aggregated world regions.

Land use balance:

$$
\sum_{s,m} A_{r,t,c,o,p,q,l,s,m} \leq L_{r,t,c,o,p,q,l} \tag{5}
$$

$$
L_{r,t,c,o,p,q,l} \leq L_{r,t,c,o,p,q,l}^{init} + \sum_{\tilde{l}} Q_{r,t,c,o,p,q,\tilde{l},l} - \sum_{\tilde{l}} Q_{r,t,c,o,p,q,l,\tilde{l}} \tag{6}
$$

$$
Q_{r,t,c,o,p,q,l,\tilde{l}} \leq L_{r,t,c,o,p,q,l,\tilde{l}}^{suit} \tag{7}
$$

where L is the available land.

GHG balance:

$$
\begin{aligned}
E_{r,t,e} = & \sum_{c,o,p,q,l,s,m}\left(\varepsilon_{c,o,p,q,l,s,m,e}^{land} \cdot A_{r,t,c,o,p,q,l,s,m}\right) \\
& + \varepsilon_{r,e,t}^{live} \cdot B_{r,t} + \sum_{m}\left(\varepsilon_{r,m,e}^{proc} \cdot P_{r,t,m}\right) \\
& + \sum_{c,o,p,q,l,\tilde{l}}\left(\varepsilon_{c,o,p,q,l,\hat{l},e}^{lucc} \cdot Q_{r,t,c,o,p,q,l,\tilde{l}}\right)
\end{aligned}
\tag{8}
$$

2.3 Critical assumptions and uncertainties

In general, the establishment of plantations is well demonstrated and commercially mature. However, the influence of former land-use and selected species on carbon stock development stresses the importance of management choices in good carbon management of these areas. There is uncertainty regarding the rate of uptake (e.g., due to water availability and climate change) and retention (e.g., losses due to fire or land conversion) at any site. The permanence of carbon stored in newly established forests depends on how these forests are managed in the future. The economic analysis of area suitable for plantation establishment or conversion of forests to other land uses in this study is subject to assumptions about the value of forestry and agricultural products, and of farm business profitability all of which are uncertain.

Potentials for avoided deforestation are highly sensitive to the baseline chosen. The establishment of a credible baseline is crutial for an estimation of associated costs of this measure. However, many assumptions on economic development, development of costs, prices and other parameters are subject to high uncertainties.

3 Forest management

3.1 Brief description of mitigation measures

Forest management in general can be referred to as the application of biological, physical, quantitative, social and policy principles to the regeneration, tending, utilization, and conservation of forests to meet specified goals (Sampson and Scholes, 2000). Today, 89 percent of forests in industrialized countries and countries in transition and about 12 percent of the total forest area of all developing countries are considered to be managed according to a formal or informal management plan or had been designated as conservation areas (Wilkie *et al.*, 2003). Mitigation options in forest management have a large potential due to the great extent of managed forest.

Rotation length (i.e., the time from stand establishment to harvest) is commonly used to manage timber yield and income from forests and thus directly influences carbon stocks in biomass, soil and products (Harmon and Marks, 2002; Kaipainen *et al.*, 2004; Liski *et al.*, 2001; Pussinen *et al.*, 2002). Changing the rotation length can therefore be considered an effective measure to manage the carbon budget of forests for climate change mitigation. Effects on biomass carbon are most evident. An increase in rotation length usually results in an increase in biomass carbon stocks.

The effect of rotation prolongation is only temporary. Once the forests have reached the steady state with the increased rotation length, they are no longer carbon sinks and the smaller revenues or the higher round wood prices are costs of maintaining the larger carbon stock (Liski *et al.*, 2001). At the same time the higher carbon stocks imply also an increased risk of unintended emissions from disturbances such as storms or fire.

3.2 Modelling approach

The forestry model G4M (for description see above) considers, geographically explicitly at a 0.5 degree resolution, carbon stock development for alternative rotation lengths in 10 percent steps from an optimal rotation time (with maximum harvest yields) to a rotation length that maximizes biomass carbon in the forest (see Figure 3.1). The model G4M total carbon production, i.e. biomass carbon accumulation of the forest by using the following equation:

$$TCP_t = TCP_{\max} \cdot e^{k \cdot \ln^2 (t / t_{\max})} \tag{9}$$

where t is forest age and k a shape factor.

$$k = c_0 \cdot e^{c_1 \cdot MAI^{c2}} \tag{10}$$

TCP is maximum at point t_{max} and can be estimated by

$$TCP_{\max} = MAI \cdot t_{\max} \cdot e^{0.25 / k} \tag{11}$$

where

$$t_{\max} = c_4 + \frac{c_5}{1 + e^{c_6 + c_7 \cdot MAI}} \tag{12}$$

The length of a rotation is site-specific and depends on the productivity of a forest and also the production target (species, timber type and timber quality). The optimal rotation is calculated in G4M by finding the rotation time where average harvest yield over the rotation is maximized.

$$t_{opt} = t_{\max} \cdot e^{0.5/k} \tag{13}$$

The average Mean Annual Increment at that point in time is

$$MAI = \frac{TCP_{t_{opt}}}{t_{opt}} \tag{14}$$

A deviation from the optimal rotation is associated with a decrease in harvest yield because beyond the optimal rotation time more biomass is lost to natural respiratory processes in the forest and various disturbances. To compare different forest management options and to allow for comparability with other mitigation measures, costs and revenues of an entire rotation are considered.

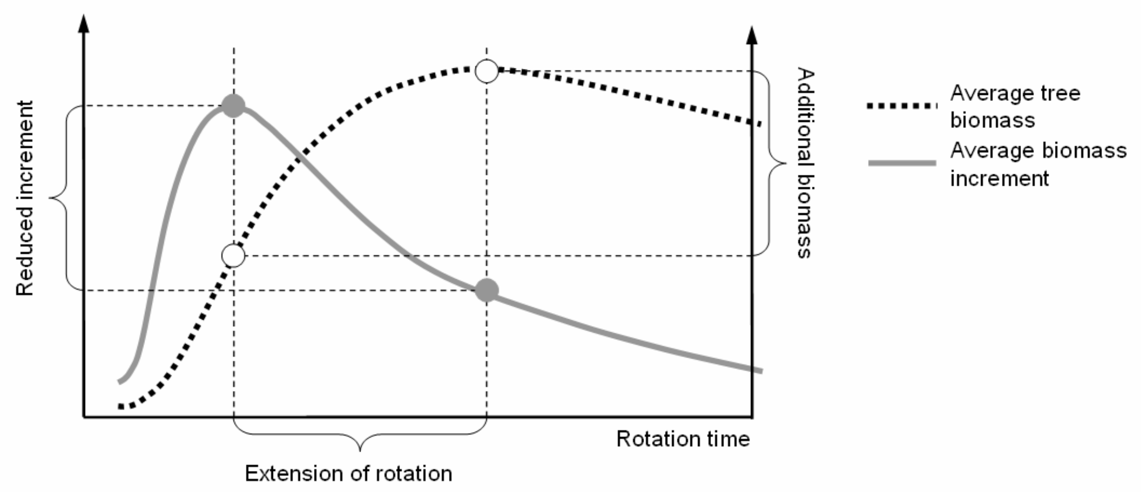

Figure 3.1: Schematic description of relationship of average tree biomass in the forest and average biomass increment for harvest. Costs of forest management mitigation options

3.3 Cost estimation

To estimate costs of rotation prolongation, harvest yields and revenues from forests with currently applied rotation length are compared to those from different rotation lengths. The decrease in harvest yield after rotation shift is translated into a financial loss of net revenue. Costs of forest management activities consider establishment cost for planting trees (i.e., cleaning and site preparation, raising and transporting of seedlings, and planting) and final harvesting costs (felling and timber extraction). These costs are offset by revenues from timber sales from both thinnings and final cuts. However, costs vary substantially by operation systems and their efficiency, such as manual or mechanical operation, productivity of forest machines and working skill of labors. To estimate establishment costs, it is assumed that seedlings are planted by hand and the planting density is 2000 trees/ha for all countries. Seedling costs, initial labor inputs and the average wages are collected from various datasets FAO, 1997; ILO, 2007; Landesforstgarten-Vorarlberg, 2008. The seedling costs and labor costs are then adjusted by the ratio of mean PPP (Power Purchase Parity) over GDP from 1994 to 2003 Heston, 2006 for all individual countries. For final harvesting costs, various datasets are compiled to estimate the average capital costs for individual harvesting machines (e.g., FPP, 1999; Jiroušek, 2007; Stokes *et al.*, 1986; Wang, 2004). Establishment costs and initial average wages at harvesting operation are based on the case of the North America and adjusted by the ratio of mean PPP for each country.

Scenarios of rotation prolongation are simulated for five different slope classes (Table 3.1) that have been derived from a global digital elevation model (based on SRTM 90m Digital Elevation Data available at http://srtm.csi.cgiar.org). The slope of a forest site in particular determines costs of timber harvest. It constrains the mobility of harvesting machines and thus the system efficiency of forest operation. In the simulation, appropriate harvest technologies are chosen along with the slope condition and the mobility constraints of machines. To illustrate this conditional change in production costs, a slope function Hartsough *et al.*, 2001 is integrated in the calculation of the overall costs.

Table 3.1: Scenarios and assumptions for forest management options

Class	Slope range [degrees]	Assumed harvest technologies
Slope class 1	0-6	Harvester with forwarder
Slope class 2	6.1-15	Harvester with forwarder
Slope class 3	15.1-30	Chain saw with skyline
Slope class 4	30.1-50	Chain saw with skyline
Slope class 5	>50	Chain saw with skyline

3.4 Critical assumptions and uncertainties

Potentials of CO_2 mitigation through forest management options highly depend on past practices and forest disturbance regimes (Böttcher, 2008). Accounting for these effects requires the establishment of credible forward-looking baselines that are based on detailed forestry models to factor out effects of past practices and disturbances to quantify the direct human-induced effects of forest carbon dynamics. The model applied for this analysis does not take these effects fully into account.

The rotation time in managed forests is often influenced by the potential product the forest owner wants to sell and the current market situation for different products. How effectively rotation extension will be implemented as a measure for climate change mitigation in the future is to a large degree dependent on economic incentives. Liski *et al.* (2001) calculated losses of mean net revenues of landowners of € 12.4 ha^{-1} $year^{-1}$, or 10 percent when increasing the rotation length in Finish spruce forests by 30 percent as a result of the decreased annual fellings. If prices for large dimensional timber are low, forest owners tend to keep high growing stocks and wait for better prices. The decreased supply of round wood would probably increase the unit price of timber transferring a part of the costs from the forest owners to the forest industry (Liski *et al.*, 2001). The trend in forest management, however, is currently towards shorter rotations because also small sized timber can be used for construction purposes as compound wood. The demand for a certain quality, quantity and type of product is changing over time, and linked to the technological development of wood processing. European pulp and paper demand during the last decades increased more rapidly compared to the demand of sawn timber (UNECE, 2005). Over the next 20 years, it is expected that renewable energy policies encourage the establishment of short-rotation forest plantations for wood fuel production (UNECE, 2005). In addition there is a trend towards compound products, resulting in a higher demand for sawn timber of smaller diameters (UNECE, 2007). It is therefore likely that economic conditions will favour a reduction of rotation time in the future in some forest regions.

Market efects have not been considered in this exercise. However, a substantial prolongation of rotations in managed forest on a large area might have significant impacts on the timber market if this measure leads to a shortage of timber. This effect would result in considerably higher costs than those anticipated here.

4 Cropland management (CO_2)

4.1 Brief description of mitigation measures

According to the UNFCCC definition, “cropland management” is the system of practices on land on which agricultural crops are grown and on land that is set aside or temporarily not being used for crop production (FCCC/CP/2001/2/Add.3/Rev.1). Trines et al. (2006) reviewed various activities in cropland management aiming at GHG mitigation. The global technical mitigation potential from agriculture by 2030, considering all gases, is estimated at 5.5–6 Pg CO_2eq. per year. Economic potentials amount 1.5–1.6, 2.5–2.7 and 4–4.3 Pg CO_2eq. per year at carbon prices of up to 20, up to 50 and up to 100 US$ t per CO_2eq., respectively. (Smith *et al.*, 2008). Compared to annual CO_2 emissions during the 1990s, agriculture could offset, at full biophysical potential, about 20 percent of total annual emissions. Of these total mitigation potentials, approximately 89 percent is from reduced soil emissions of CO_2, approximately 9 percent from mitigation of methane and approximately 2 percent from mitigation of soil N_2O emissions (Figure 4.1).

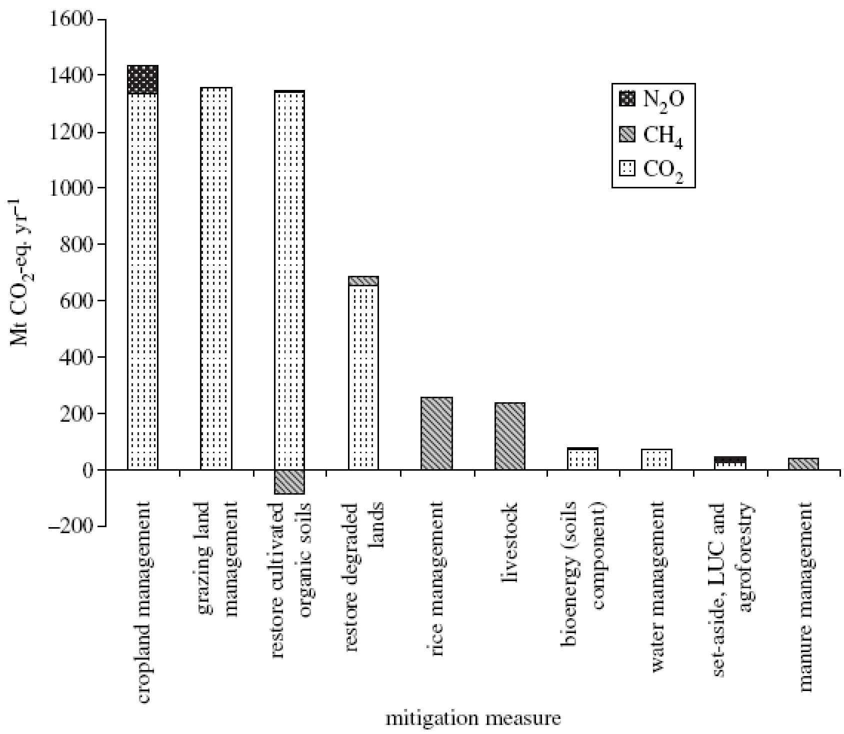

Figure 4.1: Global biophysical (biological) mitigation potential (Mt =Tg CO_2eq. year^{-1}) by 2030 of each agricultural management practice showing the impacts of each practice on each GHG stacked to give the total for all GHGs combined.

Advances in weed control methods and farm machinery now allow many crops to be grown with minimal tillage (reduced tillage) or without tillage (no-till). These practices are now increasingly used throughout the world (e.g., Cerri *et al.*, 2004). Since soil disturbance tends to stimulate soil C losses through enhanced decomposition and erosion, reduced- or no-till agriculture often results in soil C gain, though not always (West and Post, 2002; Gregorich *et al.*, 2005).

4.2 Modelling approach

Mitigation costs related to cropland soil management are based on an updated version of AROPAj (hereafter referred to as AROPA-GHG), a European agricultural supply model described in De Cara et al. (2005). The model covers also methane and nitrous oxide emissions as the costs of enhancing soil carbon sequestration through soil management are not independent from the costs of reducing GHG emissions. However, only results for soil carbon sequestration are used. Other options in agriculture are covered by other the non-CO_2 module of GAINS (Höglund-Isaksson *et al.*, 2008).

AROPA-GHG determines the allocation of crop area, animal numbers, animal feeding and animal numbers for a set of representative farm-types in the EU, based on gross margin maximization and for given values of parameters describing the economic and agricultural policy environment (prices, subsidies, quotas, etc.). Changes from the version described in De Cara et al. (2005) most notably include a revised typology of European farms and the use of more recent accountancy data from the EU Farm Accounting Data Network database (FADN 2002, see also De Cara and Jayet, 2006). The EU-FADN database provides a consistent set of information about costs, prices, area, support, farmers' revenues, and type of farming throughout the EU. Data are obtained through surveys of approximately 65,000 farmers. The surveyed farmers are representative of more than 2.5 millions of European (full-time) farmers. The basic spatial resolution of the model corresponds to the FADN regions (101 regions in the EU-15).

The model consists of a set of independent, mixed integer and linear-programming models. Each model describes the annual supply choice of a given 'farm type' (denoted by k), representative of the behavior of v_k 'real' farmers. The farm-type approach allows for representing the wide diversity of technical constraints faced by European farmers. Each farm type k is assumed to choose supply level of activity variables and input demand (x_k) in order to maximize the total gross margin (π_k). In its most general form, the generic model for farm type k can be written as follows:

$$\max_{x_k} \pi_k(x_k) = g_k \cdot x_k \tag{15}$$

subject to

$$A_k \cdot x_k \leq z_k$$

$$x_k \geq 0$$

where x_k is the n-vector of producing activities for farm type k, and g_k is the n-vector of gross-margins. A_k is the $m \times n$-matrix of the coefficients associated with the n producing activities and defining the m constraints, and z_k the m-vector of the right-hand side parameters (capacities). The components of x_k include the area and output for each crop (distinguishing between on-farm and marketed production), animal numbers in each animal category, milk and meat production, and the quantity of purchased animal feeding. g_k contains the gross margin corresponding to each producing activity: revenue (yield times price) plus – when relevant – support received, minus variable costs. As the emphasis is put on the farm-type level, each farm-type is assumed to be price-taker. All input and output prices defining the components of g_k are thus kept constant. Twenty-four crop producing activities are modeled. They represent most of the European agricultural land use. The set of crop producing activities includes fallow as well as the different CAP set-aside requirements. Crop production can be directly sold in the market or used for animal feeding purposes (feed grains, forage, pastures). In the latter case, the corresponding component of g_k only represents the variable cost of growing feed crops. Feedstuff can also be purchased. As for livestock, thirty-one animal categories are represented in the model (27 for cattle plus sheep, goats, swine and poultry).

The technically feasible production set is bounded by the constraints defined by A_k and z_k. The interested reader is referred to De Cara et al. (2005) for a detailed description of the model set-up and constraints. The constraints include: (i) crop and grassland area availability (subject to rotation constraints summarized in maximal area shares); (ii) the number of stable places at the farm-type level constrains animal numbers to vary in a ±15% range of the initial animal numbers; (iii) constraints reflecting demographic equilibrium in the distribution by age and sex classes of cattle numbers; (iv) animal feeding contraints (energy/protein requirements and maximal quantity of ingested matter for each animal category); (v) constraints related to the CAP measures (pertaining to 'Agenda 2000': set-aside requirements, milk and sugar beet quotas, inclusion of fodder maize in arable crop payments, extensification payments).

The selected sample farms are then grouped into 'farm types'. The typology has been updated compared to that of De Cara et al. (2005). Four variables are used in this typology: (i) region (101 regions in the EU-15); (ii) average elevation (three elevation classes: 0 to 300 m, 300 to 600 m, and above 600 m); (iii) main type of farming (14 types of farming in the FADN classification); (iv) economic size. Automatic classification techniques are used to address the following trade-off. On one hand, the number of sample farms grouped in any farm type has to be large enough to comply with confidentiality restrictions (at least 15 sample farms for each farm type) and to ensure the robustness of the estimations. On the other hand, the total number of farm types has to be as large as possible to reduce the aggregation bias at the regional level. Each farm type thus results from aggregation of sample farms that are located in the same region, are characterized by similar type(s) of farming and size(s) and belong to the same elevation class(es). 1074 farm types are thus obtained. Each farm type is associated with a specific supply model as defined above. Each individual farm in the FADN sample is associated with a weight indicating its representativeness in the regional population. The individual weights associated with FADN sample farms represented by farm-type k is used to extrapolate the results at the regional level.

AROPA-GHG farm-types are derived from the FADN classification. For each of the FADN regions, sample farms are grouped according to two main variables: (i) average elevation (three elevation classes); and (ii) main type of farming as reported by the FADN survey. The classification of the farm-types results from the following trade-off: The number of (real) sample farms grouped in any farm-type has to be large enough to ensure that the robustness of the estimations. At the same time, the number of modeled farm-types has to be as large as possible to reduce the aggregation bias at the regional level. Further, if the farm-type definition is too narrow in terms of agricultural activities, one may effectively reduce the aggregation bias, and thus enhance the accuracy of the fit between the simulated and observed situation for the base scenario. However, the risk is to neglect potential substitutions that might occur if new policy scenarios are implemented.

Abatement costs are measured through the introduction of an emission tax varying from 0 to 100 €/t CO_2 eq. (by steps of 10 €). The tax reflects the social value attached to agricultural emissions (converted into CO_2 eq.). Alternative management practices that entail less intensive and less disruptive tillage practices have been presented as a means of enhancing carbon sinks in agricultural soils (Freibauer *et al.*, 2004). Adoption of such practices is likely to impact: (i) crop yields, (ii) production costs, and (iii) environmental results (in particular–but not only–carbon stocks). The net impact on gross margin is therefore ambiguous, and depends on the value attached to carbon sequestration. Carbon sequestration and yields impacts are obtained from 10-year EPIC simulations, which cover arable land in the EU-25. These simulations are described in Schmid et al. 2007. They provide the evolution over time of soil organic carbon (top 30 cm layer) and crop yields for each HRU (Homogeneous Response Unit, see Skalsky *et al.*, 2008) and for each tillage management system, ie conventional, reduced, and minimum tillage. We assume that conventional tillage is the base management and refer to reduced and minimum tillage as 'alternative' tillage practices. By overlaying the HRU map and the EU-15 FADN region map2, 10-year averages of absolute changes in carbon stocks and relative changes in yields have been obtained for each alternative tillage practice, each FADN region (101 region), each elevation class (3 classes), and each crop. Alternative tillage practices (reduced and minimum) tend to lower the variable costs of crop production. Change in production costs are derived from a case study described in Schmid et al. (2005) for Baden-Württemberg.

The computation of gross margins includes the changes in variable costs and yields for each crop and each tillage system. The additional carbon sequestration associated to each crop is expressed in annual average increment in carbon stock (10-year average converted in t CO_2 eq. yr^{-1}) and subtracted from total emissions of CH_4 and N_2O. It is also assumed that if a farm-type switched from one tillage system to another, all cropland area is managed using the same tillage system. We thus exclude partial adoption of any tillage system at the farm-type level. .

Three sets of simulations are run: one for each tillage system (conventional, reduced, minimum). The tax (from 0 to 100 €/t CO_2 eq.) is applied to total net emissions (CH_4 and N_2O emissions minus annual carbon increments in case of reduced or minimum tillage). Farmers are thus rewarded for additional carbon sequestration permitted by switching away from conventional tillage. By comparing individual gross margins for each level of the tax, we then determine the optimal tillage management, and therefore the required incentive for a particular farm-type to switch from one tillage system to another.

Non-EU countries have not been considered in the analysis yet but will be included in an updated version.

4.3 Critical assumptions and uncertainties

One challenging aspect of the quantitative assessment of abatement costs in agriculture relates to the adequate apprehension of the variety of emissions sources and the complexity of interactions between them. Agriculture is the primary source of non-CO_2 emissions in the EU, and nitrous oxide (N_2O) and methane (CH_4) contribute approximately equally to total emissions from agriculture. GHG emissions involve both crop and animal producing activities. Therefore, and in contrast to other pollutants caused by agricultural activities, a wide range of farming activities is affected by the issue. Moreover, the sources of emissions are inter-related at the farm-level, leading to a variety of complementarities or substitutions and sources of potential leakages. Comprehensive assessments are thus needed in order to capture the net impact of a change in agricultural activities on emissions and abatement costs.

A second key-challenge consists in satisfactorily dealing with the heterogeneity of farmers with respect to farm management practices and environment parameters (Freibauer, 2003). Both emissions and abatement costs are highly sensitive to environmental, economic and technical parameters, such as spatial location, technological choices, output profitability, and input intensity. As a consequence, broadly averaged abatement cost estimates are of little significance for policy-relevant assessments of the impacts of mitigation instruments. The modelling approach chosen in this analysis helps to overcome these challenges.

5 Bioenergy

5.1 Brief description of abatement measures

Traditional biomass use for bioenergy, mainly in the form of fuelwood or dried dung, has long been the energy source for cooking and heating, and remains so for around one third of the population in many developing countries. However, solid or liquid biomass feedstock can be converted using numerous technologies to provide more convenient energy carriers in the form of solid fuels (e.g., wood chips, pellets, briquettes), liquid fuels (e.g., methanol, ethanol, biodiesel, bio-oil), gaseous fuels (synthesis gas, biogas, hydrogen) or direct heat (Figure 5.1).

Transportation fuels are currently produced mostly from fossil petroleum. Bioenergy comes from any fuel that is derived from biomass - recently living organisms or their metabolic byproducts. Like all methods used to generate energy, the combustion of biomass generates pollution as a by-product. Because the carbon in biofuels was recently extracted from atmospheric carbon dioxide by growing plants, the combustion of a biofuel does not however result in a net increase of carbon dioxide in the Earth's atmosphere.

Biofuels thus have a certain potential to decrease greenhouse gas emissions (Farrell *et al.*, 2006; Kim and Dale, 2006). Three different types of biofuel currently play a role in a global view, the so-called "first generation" fuels. These are ethanol, fatty acid methyl ester (FAME or biodiesel), and pure plant oil (PPO). All have reached a considerable state of the art in production and are commercially available (Bringezu *et al.*, 2007). Most of the worldwide biofuel production is ethanol, which is mainly produced in USA and Brazil from either corn or sugar cane. In Europe, potato, wheat or sugar beet is the common feedstock. While biodiesel is mainly located on the European market, PPO has only recently begun to enter the world markets as a biofuel.

The simplest biomass-biofuel conversion technology is the extraction of plant oils. The process requires cleaning and conditioning of feedstocks and the extracted oil. To use plant oils in combustion engines, conventional diesel engines have to be adapted. Another method uses chemical transesterification to produce biodiesel because plant oils differ in their properties (e.g., viscosity) from conventional fuels.

Biochemical transformation like ethanol or biogas production is based on fermentation. These processes represent technically relatively simple conversions. Depending on end-use biogas requires purification. Biogas is most often used for heat and electricity production (SRU, 2007).

The thermo-chemical transformation of biomass can be achieved through pyrolysis or gasification. Another pathway of bioenergy technology converts biomass to synthetic fuels (Biomass-to-Liquid, BtL). Such alternative processes ("second generation" processes) are still in a developmental stage (Kaltschmitt, 2001).

To study the potential effects of increased biofuel use, Farrell et al. (2006) evaluated six representative analyses of fuel ethanol. All studies indicated that current corn ethanol technologies are much less petroleum-intensive than gasoline, but have greenhouse gas emissions similar to those of gasoline. However, many important environmental effects of biofuel production are poorly understood. New metrics that measure specific resource inputs are developed, but further research into environmental metrics is needed. Nonetheless, it is already clear that large-scale use of ethanol for fuel will almost certainly require cellulosic technology.

Currently about 20 Mtoe per year of transport biofuels are produced globally, substituting for petroleum products. Production is projected to increase to 54 Mtoe by 2015 and 92 Mtoe in 2030. The additional biofuel production would come primarily from ethanol derived from energy crops (i.e., sugar and cereal grains). The share of land dedicated to biofuel production is therefore expected to increase from currently one percent of the world's available arable land (14 million hectares) to about 3 percent in 2030 (IEA, 2006).

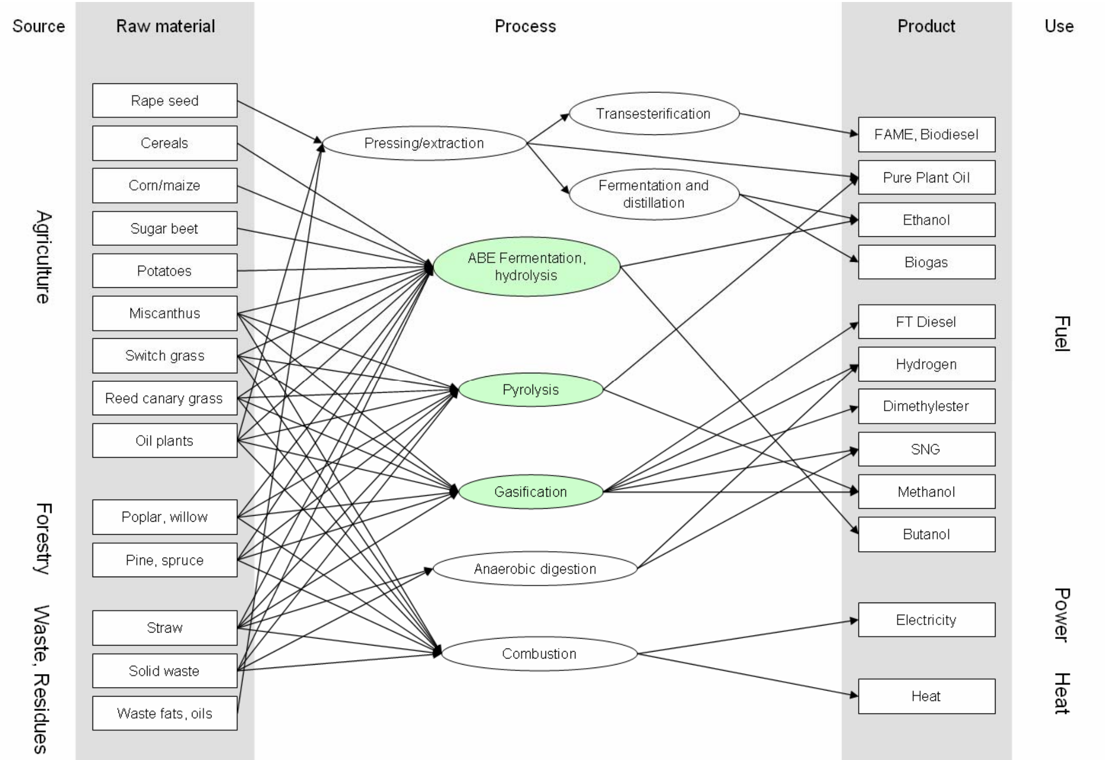

Figure 5.1: Bioenergy options overview (based on Woods and Bauen, 2003). Green ellipses describe processes related to second generation biofuel production.

5.2 Modelling approach

EUFASOM simulates detailed land use adaptations, market and trade equilibrium changes, and environmental consequences for political, technical, and environmental scenarios related to agriculture, forestry, and nature. The model has been applied to estimate the potential for bioenergy production. BIOFASOM is a partial equilibrium model that simulates resource allocations to the agricultural and forestry sectors over a specified number of optimization periods (Schneider *et al.*, 2008). While the Member States of the European Union are represented in more detail, the model also depicts non-EU regions covering the entire globe.

Likely land use responses to relevant political, societal, technical and environmental developments are determined through a constrained welfare maximization problem. The objective function maximizes economic surplus from all agricultural and forestry markets and includes the impact of policy incentives and disincentives. Technological restrictions and physical resource limitations are formulated as constraints. Model output consists of land use allocations and associated management intensities, regional resource usage, commodity supply, equilibrium market prices, and trade volumes of the agricultural and forest commodities covered in the model. The European version of FASOM is conceptually similar to a model developed at Texas A&M and other universities (Alig *et al.*, 1998).

EUFASOM is a bottom-up model and therefore data intensive. Technological options include agricultural and forest management alternatives, livestock production, bioenergy and forest industry processing. Agricultural data for conventional management options are group averages over detailed farm surveys within the Farm Accountancy Data Network (FADN). Cost differences for specific alternative agricultural management option are computed through engineering equations. Environmental impacts are simulated with the Environmental Policy Integrated Climate (EPIC) model – a biophysical process model which simulates crop growth (Schmid *et al.*, 2007). Bioenergy technology data are mainly taken from the European Non-Food Agriculture (ENFA) project. Forest management data are simulated with the OSKAR model (Franklin *et al.*, submitted). Forest industry data have been compiled in collaboration with the European Forest Institute (EFI) within the INSEA project. Agricultural and forest market data are extracted from FAOSTAT and the European New Cronos Database. Own-price-elasticities of demand are taken from Seale et al. (2003). Finally, land quality data are derived from a complex GIS analysis leading to homogenous response units as described in Skalsky (2008).

The objective function incorporates all major drivers for these changes, i.e. cost coefficients for land use and commodity processing alternatives, adjustment costs for major land use changes, market price changes for commodities and production factors, trade costs, political incentives and disincentives, and terminal values for standing forests.

$$
\text{Maximize WELF} = \sum_{t} \partial_t \cdot \left(\begin{array}{l}
\sum_{r,y} \left[\int_{y} \varphi^{DEMD}_{r,t,y} \left(\text{DEMD}_{r,t,y} \right) d(\cdot) \right] \\
- \sum_{r,y} \left[\int_{n} \varphi^{SUPP}_{r,t,y} \left(\text{SUPP}_{r,t,y} \right) d(\cdot) \right] \\
- \sum_{r,i} \left[\int_{n} \varphi^{RESR}_{r,t,i} \left(\text{RESR}_{r,t,i} \right) d(\cdot) \right] \\
- \sum_{r,j,v,c,u,q,m,p} \left(\tau^{\text{CROP}}_{r,t,j,v,c,u,q,m,p} \cdot \text{CROP}_{r,t,j,v,c,u,q,m,p} \right) \\
- \sum_{r,j,v,s,u,q,m,p} \left(\tau^{\text{PAST}}_{r,t,j,v,s,u,q,m,p} \cdot \text{PAST}_{r,t,j,v,s,u,q,m,p} \right) \\
- \sum_{r,j,v,b,u,q,m,p} \left(\tau^{\text{BIOM}}_{r,t,j,v,b,u,q,m,p} \cdot \text{BIOM}_{r,t,j,v,b,u,q,m,p} \right) \\
- \sum_{r,j,v,f,u,a,m,p} \left(\tau^{\text{HARV}}_{r,t,j,v,f,u,a,m,p} \cdot \text{HARV}_{r,t,j,v,f,u,a,m,p} \right) \\
- \sum_{r,j,v,f,u,a,m,p} \left(\tau^{\text{TREE}}_{r,t,j,v,f,u,a,m,p} \cdot \text{TREE}_{r,t,j,v,f,u,a,m,p} \right) \\
- \sum_{r,j,v,s,u,x,m,p} \left(\tau^{\text{ECOL}}_{r,t,j,v,s,u,x,m,p} \cdot \text{ECOL}_{r,t,j,v,s,u,x,m,p} \right) \\
- \sum_{r,l,u,m,p} \left(\tau^{\text{LIVE}}_{r,t,l,u,m,p} \cdot \text{LIVE}_{r,t,l,u,m,p} \right) \\
- \sum_{r,m} \left(\tau^{\text{PROC}}_{r,t,m} \cdot \text{PROC}_{r,t,m} \right) \\
- \sum_{r,l,m} \left(\tau^{\text{FEED}}_{r,t,l,m} \cdot \text{FEED}_{r,t,l,m} \right) \\
- \sum_{r,j,u,\{+,-\}} \left(\tau^{\text{LUCH}}_{r,t,j,s,u,\{+,-\}} \cdot \text{LUCH}_{r,t,j,s,u,\{+,-\}} \right) \\
- \sum_{r,\tilde{r},y} \left(\tau^{\text{TRADE}}_{r,\tilde{r},t,y} \cdot \text{TRAD}_{r,\tilde{r},t,y} \right) \\
- \sum_{r,e} \left(\tau^{\text{EMIT}}_{r,t,e} \cdot \text{EMIT}_{r,t,e} \right)
\end{array} \right)
+ \sum_{r,j,v,f,u,a,m,p} \left(\nu^{\text{TREE}}_{r,j,v,f,u,a,m,p} \cdot \text{TREE}_{r,T,j,v,f,u,a,m,p} \right) \tag{16}
$$

Mathematically, EUFASOM maximizes consumer surplus in final commodity markets plus producer or resource owner surplus in all price-endogenous factor markets minus technological, trade, adjustment, and policy related costs plus subsidies and terminal values. Future costs and benefits are discounted by an exogenously specified rate. The major variables are listed Table 5.1.

Table 5.1: Major variables in EUFASOM

Variable	Unit	Type	Description
CROP	1000 ha	≥ 0	Crop production
PAST	1000 ha	≥ 0	Pasture
LIVE	mixed	≥ 0	Livestock raising
FEED	mixed	≥ 0	Animal feeding
TREE	1000 ha	≥ 0	Standing forests
HARV	1000 ha	≥ 0	Forest harvesting
BIOM	1000 ha	≥ 0	Biomass crop plantations for bioenergy
ECOL	1000 ha	≥ 0	Wetland ecosystem reserves
LUCH	1000 ha	≥ 0	Land use changes
RESR	mixed	≥ 0	Factor and resource usage
PROC	mixed	≥ 0	Processing activities
SUPP	1000 t	≥ 0	Supply
DEMD	1000 t	≥ 0	Demand
TRAD	1000 t	≥ 0	Trade
EMIT	mixed	Free	Net emissions
STCK	mixed	≥ 0	Environmental and product stocks
WELF	1,000,000 €	Free	Economic Surplus

The technological pathways considered in this analysis are presented in Table 5.2. This study applies the EUFASOM model to estimate national bioenergy supply curves from member countries of the European Union. The purpose of these simulations is to provide input to the GAINS abatement modelling system. As a consequence, the simulated bioenergy supply curves are autarkic functions that include competition between domestic resources in each country but not competition between countries. To safeguard sustainable bioenergy production potentials, increases in food imports were not allowed. All national bioenergy supply functions represent increasing opportunity costs from increasing prices of food and timber products.

Table 5.2: Bioenergy processing pathways considered in EUFASOM simulations

Land use biomass options	Technological processes	Non-food product options	End use
Miscanthus, switchgrass	Gasification	Methanol	Bioenergy and biofuels
	Hydrolysis	Hydrogen, bioethanol	
	Fischer-Tropsch process	Fischer-Tropsch diesel	
	Combustion	Bioelectricity, bioheat	
Red canary grass	Pelletizing	Pellets	Fuel for combustion, co-firing, bioenergy
Willow	Combustion, combined heat and power	Bioelectricity, bioheat	Bioenergy
Cardoon	Pelletizing	Pellets, (bales)	Fuel for combustion, co-firing, bioenergy
Poplar	Pelletizing	Pellets, (chips)	Fuel for combustion, co-firing, bioenergy
Giant reed	Pelletizing	Pellets, (chips)	Fuel for combustion, co-firing, bioenergy
Eucalyptus	Pelletizing	Pellets, (chips)	Fuel for combustion, co-firing, bioenergy
Hemp, flax, kenaf		Straw and fibre products	Biomaterials
Maize, sugar beet, sugar cane	Fermentation process (oilseeds)	Bioethanol	Biofuel
Rape, sunflower	Esterification process	Biodiesel	Biofuel

5.3 Critical assumptions and uncertainties

It should be noted that model are rather sensitive against the boundary conditions for which the model instance is calibrated. Therefore findings are valid in the context of the settings that govern the simulations. All empirically obtained input data are subject to inherent uncertainties, which is transferred into the model. Possible changes in energy policy or technical progress concerning biofuel production can have a profound influence on the efficiency of incentives to produce biofuels.

References

Achard, F., H. D. Eva, P. Mayaux, H. J. Stibig and A. Belward (2004). Improved estimates of net carbon emissions from land cover change in the tropics for the 1990s. Global Biogeochemical Cycles **18**(2).

Alig, R. J., D. M. Adams and B. A. McCarl (1998). Impacts of Incorporating Land Exchanges Between Forestry and Agriculture in Sector Models. Journal of Agricultural and Applied Economics **30**(2): 389-401.

Benítez, P., I. McCallum, M. Obersteiner and Y. Yamagata (2004). Global Supply for Carbon Sequestration: Identifying Least-Cost Afforestation Sites Under Country Risk Consideration. International Institute for Applied System Analysis,

Benítez, P. C. and M. Obersteiner (2006). Site identification for carbon sequestration in Latin America: A grid-based economic approach. Forest Policy and Economics **8**(6): 636-651.

Böttcher, H. (2008). Forest Management for Climate Change Mitigation: Modeling of Forestry Options, their Impact on the Regional Carbon Balance and Implications for a Future Climate Protocol, Vdm Verlag Dr. Müller (September 2008).

Bringezu, S., S. Ramesohl, K. Arnold, M. Fischedick, J. v. Geibler, C. Liedtke and H. Schütz (2007). Towards a sustainable biomass strategy. What we know and what we should know. Wuppertal Paper no. 163 Wuppertal Institute for Climate, Environment and Energy,

Cerri, C. C., M. Bernoux, C. E. P. Cerri and C. Feller (2004). Carbon cycling and sequestration opportunities in South America: The case of Brazil. Soil Use and Management **20**(SUPPL.): 248-254.

Ciais, P., M. J. Schelhaas, S. Zaehle, S. L. Piao, A. Cescatti, J. Liski, S. Luyssaert, G. Le-Maire, E. D. Schulze, O. Bouriaud, A. Freibauer, R. Valentini and G. J. Nabuurs (2008). Carbon accumulation in European forests. Nature Geosci **1**(7): 425-429.

Davis, M. R. and L. M. Condron (2002). Impact of grassland afforestation on soil carbon in New Zealand: a review of paired-site studies. Australian Journal of Soil Research **40**(4): 675-690.

De Cara, S., M. HouzeÌ and P. A. Jayet (2005). Methane and nitrous oxide emissions from agriculture in the EU: A spatial assessment of sources and abatement costs. Environmental and Resource Economics **32**(4): 551-583.

De Cara, S. and P.-A. Jayet (2006). Mitigation of greenhouse gas emissions in EU agriculture: An assessment of the costs of reducing agricultural emissions and enhancing carbon sinks in agricultural soils. INSEA Final report SSP1-CT-2003-503614-Final. INRA and International Institute of Applied Systems Analysis (IIASA), Laxenburg, Austria,

De Koning, F., R. Olschewski, E. Veldkamp, P. Benítez, M. López-Ulloa, T. Schlichter and M. De Urquiza (2005). The ecological and economic potential of carbon sequestration in forests: Examples from South America. Ambio **34**(3): 224-229.

DeFries, R. S., C. B. Field, I. Fung, G. J. Collatz and L. Bounoua (1999). Combining satellite data and biogeochemical models to estimate global effects of human-induced land cover change on carbon emissions and primary productivity. Global Biogeochemical Cycles **13**(3): 803-815.

Dyson, F. J. (1977). Can we control the carbon dioxide in the atmosphere. Energy (UK) **2**: 287-291.

FAO (1997). Labor-intensive harvesting of tree plantations in the southern Philippines. FOREST HARVESTING CASE-STUDY 9. Bangkok, Thailand, RAP PUBLICATION. **1997/41**.

FAO (2005). Global Forest Resources Assessment 2005. 147, Food and Agriculture Organization of the United Nations, Rome, Italy, www.fao.org/forestry/site/fra2005/en

FAO (2006). Global Forest Resources Assessment 2005. Progress towards sustainable forest management., Food and Agriculture Organization of the United Nations, Rome,

Farrell, A. E., R. J. Plevin, B. T. Turner, A. D. Jones, M. O'Hare and D. M. Kammen (2006). Ethanol can contribute to energy and environmental goals. Science **311**(5760): 506-508.

FPP (1999). Holzernte in der durchforstung; Leistungszahlen Kosten - OeBF Seiltabelle Sortimentverfahren (SKM-TAB). Vienna, Austria, Kooperationsabkommen Forst-Platte-Papier.

Franklin, O., E. Moltchanova, M. Obersteiner, F. Kraxner, R. Seidl, H. Böttcher and D. Rokityiansky (submitted). A European scale forest growth and thinning model - deducing productivity and stand density from inventory data. Annals of Forest Science.

Freibauer, A. (2002). Biogenic Greenhouse Gas Emissions from Agriculture in Europe - Quantification and Mitigation. Institut für Landwirtschaftliche Betriebslehre, Universität Hohenheim: 180.

Freibauer, A. (2003). Regionalised inventory of biogenic greenhouse gas emissions from European agriculture. European Journal of Agronomy **19**(2): 135-160.

Freibauer, A., M. D. A. Rounsevell, P. Smith and J. Verhagen (2004). Carbon sequestration in the agricultural soils of Europe. Geoderma **122**(1): 1-23.

GGI Scenario Database. (2007). "International Institute for Applied System Analysis (IIASA) GGI Scenario Database, 2007. Available at: http://www.iiasa.ac.at/Research/GGI/DB/." 2007.

Gregorich, E. G., P. Rochette, A. J. VandenBygaart and D. A. Angers (2005). Greenhouse gas contributions of agricultural soils and potential mitigation practices in Eastern Canada. Soil and Tillage Research **83**(1 SPEC. ISS.): 53-72.

Guo, L. B. and R. M. Gifford (2002). Soil carbon stocks and land use change: A meta analysis. Global Change Biology **8**(4): 345-360.

Gusti, M., P. Havlik and M. Obersteiner (2008). Technical Description of the IIASA Model Cluster, The Eliasch Review; Office of Climate Change, UK [2008].

Harmon, M. E. and B. Marks (2002). Effects of silvicultural practices on carbon stores in Douglas-fir-western hemlock forests in the Pacific Northwest, USA: results from a simulation model. Canadian Journal of Forest Research-Journal Canadien de la Recherche Forestiere **32**(5): 863-877.

Hartsough, B. R., X. Zhang and R. D. Fight (2001). Harvesting cost model for small trees in natural stands in the Interior Northwest. Forest Products Journal **51**(4): 54-61.

Heston, A., Summers, R., Aten, B. (2006). Penn World Table Version 6.2, Center for International Comparisons of Production, Income and Prices at the University of Pennsylvania.

Höglund-Isaksson, L., W. Winiwarter and A. Tohka (2008). Potentials and costs for mitigation of non-CO_2 greenhouse gases in Annex I countries - Methodology. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria,

Houghton, R. A. and J. L. Hackler (2001). Carbon Flux to the Atmosphere from Land-Use Changes: 1850 to 1990. ORNL/CDIAC-131, NDP-050/R1. Carbon Dioxide Information Analysis Center, U.S. Department of Energy, Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A., http://cdiac.esd.ornl.gov/ndps/ndp050.html

Houghton, R. A. and J. L. Hackler (2003). Sources and sinks of carbon from land-use change in China. Global Biogeochemical Cycles **17**(2).

House, J. I., I. C. Prentice and C. Le Quere (2002). Maximum impacts of future reforestation or deforestation on atmospheric CO2. Global Change Biology **8**(11): 1047-1052.

IEA (2006). World Energy Outlook 2006. Paris, France, International Energy Agency (IEA).

ILO (2007). Occupational Wages and Hours of Work and Retail Food Prices, Statistics from the ILO October Inquiry.

IPCC (2001). Climate Change 2001: Mitigation. Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Cambridge University Press, UK,

Izaurralde, R. C., J. R. Williams, W. B. McGill, N. J. Rosenberg and M. C. Q. Jakas (2006). Simulating soil C dynamics with EPIC: Model description and testing against long-term data. Ecological Modelling **192**(3-4): 362-384.

Jandl, R., M. Lindner, L. Vesterdal, B. Bauwens, R. Baritz, F. Hagedorn, D. W. Johnson, K. Minkkinen and K. A. Byrne (2007). How strongly can forest management influence soil carbon sequestration? Geoderma **137**(3-4): 253-268.

Jiroušek, R., Klvač, R., Skoupy, A. (2007). Productivity and costs of the mechanised cut-to-length wood harvesting system in clear-felling operations. Journal of Forest Science **53**(10): 476-482.

Kaipainen, T., J. Liski, A. Pussinen and T. Karjalainen (2004). Managing carbon sinks by changing rotation length in European forests. Environmental Science & Policy **7**(3): 205-219.

Kaltschmitt, M. (2001). Grundlagen der Festbrennstoffnutzung - Begriffsdefinitionen. Energie aus Biomasse - Grundlagen, Techniken und Verfahren. M. Kaltschmitt and H. Hartmann. Berlin, Springer: 770.

Kim, S. and B. E. Dale (2006). Ethanol fuels: E10 or E85 - Life cycle perspectives. International Journal of Life Cycle Assessment **11**(2): 117-121.

Kindermann, G. E., M. Obersteiner, E. Rametsteiner and I. McCallum (2006). Predicting the deforestation-trend under different carbon-prices. Carbon Balance and Management **1**(1).

Kindermann, G. E., I. McCallum, S. Fritz and M. Obersteiner (2008). A global forest growing stock, biomass and carbon map based on FAO statistics. Silva Fennica **42**(3): 387-396.

Körner, C. (2003). Slow in, rapid out - Carbon flux studies and Kyoto targets. Science **300**(5623): 1242-1243.

Landesforstgarten-Vorarlberg (2008). Preisliste 2008. Landesforstgarten-Vorarlberg. Rankweil, Vorarlberg, Austria.

Liski, J., A. Pussinen, K. Pingoud, R. Makipaa and T. Karjalainen (2001). Which rotation length is favourable to carbon sequestration? Canadian Journal of Forest Research **31**(11): 2004-2013.

Marland, G. and S. Marland (1992). Should we store carbon in trees? Water, Air, and Soil Pollution **64**: 181-195.

McCarl, B. A. and T. H. Spreen (1980). Price Endogenous Mathematical Programming as a Tool for Sector Analysis. American Journal of Agricultural Economics **62**: 87-102.

MEA (2005). Millennium Ecosystem Assessment. Ecosystems and human well-being: Scenarios. Findings of the Scenarios Working Group., Island Press, Washington D.C.,

Mund, M. and E. D. Schulze (2006). Impacts of forest management on the carbon budget of European beech (Fagus sylvatica) forests. Allgemeine Forst Und Jagdzeitung **177**(3-4): 47-63.

Paul, K. I., P. J. Polglase, J. G. Nyakuengama and P. K. Khanna (2002). Change in soil carbon following afforestation. Forest Ecology and Management **168**(1-3): 241-257.

Paul, K. L., P. J. Polglase and G. P. Richards (2003). Predicted change in soil carbon following afforestation or reforestation, and analysis of controlling factors by linking a C accounting model (CAMFor) to models of forest growth (3PG), litter decomposition (GENDEC) and soil C turnover (RothC). Forest Ecology and Management **177**(1-3): 485-501.

Pussinen, A., T. Karjalainen, R. Makipaa, L. Valsta and S. Kellomaki (2002). Forest carbon sequestration and harvests in Scots pine stand under different climate and nitrogen deposition scenarios. Forest Ecology and Management **158**(1-3): 103-115.

Rokityanskiy, D., P. C. Benitez, F. Kraxner, I. McCallum, M. Obersteiner, E. Rametsteiner and Y. Yamagata (2007). Geographically explicit global modeling of land-use change, carbon sequestration, and biomass supply. Technological Forecasting and Social Change **74**(7): 1057-1082.

Sabine, C. L., M. Heimann, P. Artaxo, D. C. E. Bakker, C.-T. A. Chen, C. B. Field, N. Gruber, C. L. Quere, R. G. Prinn, J. E. Richey, P. R. Lankao, J. A. Sathaye and R. Valentini (2004). Current status and past trends of the global carbon cycle. SCOPE 62: The Global Carbon Cycle. C. B. Field and M. R. Raupach. Washington, Covelo, London, Island Press.

Sampson, R. N. and R. J. Scholes (2000). Additional Human-Induced Activities - Article 3.4. Special Report on Land-Use, Land-Use Change and Forestry. R. T. Watson, I. R. Noble, B. Bolin, N. H. Ravindranath, D. J. Verardo and D. D. J. Cambridge, Cambridge University Press: 182-248.

Sathaye, J. and D. Bouille (2001). Barriers, Opportunities, and Market Potential of Technologies and Practices. Climate change 2001: Mitigation. Contribution of Working group III to the Third assessment report of the Intergovernmental Panel on Climate Change. B. Metz, D. O., R. Stewart and P. J. Cambridge, Cambridge University Press: 345-398.

Schmid, E., S. D. Cara, J. Balkovic, R. Skalsky, D. Blank, U. A. Schneider and M. Obersteiner (2005). Environmental and economic impact analysis of alternative management practices in Baden-Württemberg. Technical report (Soil Thematic Strategy). European Commission (DG Environment) and IIASA, Laxenburg, Austria,

Schmid, E., J. Balkovic and R. Skalsky (2007). Biophysical impact assessment of crop land management strategies in EU25 using EPIC. Carbon Sink Enhancement in Soils of Europe: Data Modelling, Verification. JRC Scientific and Technical Reports. S. V., L. Montanarella and P. Panagos, European Communities 2007, Luxembourg: 160 - 183.

Schneider, U. A., B. A. McCarl and E. Schmid (2007). Agricultural sector analysis on greenhouse gas mitigation in US agriculture and forestry. Agricultural Systems **94**(2): 128-140.

Schneider, U. A., J. Balkovic, S. D. Cara, O. Franklin, S. Fritz, P. Havlik, I. Huck, K. Jantke, A. M. I. Kallio, F. Kraxner, A. Moiseyev, M. Obersteiner, C. I. Ramos, C. Schleupner, E. Schmid, D. Schwab and R. Skalsky (2008). The European Forest and Agricultural Sector Optimization Model - EUFASOM. Research Unit Sustainability and Global Change, Working Paper FNU-156, Hamburg, Germany, http://www.fnu.zmaw.de/fileadmin/fnu-files/publication/working-papers/wp156_eufasom.pdf

Seale, J., A. Regmi and J. Bernstein (2003). International Evidence on Food Consumption Patterns. ERS/USDA, Technical Bulletin No.1904, Washington, D.C, Skalsky, R., Z. Tarasovičová, J. Balkovič, E. Schmid, M. Fuchs, E. Moltchanova, G. Kindermann and P. Scholtz (2008). GEO-BENE global database for bio-physical modeling v. 1.0 - concepts, methodologies and data. The GEO-BENE database report., International Institute for Applied Systems Analysis (IIASA), Austria,

Smith, K. A. and F. Conen (2004). Impacts of land management on fluxes of trace greenhouse gases. Soil Use and Management **20**(SUPPL.): 255-263.

Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice, B. Scholes, O. Sirotenko, M. Howden, T. McAllister, G. Pan, V. Romanenkov, U. Schneider, S. Towprayoon, M. Wattenbach and J. Smith (2008). Greenhouse gas mitigation in agriculture. Philosophical Transactions of the Royal Society B: Biological Sciences **363**(1492): 789-813.

SRU (2007). Klimaschutz durch Biomasse. Sachverständigenrat für Umweltfragen (SRU), Berlin,

Stokes, B. J., D. J. Frederick and D. T. Curtin (1986). Field trials of a short-rotation biomass feller buncher and selected harvesting systems. Biomass **11**(3): 185-204.

Thuille, A. and E. D. Schulze (2006). Carbon dynamics in successional and afforested spruce stands in Thuringia and the Alps. Global Change Biology **12**(2): 325-342.

Trines, E., N. Höhne, M. Jung, M. Skutsch, A. Petsonk, G. Silva-Chavez, P. Smith, G.-J. Nabuurs, P. Verweij and B. Schlamadinger (2006). Integrating agriculture, forestry and other land use in future climate regimes: Methodological issues and policy options. WAB Report 500102002. Netherlands Environmental Assessment Agency, Bilthoven, the Netherlands,

Tubiello, F. N. and G. Fischer (2007). Reducing climate change impacts on agriculture: Global and regional effects of mitigation, 2000-2080. Technological Forecasting and Social Change **74**(7): 1030-1056.

UNECE (2005). European Forest Sector Outlook Study. United Nations Economic Commission for Europe / Food and Agriculture Organization of the United Nations, Geneva, Switzerland,

UNECE (2007). FOREST PRODUCTS ANNUAL MARKET REVIEW. 2006-2007. United Nations Economic Commission for Europe,

Wang, J., Long, C., McNeel, J., Baumgras, J. (2004). Productivity and cost of manual felling and cable skidding in central Appalachian hardwood forests. Forest Products Journal **54**(12): 45-51.

West, T. O. and W. M. Post (2002). Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. Soil Science Society of America Journal **66**(6): 1930-1946.

Wilkie, M. L., H. Abdel-Nour, C. M. Carneiro, P. Durst, D. Kneeland, P. D. Kone, C. F. L. Prins, C. Brown and T. Frisk (2003). Forest area covered by management plans: global status and trends. Unasylva **54**(214/215): 35-36.

Williams, J. R. (1995). The EPIC Model. Computer Models of Watershed Hydrology. V. P. Singh, Water Resources Publications, Highlands Ranch, Colorado: 909-1000.

Woods, J. and A. Bauen (2003). Technology Status Review and Carbon Abatement Potential of Renewable Transport Fuels in the UK. B/U2/00785/REP URN 03/982, DTI New and Renewable Energy Program, http://www.berr.gov.uk/files/file15003.pdf