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Estimating the costs of reducing CO₂ emission via avoided deforestation with integrated assessment modeling

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Abstract

Estimates for deforestation and forest degradation were shown to account for about 17% of greenhouse gas emissions. The implementation of REDD is suggested to provide substantial emission reductions at low costs. Proper calculation of such a costs requires integrated modeling approach involving biophysical impact calculations and estimation economic effects of these. However, only few global modeling studies concerning this issue exist, and the actual implementation can take many forms. This study uses the approach of assuming that non Annex-I countries protect carbon rich areas from deforestation, and therefore loose the opportunity to use it as agricultural area. The opportunity costs of reducing deforestation within the framework of REDD are assessed with the global economic model LEITAP and the biophysical model IMAGE. A key methodological challenge is the representation of land use and the possibility to convert forestry land into agricultural land as REDD policies might prevent the use of forest for agriculture. We endogenize availability of agricultural land by introducing a flexible land supply curve and proxy the implementation of the REDD policies as a shift in the asymptote of this curve representing maximal agricultural land availability in various regions in the world. In a series of experiments, increasingly more carbon rich areas are protected from deforestation, the associated costs in terms of GDP reduction are calculated with the economic model. The associated reduction in CO₂ emissions from land use change are calculated by the IMAGE model. From this series of experiments, abatement cost curves, relating CO₂ emission reduction to costs of this reduction, are constructed. The results show that globally a maximum CO₂ reduction of around 2.5 Gt could be achieved. However, regional differences are large, ranging from about 0 to 3.2 USD per ton CO₂ in Africa, 2 to 9 USD in South and Central America, and 20 to 60 USD in Southeast Asia.

Keywords: *REDD, (avoiding) deforestation, scenario analysis, carbon price, abatement curve, land supply, CGE, IMAGE, LEITAP.*

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1 Introduction

1.1 Emissions from deforestation and REDD

Deforestation and forest degradation accounted for about 17% of global greenhouse gas emissions in 2004 (Rogner et al., 2007). A large part of the emissions from deforestation and forest degradation take place in developing countries, where the share of deforestation related greenhouse gas emissions is estimated to be about 25% (Houghton, 2005). Deforestation is a complex process, with a wide range of drivers interacting across different scales (Geist and Lambin, 2002). Although deforestation dynamics vary between regions, agricultural expansion is recognized as one of the major proximate causes of deforestation in most regions (Geist and Lambin, 2002).

Despite the large contribution of deforestation in developing countries to global greenhouse gas emissions, they are not part of any climate treaty. Under the Kyoto protocol land use activities are incorporated for Annex I countries (LULUCF, limited to afforestation, reforestation and deforestation). At the COP 13 held at Bali (2007) mechanisms for Reducing Emissions from Deforestation and forest Degradation in developing countries (REDD) was put on the agenda of the United Nations Framework Convention on Climate Change (UNFCCC). “REDD strategies aim to make forests more valuable standing than they would be cut down, by creating a financial value for the carbon stored in trees” (UN-REDD). The United Nations REDD programme (UN-REDD) is in place since 2008 aiming at assisting developing countries to prepare and implement national REDD strategies¹. Going beyond the reduction of emissions from deforestation and forest degradation, REDD has been extended to the so-called REDD+, and includes then also conservation, sustainable management of forests and enhancement of forest carbon stocks. So far, there is no post-Kyoto climate treaty. So, REDD+ is not yet included in any climate treaty. However, without having a globally agreed financing mechanism for REDD+, REDD activities are carried out in a variety of ways in a variety of places. At the COP-16 in Cancun a REDD agreement has been achieved that encourages all countries to engage in activities aiming at halting and reversing forest loss, though important questions related to permanence, reference emissions, and financing are still open².

REDD mechanisms aim to create an incentive for developing countries to a more sustainable (land) development path and therefore reduce emissions. The actual implementation of these mechanisms can take many forms, ranging from international agreements between countries, bilateral agreements such as between Norway and Indonesia³, to smaller scale activities where project based initiatives at the sub-national or single land-owners level offer carbon credits.

Three cost elements can be distinguished related to REDD measures: opportunity costs, implementation costs and transaction costs. Opportunity costs result “from the forgone benefits that deforestation would have generated for livelihoods and the national economy” (WorldBank, 2011). These could be direct, on-site opportunity costs, indirect off-site opportunity costs, but also social-cultural opportunity costs, which are not easily valued in monetary terms. Implementation costs result from the efforts required to get forest protection in place. Transaction costs result from the efforts for all parties involved in a transaction of a REDD payment (establishing the REDD program, negotiating the costs, monitoring, reporting and verifying emission reductions). The transaction costs are different from the implementation costs, as by themselves, they do not reduce deforestation. (WorldBank, 2011). Many suggest that reducing deforestation is one of the most cost efficient ways to reduce carbon emissions (e.g. Agrawal et al., 2011; Strassburg et al., 2009). However, the costs of CO₂ emission reduction via REDD schemes is assessed in relatively few studies, some at the global scale, using modeling approaches (Kindermann et al., 2008; Sohngen and Sedjo, 2006;

¹ <http://www.un-redd.org/AboutUNREDDProgramme/tabid/583/Default.aspx>

² <http://unfccc.int/resource/docs/2010/cop16/eng/07a01.pdf#page=2>

³ http://www.regjeringen.no/upload/SMK/Vedlegg/2010/Indonesia_avtale.pdf

Strassburg et al., 2009), and some at local scales (Bellassen and Gitz, 2008; Grieg-Gran, 2006; Nepstad et al., 2007), often using some form of modeling framework also. However, the question of what mechanisms, and at what scale, may be effective and efficient in reducing deforestation remains largely unanswered. Most of the estimates of costs of REDD only include opportunity costs. In doing so, most studies assume single landowners to be the actors in a REDD framework. To assess costs for implementing REDD, they either evaluate the opportunity costs when reducing CO₂ emissions from deforestation, or explicitly assess a landowner's behavior under possible payments for REDD. However, the development of REDD strategies is more likely to take place on a national level, as this is the first stage of the UNFCCC REDD phase approach to implement REDD policies.

1.2 Objectives

In this paper we aim at estimating costs of REDD from the perspective of a REDD framework where countries are the principal actors. The methodology focuses on the economic income foregone by countries and regions as a result of the protection of carbon rich areas. Non-Annex I countries are assumed to protect carbon rich areas from deforestation, and thereby lose the opportunity to convert these areas to agricultural land. To our knowledge, this is the first assessment of REDD costs that takes the country perspective, rather than the perspective of the landowners.

2 Methods

2.1 Overview

In this study we performed a modeling experiment with a combination of the economic (computable general equilibrium) model LEITAP and the integrated, biophysical model IMAGE, which includes the carbon cycle and climate change effects from land-cover and land-use changes. Both models are described in more detail below. The modeling exercise was performed for the period 2005 - 2030.

A baseline scenario, developed for the OECD Environmental Outlook to 2050 (OECD, 2012) follows conventional wisdom and excludes specific climate policies, has been used as the point of reference for our calculations. Leaving all other assumptions unchanged from the baseline, a series of scenarios with increasing protection of carbon rich areas have been calculated. The stepwise exclusion of areas, ordered by decreasing carbon content per unit of area⁴, from agricultural expansion is based on a terrestrial carbon map calculated by IMAGE. These reductions in available area for potential agricultural expansion were used to constrain land availability in the LEITAP model via the so-called land supply curve (van Meijl et al., 2006). Under this additional constraint, the LEITAP model adjusts agricultural demand, trade and production, and calculates net GDP effects in each world region. Then, IMAGE assesses the CO₂ emissions from the conversion of forested land and other nature areas to agricultural land. The model set-up is outlined in Figure 1. Because of the model restrictions, forest degradation and (changes in) forest management were not taken into account in this study. By comparing both GDP and CO₂ emissions to the baseline, and then relating the GDP change to the reduction in CO₂ emissions, abatement cost curves for REDD were developed. Before describing the experimental setup in more detail, the models used and their interaction are presented.

⁴ The carbon content of each gridcell, relevant for the deforestation impact is estimated as the carbon in the above-ground biomass, and one quarter of the below-ground carbon stock.

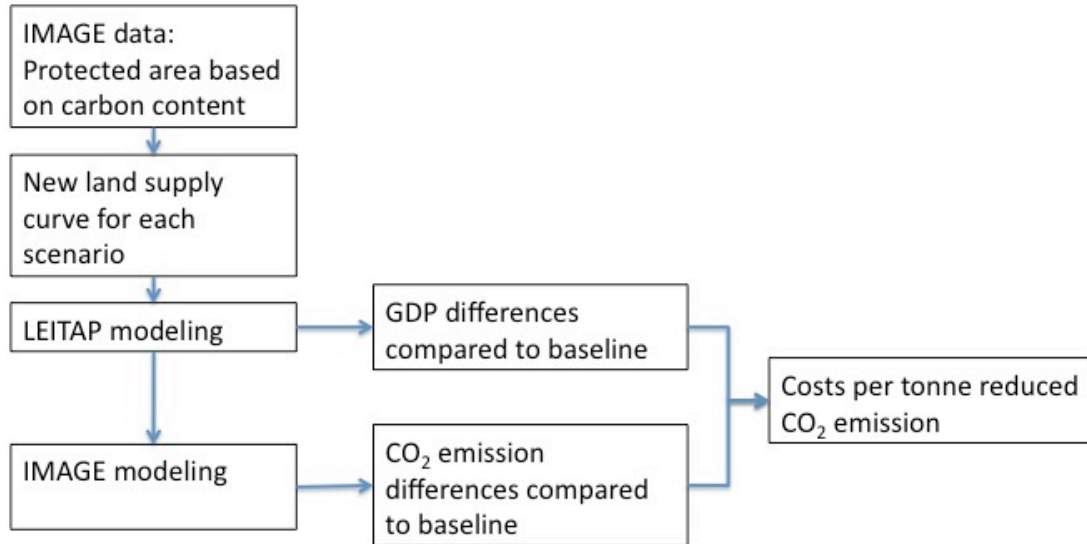


Figure 1: Overview of the method and the interactions between the models.

2.2 Models used

The LEITAP model and database

The LEITAP model is a multi-regional, multi-sectoral, static, applied general equilibrium model based on neo-classical microeconomic theory (Hertel, 1997). It is an extended version of the standard GTAP model (Nowicki et al., 2007; van Meijl et al., 2006), using a multilevel nested CES (constant elasticity of substitution) production function. In the primary value added nest, the multilevel CES production function describes the substitution of different primary production factors (land, labor, capital and natural resources) and intermediate production factors (e.g. energy and animal feed components). The CES nest is also introduced to allow for substitution between different energy sources including biofuels (Banse et al., 2011; Banse et al., 2008) and different animal feed components including biofuel byproducts. The model uses fixed input-output coefficients for the remaining intermediate inputs.

On the consumption side, the regional household is assumed to distribute income across savings and (government and private) consumption expenditures according to fixed budget shares. Consumption expenditures are allocated across commodities according to a non-homothetic dynamic CDE expenditure function, which allows for changes in income elasticities when purchasing power parity (PPP)-corrected real GDP per capita changes. Government expenditures are allocated across commodities according to fixed shares. The commodities consumed by firms, government and households are CES composites of domestic and imported commodities. In addition, imported commodities are differentiated by region of origin using Armington elasticities.

Regional endowments of labor, capital and natural resources are fixed and fully employed. Labor is divided into two categories: skilled and unskilled. These categories are considered imperfect substitutes in the production process.

Land and natural resources are heterogeneous production factors, and this heterogeneity is introduced by using a CET transformation function, which allocates these factors among the agricultural sectors. Capital and labor markets are segmented between agriculture and non-agriculture. Labor and capital are assumed to be fully mobile within each of these two groups of sectors, but imperfectly mobile across them. This leads to differences in prices of capital and labor between agriculture and non-agriculture. This is implemented by using a dynamic CET function where changes in capital and labor supply in agricultural and non-agricultural sectors depend on relative agricultural to non-agricultural remuneration of these factors and total factor supply.

In LEITAP, a technological change parameter is specified for each country. The country level technological change parameter is translated to sector and input factor specific technological change. The transformation equation allows on Hicks neutral technical change for each sector as well as factor on biased technical change. A treatment of technological progress embodied in land deviates from this approach. Agricultural yields growth is set independently from country specific technological parameter.

Base data for the LEITAP model come from version 6 of the GTAP data (Dimaranan, 2006). The GTAP database contains detailed bilateral trade, transport and protection data characterizing economic linkages among regions, linked together with individual country input-output databases which account for intersectoral linkages. All monetary values of the data are in \$US millions and the base year for version 6 is 2001. This version of the database divides the world into 88 regions. The database distinguishes 57 sectors in each of the regions. That is, for each of the 88 regions there are input-output tables with 57 sectors that depict the backward and forward linkages amongst activities.

The initial database was aggregated and then adjusted to implement two new sectors – ethanol and biodiesel – to represent biofuel policy in the model. These new sectors produce two products each: the main product and a byproduct. The ethanol byproduct is Dried Distillers Grains with Solubles (DDGS) and biodiesel byproduct - oilseed meals (BDBP)).

Furthermore, the LEITAP model distinguishes 45 regions, 26 sectors and 28 products. The sectoral aggregation includes, between others, agricultural sectors that use land (e.g. rice, grains, wheat, oilseed, sugar, horticulture, other crops, cattle, pork and poultry, and milk), the petrol sector that demands fossil (crude oil, gas and coal) and bioenergy inputs (ethanol and biodiesel) and biofuels production byproducts. The regional aggregation includes all EU-15 countries (with Belgium and Luxembourg as one region) and all EU-12 countries (with Baltic regions aggregated to one region, with Malta and Cyprus included in one region and Bulgaria and Romania aggregated to one region) and the most important countries and regions outside EU from an agricultural production and demand point of view.

Finally, the database was updated to 2010 to take into account the European Union enlargement, the Agenda 2000 reform and the 2003 CAP reform, together with the macro-economic development of the world economy. Also, the 2007 EU biofuel shares in transport were targeted.

IMAGE model

The IMAGE model is an integrated assessment model to study global environmental change (Bouwman and Kram, 2006; www.pbl.nl/image). It has been used extensively to study climate change and global climate policy strategies (e.g. van Vuuren et al., 2010), and has contributed to several global assessments and environmental outlooks (IAASTD, 2008; OECD, 2012; UNEP, 2002, 2007). The model consists of a global energy model (van Ruijven et al., 2007), an agricultural economy model (via the link to LEITAP (van Meijl et al., 2006) or IMPACT (Rosegrant et al., 2008)), a terrestrial ecosystem model that includes modules for land use, crop and livestock production, vegetation distribution, carbon dynamics, land use and livestock emission, and a simple climate model that calculates global climate change as a result of energy and land use emissions. In the context of this study, the terrestrial ecosystem model is most relevant and will be described in more detail. All processes are calculated on 0.5 degree spatial resolution, mostly with a time step of one year.

The agricultural model of IMAGE distinguishes pasture, seven crop groups and five animal categories. The productivity of cropland and pastures is calculated based on the Agro-Ecological Zone (AEZ) approach (Leemans and Van der Born, 1994). Starting from a land cover map based on satellite and statistical information historical land use change for the period 1970–2000 is calibrated to FAO statistics (FAO, 2007). From 2000 onwards, scenarios of agricultural demand, trade and production are either prescribed from sources like FAO, or obtained from an agricultural economy model linked to IMAGE, in this case LEITAP (see above). The agricultural production per world region is allocated to the land use map, following an assessment of land suitability based on distance to infrastructure, existing agriculture, and potential crop productivity (Alcamo et al., 1998). The land area needed to

meet the regional production depends not only on the domestic demand itself, but also on changes in crop and grass productivity, which are influenced by climate change, change in the location of agricultural area, and management. If the increase in production is larger than the increase in yields, agricultural area expands into natural vegetation, resulting in emissions of CO₂ and N₂O caused by this conversion, and other emissions associated with biomass burning. The CO₂ emissions from the conversion of natural areas depend on the vegetation type, and its carbon content in the vegetation and in the soil. The distribution of 14 natural land-cover types is computed with a modified version of the BIOME model (Prentice et al., 1992) on the basis of climate, soil and atmospheric CO₂ concentration. The terrestrial C cycle modeling in IMAGE as affected by changes in land cover and climate is described in detail elsewhere (Klein Goldewijk et al., 1994; Van Minnen et al., 2000).

Interaction LEITAP IMAGE

The interaction between the LEITAP and the IMAGE model is realized via a soft-coupling, whereby LEITAP provides regional production of agricultural commodities and the change in yields due to economically driven intensification to IMAGE. IMAGE allocates the required production within a region as described above. Both models use the same autonomous technological change as external input. The impact of climate change on crop yields is calculated in IMAGE and provided to LEITAP as an external change of agricultural productivity.

Modeling land availability in IMAGE and LEITAP

In LEITAP, the land market in each region is represented by a land supply function (Figure 2), which specifies the relation between land supply and the real land price. (Eickhout et al., 2009; Nowicki et al., 2009; van Meijl et al., 2006). A higher real land price is pushing up land supply closer towards the maximum available land area suitable for agriculture. The total land availability of agricultural land suitable for agriculture can change over time due to, e.g., increase of demand for land necessary for non-agricultural uses such as housing and infrastructure. Another cause could be land degradation, protection of natural areas, protection of forest or environmental protection of areas potentially suitable for agriculture. This process can be represented by an inward moving asymptote of the land supply function (Figure 4). Consequently, the asymptote of land supply function is treated not as the parameter of the model but as model variable that could be modified.

The land supply function is defined by the following formula:

$$P/PI = \alpha / [\exp\{\beta \cdot (A/LI - L/LI)\} - 1],$$

where L is land supply, P is the real land price, LI and PI are agricultural land area and the real land price in the initial situation (benchmark equilibrium) respectively, A is the land asymptote (or maximal potentially available agricultural land), and α and β are parameters of land supply function. Both α and β must be of the same sign (either both positive or both negative) to get P positive for all L. Also for all $P > 0$ land agricultural land use cannot go below zero. For given values of the parameters α and β , A is the asymptote (upper bound) on land use.

The parameters of the new land supply function are defined as variables of the model. They are automatically recalibrated to the initial equilibrium position when the asymptote is changed. To do this, we assume that the elasticity of land supply in respect of real land price in the neighborhood of initial equilibrium position is (approximately) equal to exogenous given value. So, the elasticity defines an “anchor” point of the land supply function. The land supply elasticities are taken from price Cixous (2006) for EU countries or derived from biophysical data from the modeling framework IMAGE (Eickhout et al., 2009).

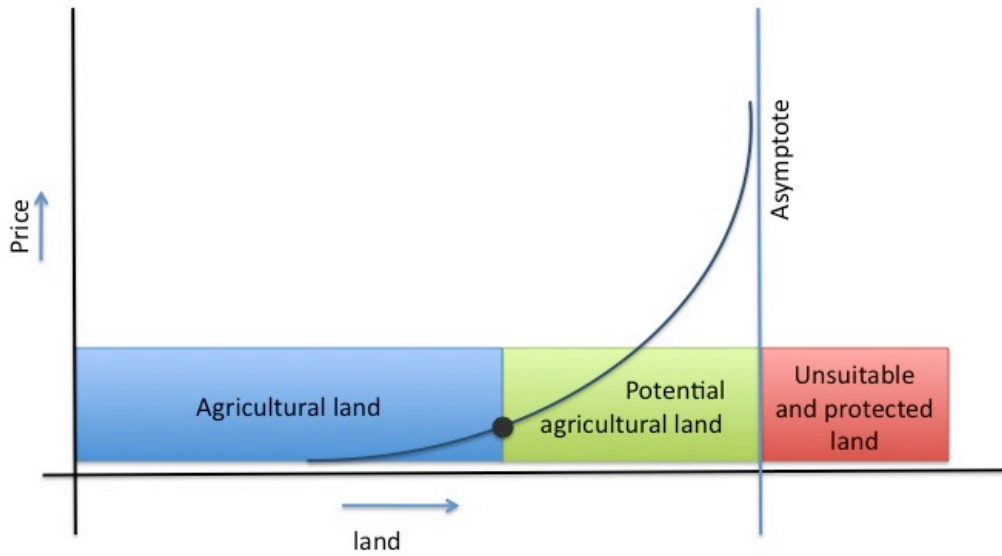


Figure 2: Land supply curve (after Eickhout et al. 2009).

With the land supply curve we endogenize availability of agricultural land. We proxy the implementation of the REDD policies as a shift in the asymptote for agricultural land in various regions in the world.

2.3 Design and implementation of the scenarios

Baseline

The baseline scenario is a no new policies scenario that depicts possible world development in the period 2010 – 2030 based on economic trends and under an assumption of no new policies. The expected GDP and population growth determines to a large extent the future demand for produced commodities and the supply of primary production factors. Furthermore, labor and capital availability together with technological progress determine the production possibilities.

The baseline scenario assumes the macroeconomic development as used by the OECD Environmental Outlook to 2050 (OECD, 2012). The world GDP is assumed to grow by 3.1% per year, and the population by 0.9% per year on average during the period 2010-2030. Conforming to stylized facts of long-term economic growth, capital is assumed to grow at the same rate as GDP and long term employment growth is equal to population growth. The baseline scenario assumes no policy changes and no new policies in the simulation period, but only applies existing policies and those agreed upon for the future, such as milk quota abolition in EU or the mandatory biofuel targets.

The economic and population developments differ between countries and regions (Figure 3). Real GDP growth in most of the developing countries is higher than 3.5% per year while the economic growth in developed economies does not exceed 2.6% per year. The highest population growth - 2% per year - is projected in Sub-Saharan Africa (SSA, see Annex 2 for regional aggregation and abbreviations). Population of North Africa and Middle East (NAFME), India (INDIA+) and Oceania (OCEA) is growing more than 1% while in the

remaining regions the population is growing slower than the world average, and in Former Soviet Union (FUSSR) the population even slightly decreases by 0.05% per year. The combined effect of rising income per capita and population growth in developing countries drives up the demand for agro-food products in these regions.

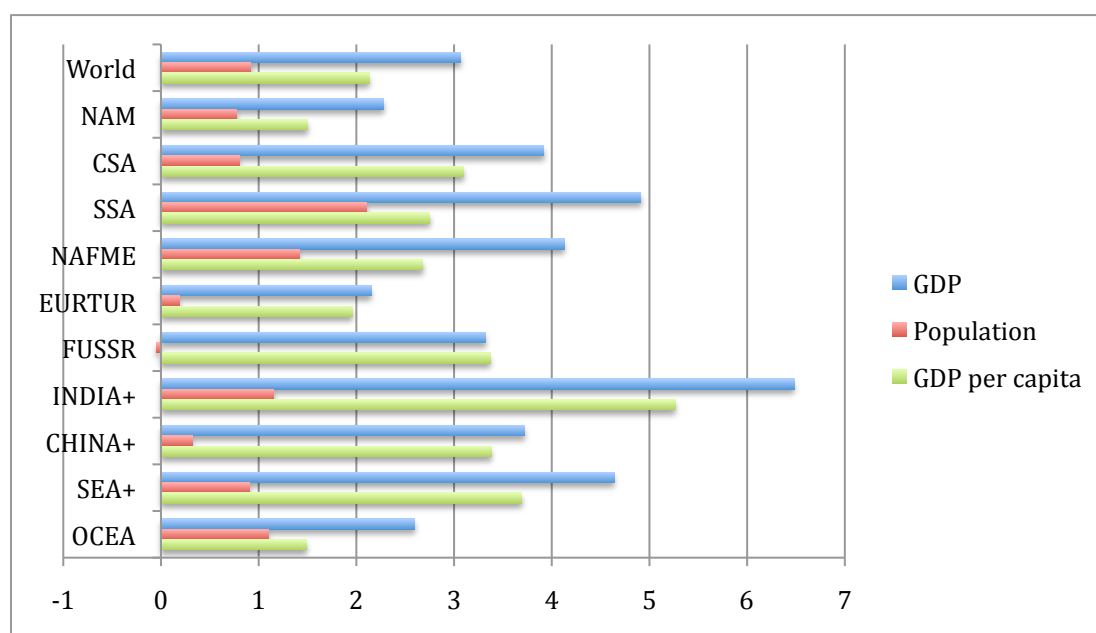


Figure 3. Macro-economic assumptions – average yearly growth rates of GDP, population and GDP per capita in 2010 - 2030. (See for the regional aggregation Annex 2).

In the calibration stage in LEITAP, exogenous GDP targets are achieved by endogenously determined technical progress given the exogenous estimates on factor endowments - skilled labor, capital and natural resources - and population. This technological change is in turn exogenous in the baseline and simulation experiments.

The yield improvements are derived from FAO information on future yields development (Bruinsma, 2003) and land availability comes from IMAGE. Globally, agricultural yields increase by 1.7% per year. For Sub-Saharan Africa, North Africa and Middle East and China yields growth are expecting to increase faster than the world average whereas in other regions lower than 1.5% per year growth is predicted (Table 1).

Table 1: Exogenous yields growth and land availability in baseline scenario.

	Average yearly yields growth rates in 2010 - 2030	Share of current agricultural land in total available land (%) in 2010
World	1.7	58
NAM	0.9	37
CSA	1.4	47
SSA	2.3	61
NAFME	2.3	99
EURTUR	0.9	81
FUSSR	0.8	44
INDIA+	1	99
CHINA+	2.2	90
SEA+	1.3	34
OCEA	1.3	72

Worldwide, only 58% of available agricultural area is used according to biophysical IMAGE data, North Africa and Middle East (NAFME), Europe (EURTUR), India (INDIA+) and China (CHINA+) use more 80% of their agricultural land. In the remaining regions, the agricultural land still can increase significantly into natural land, such as forests.

REDD scenarios

In order to study the cost effects of REDD measures, a series of scenarios have been developed, indicated as a, b, c, d, e, f, g, q and s. In these scenarios all but one model input are the same as in the baseline scenario. The parameter that is altered is the area of protected carbon-rich land in both IMAGE, in the form of protected area maps, and LEITAP by adjusting the land supply curves. Part of the land that is potential agricultural area in the baseline is protected additionally in the REDD scenarios.

Maps of protected carbon-rich land were developed using maps of terrestrial carbon stocks from the IMAGE model. 100% of the aboveground carbon and 25% of soil carbon (Searchinger et al., 2008) was included in the total terrestrial carbon stock calculation. Then in the experimental scenarios increasingly more carbon rich areas (Figure 6, Annex 1) are protected from deforestation starting with the least protection in scenario a and the most protection in scenario s. The protected areas of high carbon content identified in IMAGE are assumed to be not available for agricultural expansion. Per region (i.e. IMAGE modeling region) this restricted land availability was determined from these maps. This reduced availability of agricultural land was implemented in the LEITAP economic model through the land supply curve. Subsequently, the baseline model was re-run with this new land availability. The implementation of the extra restriction in the land supply curve is schematically depicted in Figure 4. The percentage of potentially available agricultural land that is additionally protected per region is shown in Figure 5. The associated carbon stocks protected in the scenarios a to s are presented in Figure 6. The exact figures of area and carbon that is protected in the scenarios is in Annex 2.

So, from Figure 4 and 5 one can see the relation between the carbon maps from the IMAGE database with the constraint on agricultural land in LEITAP. In Figure 4 'b-y' and 'b-x' show the extra land that is protected in a scenario, calculated from the terrestrial carbon content maps. In Figure 5 this is expressed as percentage of the original 'potential agricultural area in the baseline', which is the green area in Figure 2 and 4. The additional restriction results in a new equilibrium with different land use, land prices, consumption, production. Subsequently, this information was used in IMAGE by allocating land use with the new protected area map and the altered land use demand from LEITAP.

Comparing Figure 5 and 6 one can see that the regions with most protected carbon are not the same as the regions with the highest percentage of land protected. This is because not all land has the same carbon content. Because the method aims at protecting land in order of its carbon content, a higher percentage of the land in Southeast Asia (high carbon content) is protected than land in Sub-Saharan Africa (lower carbon content). Additionally, the total land area available for conversion to agriculture is very different in each region. This makes comparison between Figure 5 and 6 not useful. Figure 5 gives an indication of the land availability and restriction. Figure 6 gives an indication of total carbon under protection.

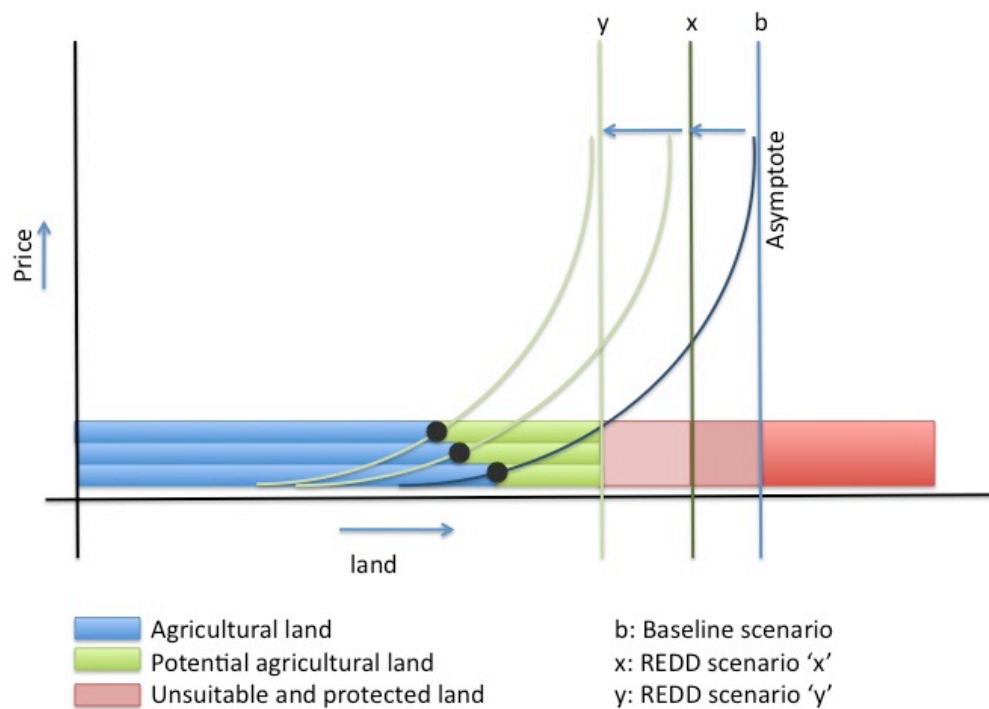


Figure 4: Schematic land supply curve adjustments.

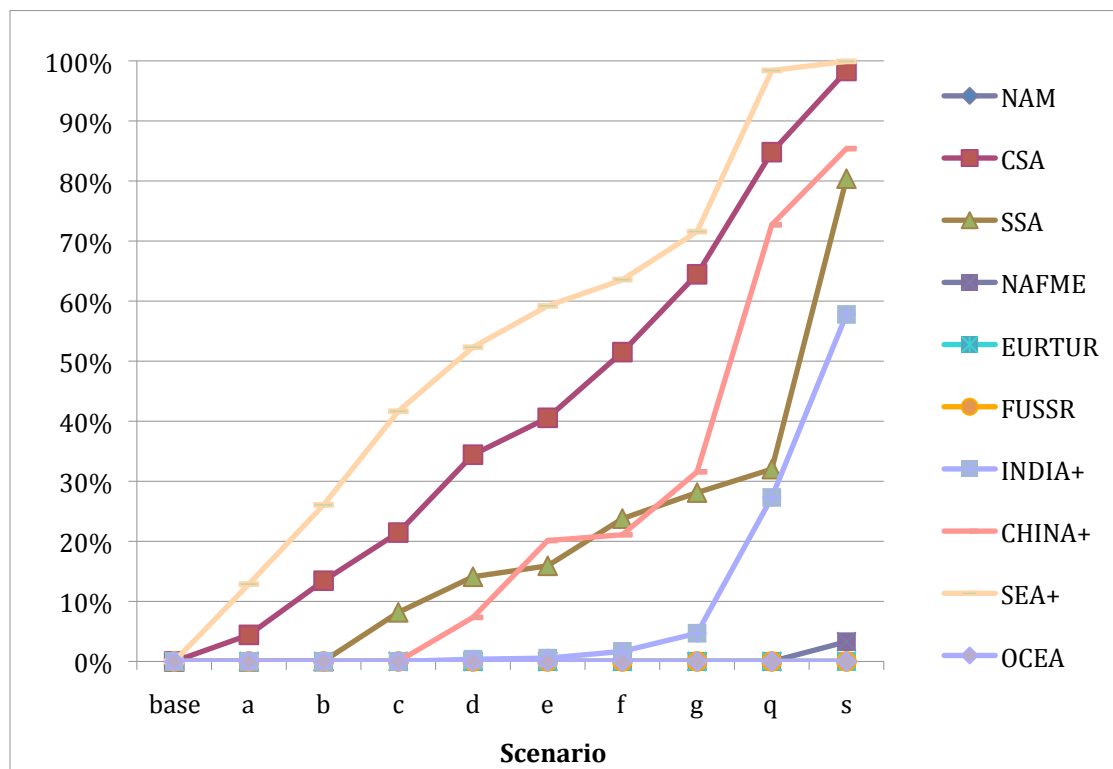


Figure 5: Percentage of the land reserve (natural land that could potentially be used as agriculture) that is protected in the scenario. (See for the regional aggregation Annex 2).

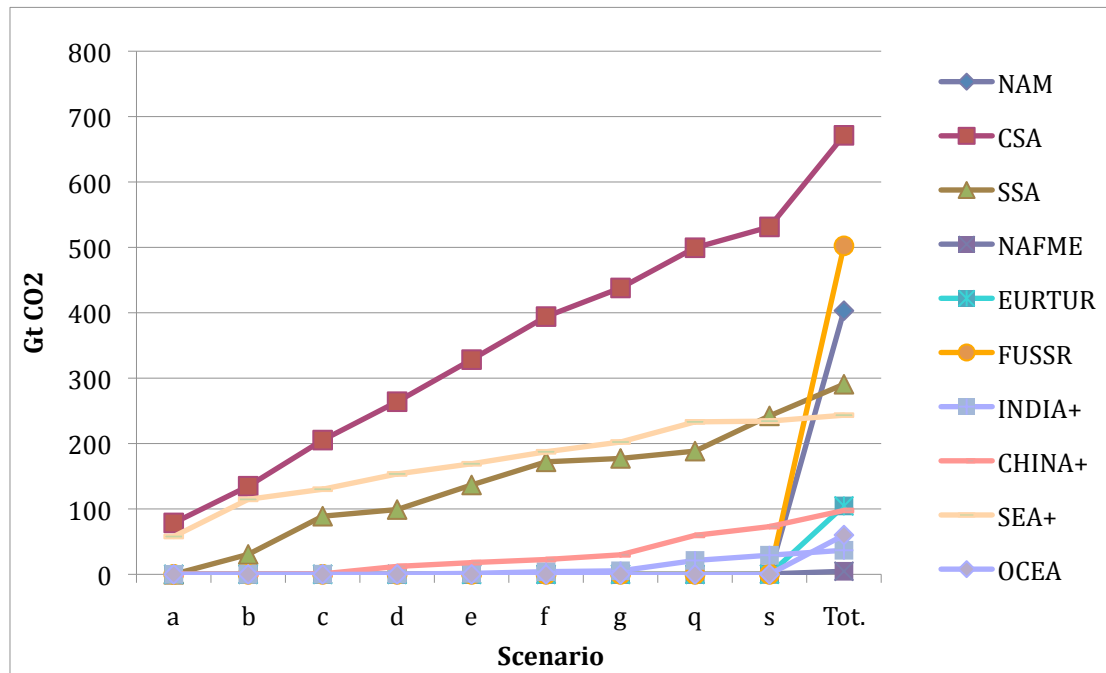


Figure 6: Total terrestrial carbon in the protected areas (expressed in CO₂) per scenario and the total level (Tot.) of all carbon present in the potential agricultural areas. (See for the regional aggregation Annex 2).

As a result of the reduced land availability, GDP is reduced in the respective countries. The cost associated with the REDD in terms of GDP reduction are calculated by comparing GDP from the baseline with the GDP in the REDD scenarios. These changes in GDP are considered as the costs of the REDD measures. For this GDP loss countries could be compensated. Furthermore, agricultural production and land productivity are affected.

The reduction in GHG emissions associated with protection of high carbon areas in each scenario experiment is calculated by the IMAGE model. They follow from land use changes has been calculated by IMAGE, which was fed from of LEITAP with regional production and productivity changes calculated. In IMAGE the same maps of protected high carbon areas are used to prevent carbon rich land from being converted into agriculture in the spatial explicit calculations.

From this series of experiments, abatement cost curves, relating CO₂ emission reduction to costs of this reduction, are constructed. For the 2005-2030 we calculate the cost per ton CO₂ as the average of the 25-year period by dividing the cumulative GDP losses by the cumulative CO₂ reductions.

3 The impact of REDD scenarios

3.1 Baseline results

The baseline scenario shows 11% increase in agricultural land between 2010 and 2030 (Figure 7), whereby Sub-Saharan Africa (SSA) and Southeast Asia (SEA+) show the highest growth in total agricultural land use. The high availability of agricultural land from the supply side and high per capita income and population growth from the demand side are important determinants of this increase. In these regions agricultural land can still be expanded without leading to a high increase in the rental rate for land. The low level of income and high-income elasticities of consumption accompanied by high-income growth stimulates consumption increase. Additional demand for agricultural products comes also from biofuel sector since the biofuel directive is in place in many regions. The significant agricultural land increase in North America is mostly driven by domestic and foreign demand for biofuel crops. High

availability of agricultural land makes and highly world market oriented agricultural sector make this increase possible.

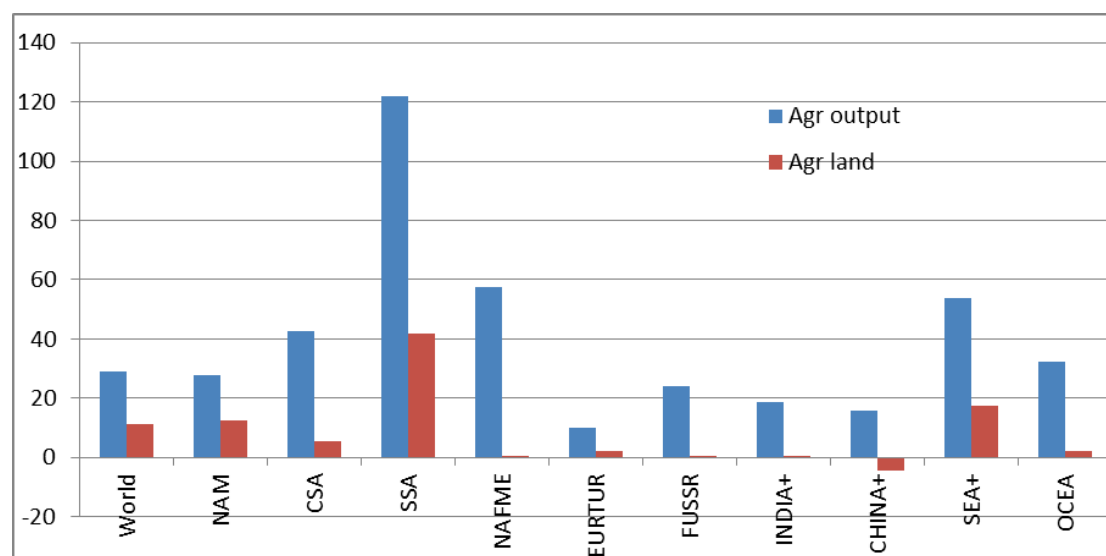


Figure 7: The agricultural output and land increase in % in 2010 – 2030 for the baseline scenario. (See for the regional aggregation Annex 2).

In the baseline in 2030 the agricultural land expansion leads to (further) significant deforestation in Central and South America (CSA) and Southeast Asia (SEA) and Sub-Saharan Africa (SSA). This can be seen from Figure 8 below as the agricultural land used in 2030 (red bars) is larger than the available non-forest no wood lands (i.e. larger than 100%). In these Non-Annex I regions, therefore the most pronounced impact of REDD is expected as protecting the forest and wood land limits the growth possibilities of agricultural land use in these countries. North America, Europe and Oceania have the most significant no forest and wood land reserves which can be converted to agricultural land when forest in Non-Annex I will be protected.

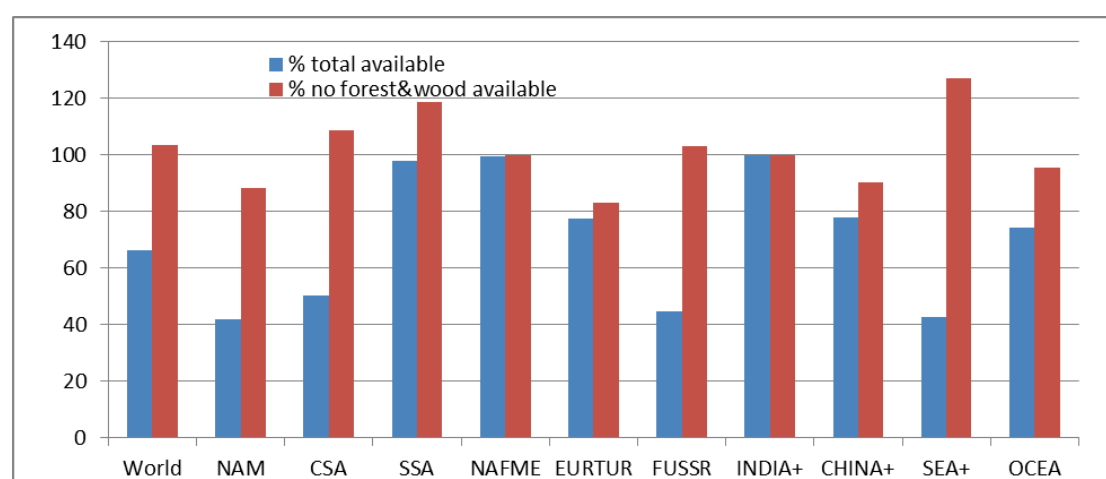


Figure 8: Availability of new agricultural land in the baseline scenario in 2030 as a percentage of total available land in 2001 (blue bar) and 2001-2030 agricultural expansions as a percentage of land that is not covered by forests and wood (red bar) in 2001. If the red bar is larger than 1 than we observe deforestation in the baseline and scenarios that protect the forest and woods limit agricultural production.

The increase of agricultural land already accounts for significant yields improvement assumed in the baseline. This is especially the case in Central and South America, Sub-Saharan Africa and North Africa and the Middle East.

Emissions from land use change are mainly due to conversions from forest into agriculture. Figure 9 depicts the locations of deforestation in the baseline. Although there is quite some non-forested area available in developed countries there is also deforestation projected in the baseline. Emissions from land use change in the baseline scenario are modeled to be 125 Gt CO₂ globally between 2005 and 2030. For Central and South America (CSA), Southeast Asia (SEA+) and Sub-Saharan Africa (SSA) the baseline emissions from land use are 42, 11 and 65 Gt CO₂, respectively, for the same period. The maximum possible emission reductions from REDD that could be realized are these baseline emissions.

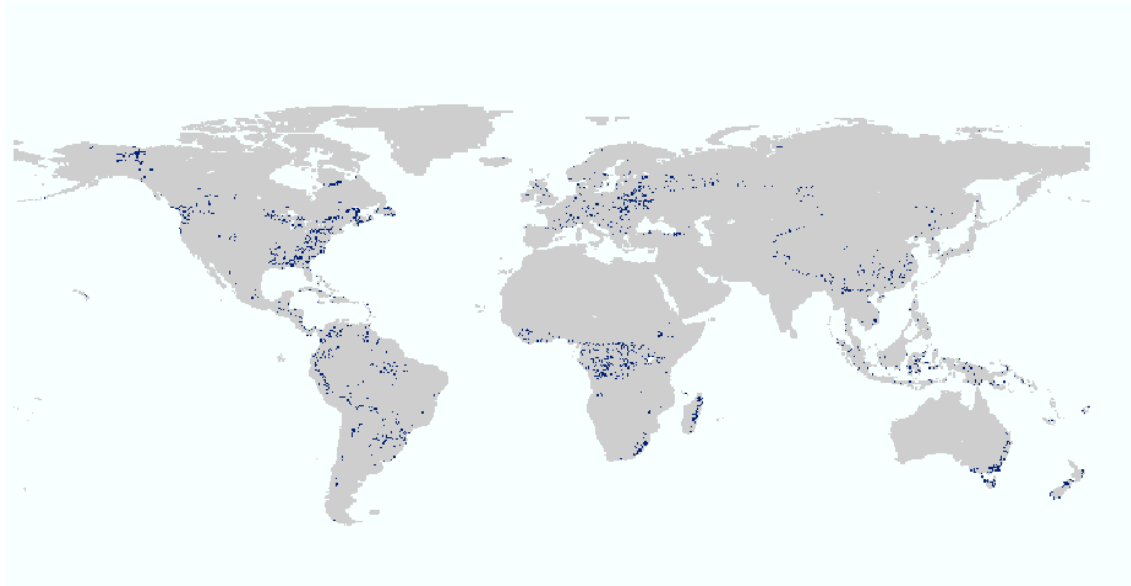


Figure 9: Deforestation, in blue, between 2005-2030 in the baseline scenario.

3.2 REDD scenarios and REDD cost curves

Agricultural land

The land constraints imposed on the model in the different scenarios lead in the first instance to lower land availability and therefore to lower agricultural land use compared with the baseline scenario. As expected, the agricultural land is decreasing in Non-Annex I countries and also globally. In the most restricted scenario (scenario s), assuming 91% of global terrestrial carbon protection, world agricultural land decreases by 11% in 2030 compared to the baseline (Figure 10). The most affected regions are Sub-Saharan Africa (SSA) and Southeast Asia (SEA+) where agricultural land use in 2030 is 35% and 26% lower (Figure 10), respectively, in scenario s compared to baseline in 2030. In absolute terms the two main regions where agricultural land is decreasing are Sub-Saharan Africa (SSA) and Central and South America (CSA) by 6.4 million and 1.3 million square kilometers respectively in scenario s compared to the baseline in 2030. The highest increase of agricultural land in relative (17%, see Figure 10) and absolute terms (0.9 million square kilometers) is expected in North America (NAM).

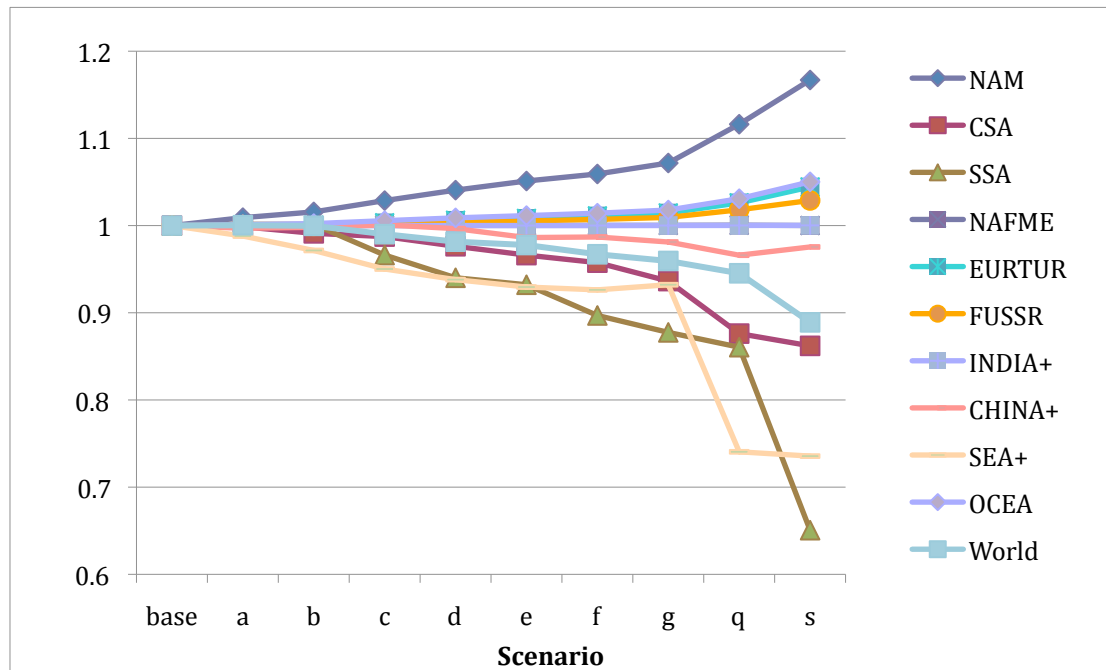


Figure 10: Fraction agricultural land in 2030 relative to the baseline scenario (baseline in 2030 = 1) resulting from different levels of terrestrial carbon protection (a to s)

GDP

Restricting land from being used for economic purposes such as agriculture has a visible effect on the economy in Non-Annex I countries. Protecting carbon rich areas from deforestation leads to reduced availability of land. Also, since carbon rich areas are often on fertile and potentially productive areas, the protection of these areas results in expansion of agricultural activities to less productive land. Therefore, reduced availability of this primary production factor cause often significant GDP reduction in Non-Annex I countries (Figures 11 and 12).

The results show that land use and GDP changes in Non-Annex I countries are strongly correlated. Compared with the baseline scenario, the strongest percentage reductions of GDP, about 2% in the most restricted scenario s, are observed in Sub-Saharan Africa and Southeast Asia.

Since increases of GDP in Annex I countries is negligible, worldwide GDP decreases gradually when more carbon rich areas are protected. In the most restricted scenario s, the world GDP decreases by about 0.24% or by 177 bln (2001 USD) in 2030 compared with the baseline scenario (Figures 11 and 12). The absolute GDP losses are highest in Southeast Asia (SEA+) (54 bln, USD 2001 in scenario s, which is 2.2%). Sub-Saharan Africa (SSA) has a GDP loss of 27 bln (2%) and Central and South America (SEA) have a GDP loss of 28 bln (0.5%).

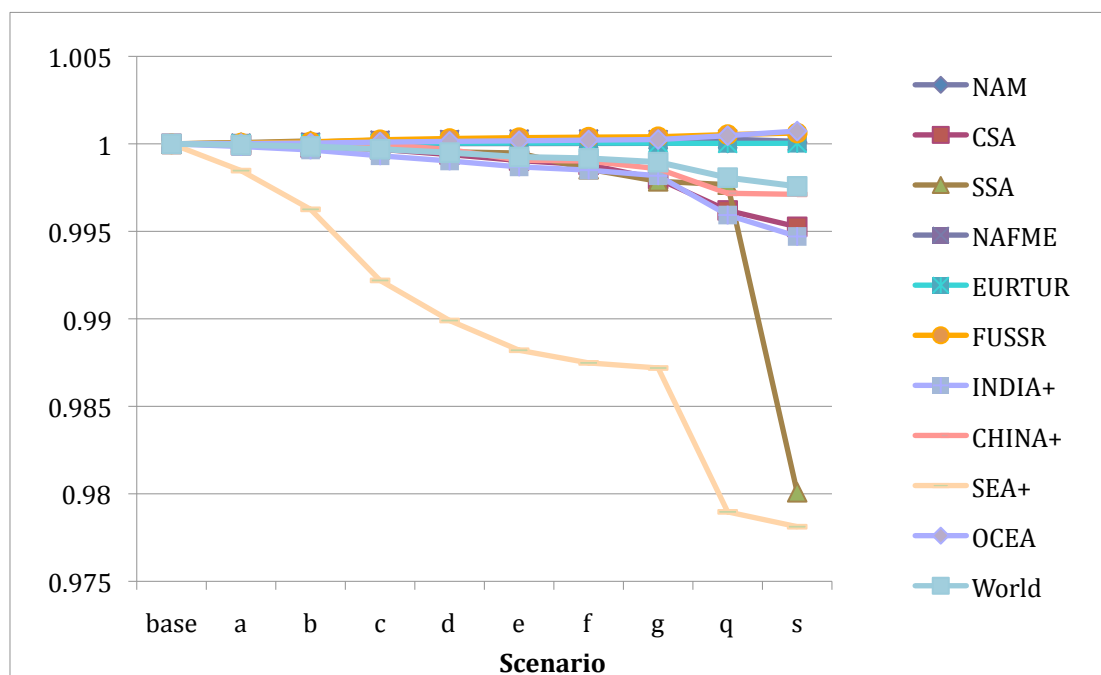


Figure 11: GDP changes in 2030 relative to the baseline scenario (land use = 1) resulting from different levels of terrestrial carbon protection.

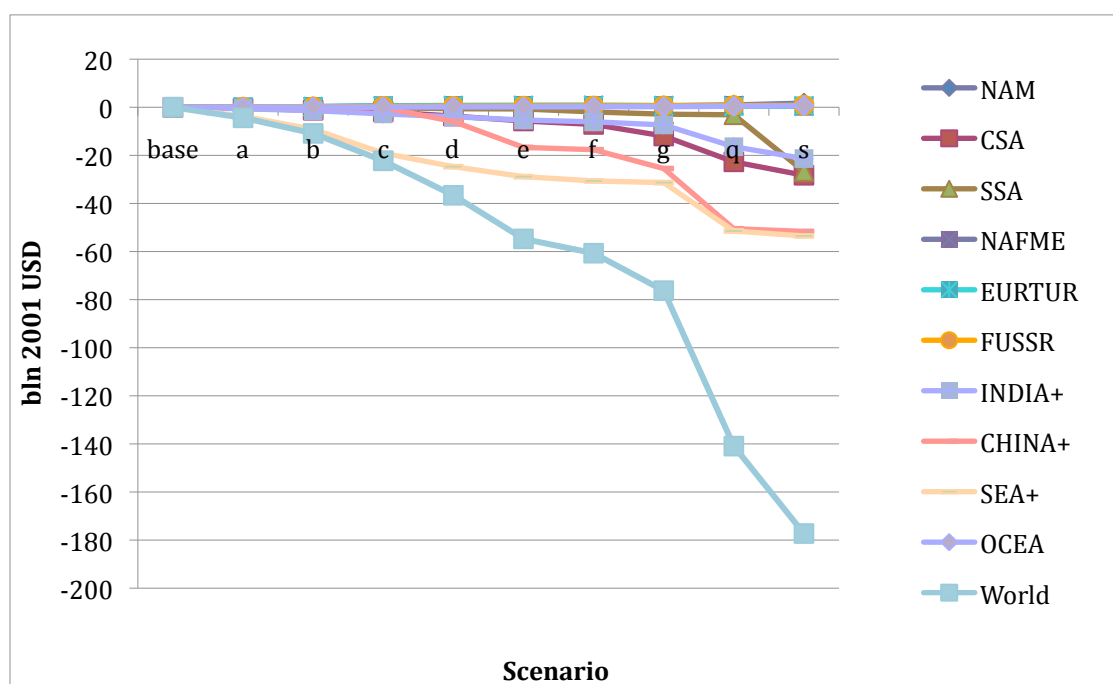


Figure 12: GDP differences in 2030 relative to the baseline scenario in bln 2001 USD.

Carbon emissions

Figure 13 shows the cumulative reduction in carbon emissions from land use in the series of scenarios. By protecting more forests in Non-Annex I countries less carbon from land use sources is emitted. Between 2005 and 2030 the emission reduction relative to baseline becomes larger each year. This is possible because the baseline emissions show yearly land use emissions between 2005 and 2030. The other way around, if the baseline would not show yearly emissions from land use from a certain year onwards the cumulative reductions cannot increase either.

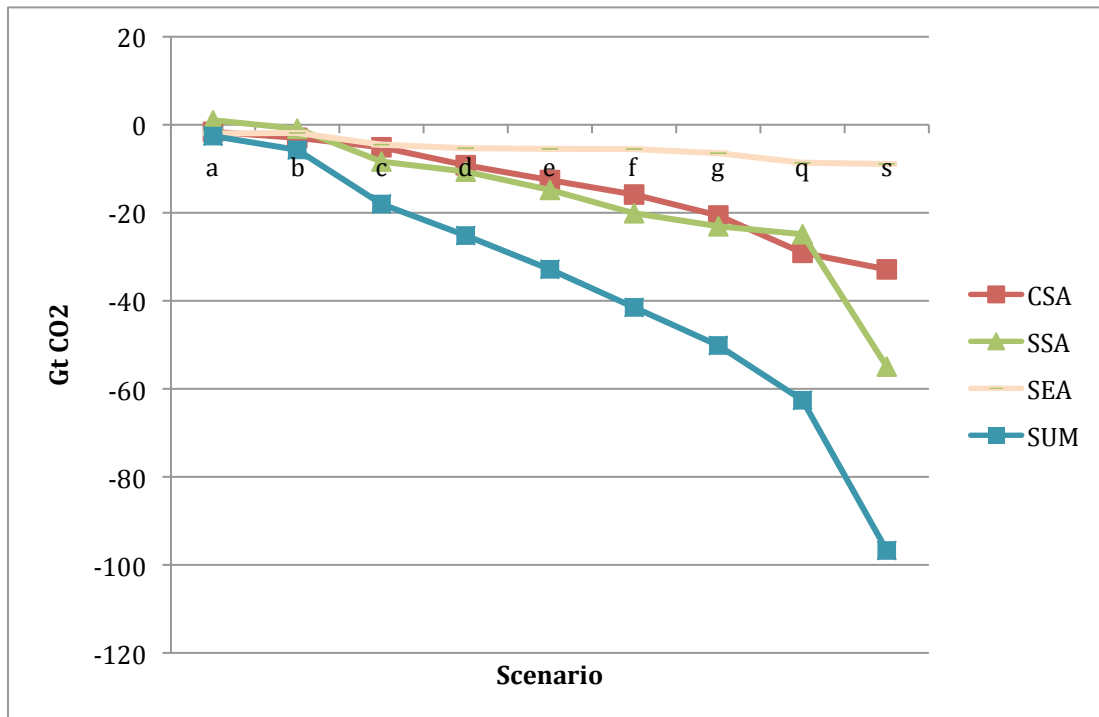


Figure 13: Absolute difference in global emissions from land use change compared to baseline under the various protection regimes (Gt CO₂) for SEA+, CSA, SSA and the sum of these 3 regions (Cumulative between 2005 and 2030).

The emission reductions are not equally distributed over the regions. Southeast Asia (SEA+) and Central and South America (CSA) dominate scenarios (a) and (b), from then CSA and Sub-Saharan Africa (SSA) have a similar share and SEA reduces less, mainly because most areas are already protected. In the final scenario s SSA reduces most, mainly because large areas are protected extra (see Figure 5).

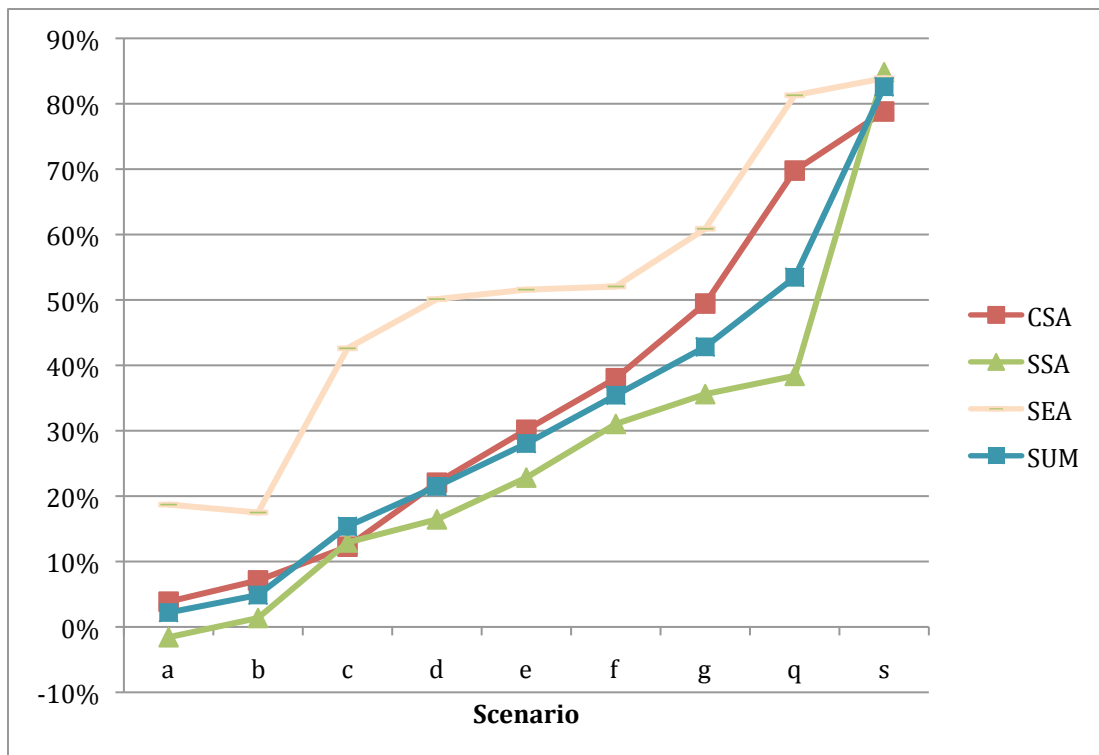


Figure 14: Emission reduction as percentage of the emissions in the baseline.

Abatement cost curves for REDD

By dividing average yearly GDP losses (\$/yr) by the average annual carbon savings (in ton CO₂/yr) we calculate the average price per tonne CO₂, for each scenario over the period 2005-2030. These “data points” are then used to construct so called “marginal abatement cost curves” (MACs), relating a CO₂ price to the abatement level.

Figure 15 shows the relation between average yearly carbon savings from land use and the price per ton CO₂ based on lost GDP, using the scenarios as data points. The scenarios a, b, c, d, e, f, g, q, s form together the abatement cost curve for REDD, showing an increasing price with increasing carbon savings. The cost curves have an asymptote, which is the maximum amount of carbon that can be saved (all carbon that is yearly emitted in the baseline).

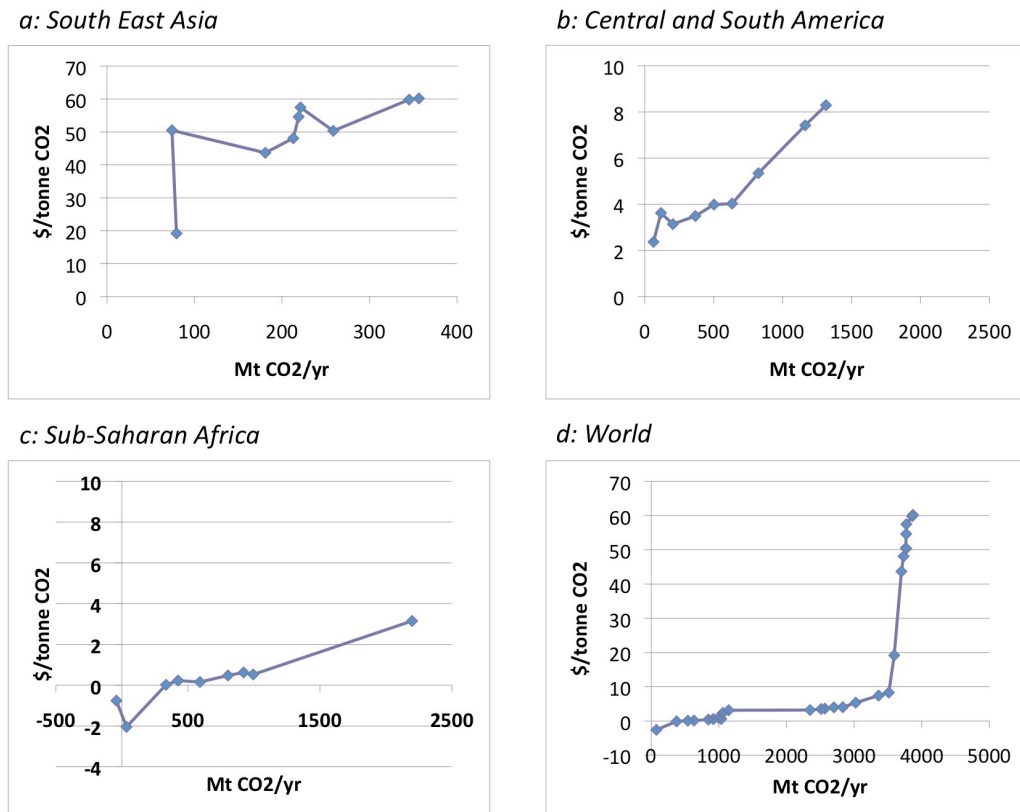


Figure 15: Average abatement cost curves for REDD 2005-2030, a: Southeast Asia, b: Central and South America, c: Sub-Saharan Africa, d: abatement curve for the world, composed of the average abatement curves of Central and south America, Africa and Southeast Asia.

Between the regions large differences occur. Central and South America (CSA) shows prices between 2 and 9 dollar per ton CO₂. Southeast Asia (SEA+) shows significantly higher prices between 20 and 60 US dollar per ton. As we saw earlier, the relative area that is protected in SEA is much higher than in CSA. Expansion of agricultural crops is difficult, causing prices to rise and also production moves to other regions. The steps in protecting carbon were determined globally not regionally, so the amount of extra land protected in the different scenarios can vary a lot. The irregular sequence of protection can cause the irregular pattern in carbon costs as the graph of SEA shows.

Sub-Saharan Africa shows a quite different pattern. First, the carbon prices per ton CO₂ are very low: between 0 and 3.2 dollar. Second, scenario (a) shows a negative emission reduction. This may be caused by extra production that shifts from other regions that have more protected areas. The second point (scenario b) shows negative costs. Due to the global market Sub Saharan Africa shows a small emission reduction, but has actually a higher GDP due to

effects in other world regions. The remaining scenarios show the expected rise of carbon costs with increasing protection efforts.

In the experiment of this study the data points in the three abatement curves are not independent. The data point of each scenario in one region is connected with the data point of that specific scenario in other regions since a decrease in production in one region may influence another region, for example by having a higher production. The abatement curves presented here are the average of more regions which all have their reaction on the protection of carbon rich areas (some may win GDP and extend their agriculture, other protect their carbon rich forests and loose GDP). For now we assume that the largest economic effect takes place within the regions. Then these abatement curves could be use separately and a world abatement curve could be constructed using these regional data points instead of averaging all emission reductions and GDP effects for the whole world. Advantage of this method is that the details of different emission savings at different costs are saved. The result of this exercise is the abatement curve for the world in Figure 15d.

In the abatement curve of the world we see the regional curves reflected in one picture. The data points with the lowest costs are mainly from the case of Sub-Saharan Africa, while the highest costs are originating from the Southeast Asia case. This representation suggests the theoretical asymptote, which is the maximum amount of carbon that can be saved in 2030, which is 4680 Mt for these three regions together.

4 Discussion

Using an agricultural economy model, LEITAP, coupled to an integrated assessment model, IMAGE, we evaluated a series of scenarios of restricted deforestation, and used the change in GDP and CO₂ emissions to estimate the costs of REDD and to construct marginal abatement cost curves. While most other global modeling approaches estimating costs of REDD all used a global carbon tax addressing representative landowners (e.g. Kindermann et al., 2008), our approach focuses on countries and regions as the actors in a global REDD framework. Given current discussions and negotiations on additionality, leakage, permanence and determination of national baselines, it is clear that countries will play an important role in any REDD framework. And also with a specific country, it is very likely that the measures to reduce deforestation and emissions from deforestation will not apply a carbon tax, but rather improved land use management and planning, and law enforcement. While a carbon tax approach may be more straightforward in the technical model implementation, we regard a country-based approach as more realistic. Interestingly, though, our results agree well with the costs estimates from other studies, and also show a similar distribution of costs across regions, with lowest costs in Sub-Saharan Africa (SSA), and highest cost in Southeast Asia (SEA+).

In our approach we analyze the stepwise increase in protection of carbon rich lands, starting from the most carbon rich land onwards. This leads to simultaneous protection of land in various regions, but at different costs. Following a pure least-cost approach, e.g. following from an implementation of the carbon-tax based approach, global REDD schemes would first reduce a large share of baseline emissions in Sub-Saharan Africa, followed by Central and South America, while the most expensive reductions in Southeast Asia would come in only at high global carbon prices. However, at the moment the prospects for effectively reducing emissions from deforestation are certainly higher outside Sub Saharan Africa, as it is also reflected in emerging agreements e.g. between Norway and Indonesia. Additionally, also the potential benefits of REDD++ with biodiversity and other ecosystem services call for simultaneous protection of carbon rich land in all regions. Cost estimates of REDD depend, among others, on the participation of regions in a REDD scheme. So far, however, all REDD modeling studies including ours assume full participation, and no estimates are available in the literature on the costs changes and, more important, on the leakages under fragmented participation.

Considering the above, it is clear that the abatement curves presented should be interpreted with care. The costs associated with emission reduction in one region are dependent on the protection on other regions, since we have simultaneously protected areas in different regions. Protecting carbon rich land starting with the most carbon rich areas is a logical approach. However, from an economical perspective, and especially when considering the market for carbon reduction and REDD measures as a global market, one would search for the largest emission reduction per dollar. This does not necessarily have to be the most carbon rich area first, but more likely is an area where carbon can be saved without hampering the agricultural development. (Agricultural expansion would then only be diverted to land with less carbon stored). In fact the approach of Figure 15d follows this line of reasoning. Remind that indeed here the assumption was made that the different regions are independent, i.e. a protection in one region does not affect the agricultural/economic system of any of the other regions. In case the assumptions hold we now can choose a level of payments per tonne and see what amount of carbon can be saved yearly. It is clear the most cost effective areas to be protected are in Sub-Saharan Africa, followed by Central and South America and Southeast Asia, which has by far the highest opportunity costs of protecting carbon. An alternative approach would be to model payments and including those areas gradually that have opportunity costs lower than the amount offered (and assume all land owners/land managers would participate): a land rent method.

The model experiment in this study is stylized and therefore it represents only a part of reality. Most probably the protection of carbon rich land will follow neither of the pathways described above. Secondly, as described in the methods section, transaction costs and implementation cost are not included, nor is a possible compensation for the opportunity costs, for example a money transfer from a REDD fund or a taxation measure. These effects have an influence on the GDP changes as modeled in this study. The presented results can therefore best be described as a first order effect.

Another aspect of forest protection is the feasibility of implementing forest protection. In the past many efforts have been undertaken to protect forest for various reasons. Especially in developing countries forest protection is not an easy task. Agriculture is often an important economic sector and many depend on farming for their livelihood. Population is often increasing and agricultural development is an important driver for economic growth. Additionally, the lack of institutional development and law enforcement often cause forest protection measures to be unsuccessful if implemented at all. This study does not take all of this into account and assumes full protection (and does not include a cost for implementation).

In the discussion on REDD, permanence is a crucial issue, and also for the application REDD in global climate strategies this is crucial. While many approaches assume no further costs of REDD from the year onwards in which baseline emissions are projected to be zero, we find continuous and increasing GDP effects after 2030. In very general terms that is related to the fact that REDD puts an additional constraint to land use activities, and thus makes the system less (economically) efficient than without. Maintaining the constraint thus leads to continuous higher costs. In that sense, emission reduction from deforestation is fundamentally different than reducing emissions from energy plants, where a pure reference to baseline emissions is justified. Once an emission from an energy plant is reduced in a certain year t (even if the next year the energy plant is back to “normal”) this certain amount of CO₂ avoided in year t is really reduced “permanently”. The cost calculation can be made and in the future no extra cost will arise. In reducing deforestation this is somewhat different. REDD measures stop, land use area might, in the most extreme case, return to the baseline level, and in doing so, emit the same amount of CO₂ as under the baseline, but in a different time trajectory. We have presented cost for the period 2005-2030, but as the underlying demand for agricultural products is no different than in the baseline, there need to be measures (money transfer for example) in place after 2030, in order to avoid that the forest will be cut after all and the CO₂ reduction has only been in place temporary. Moreover, even if the baseline does not show any land expansion anymore, for example in 2050, the land situation is still

‘constrained’ and there will still be a yearly GDP difference (loss) compared to a situation where the constraint is removed. The question on whether removal of the constraints (i.e. the discontinuation of REDD measures or payments) will lead to a full or partial return of land use area towards the baseline level depends on several factors, among which the structural economical and agricultural change that has been triggered and taken place in the meantime. This dynamics are fundamentally different from abatement of other CO₂ sources and should actually be addressed in future work.

Another crucial issue, for REDD but also for GHG mitigation in all other sectors, is ‘leakage’. Leakage is the effect that protection in one region or country leads to an increase of deforestation or land use in another region, which partly or completely annuls the effect of the initial reduction of deforestation. Our modeling study includes the global economy and physical effects of land use change and therefore the effects of leakage are fully incorporated in the outcomes (though depending on the assume full participation path, as described above). At sub-regional and country level we actually do see the leakage effects of protecting carbon. This leads to increased agricultural expansion in areas that have lower carbon contents, for example Africa in scenarios a and b. Accordingly, these areas may benefit by having a larger GDP than in the baseline. However, by protecting more and more area with each scenario we observe that the leakage effect is reduced.

Leakage may also influence land use in Annex I countries. In theory deforestation in Annex I countries is unlikely, since Annex I countries are obliged to include changes in forest cover (and the associated carbon losses) in the Kyoto agreements through the agreements on LULUCF. However, there are still some non-forested land reserves available for agricultural expansion, and in the modeling set-up the LULUCF restriction in Annex I countries are not included yet. Therefore, some leakage occurs to Annex I countries, as land use expansion is higher than under the baseline and includes also some deforestation.

From a policy perspective it is important to understand that REDD measures are only necessary since not all countries participate in a climate treaty (currently the Kyoto protocol). In case all countries are obliged to include their forest in their national emission no extra REDD measures would be necessary and leakage causes an emission source for a country.

The combined economic and environmental assessment approach enables to assess the effects in an integrated manner at regional to global scale. CO₂ emissions from land use is a main indicator. The costs that result from the protection measures are estimated as being the loss of GDP in the economic system. Together these form an estimate of the opportunity cost per ton CO₂ emission that is reduced under the different scenario assumptions. This economic system is complex and includes several effects. The land constraints imposed on the models in the different scenarios lead to changes in the agricultural system compared to the baseline scenario. Additional demand that is projected in the baseline to cause land expansion on carbon rich lands will be fulfilled differently in the scenarios with constrained land use (and might even lead to less production and consumption). For example, instead of expanding agricultural land use on forested land the expansion will occur in less carbon rich biomes, e.g. in savanna. In case this land is less productive also more land expansion might be expected.

Economically, the land constraints have a series of effects. The diminished availability of land in general and the production on less suitable land tends to increase land and consequently production prices. From a regional perspective this decreases competitiveness against other regions. From a global perspective this reduces prosperity and global GDP. Because prices of agricultural commodities increase, consumption (demand) may be lower. On the other hand, higher prices trigger technical (or other) improvements that increase yield, which (partly) compensates the lower production. So, consumption may be lower, production shifts to other locations and the management of the land improves in order to attain higher yields. This system dynamics is resolved in the LEITAP model.

In a REDD mechanism the costs of forest protection could be compensated somehow, for example through international funds or via a carbon market. This money transfer is not included in this analysis. However, it would probably also affect the economic system, as well

as transaction costs and implementation costs. These effects are not presented in this study. However these effects are important in many aspects and have to be taken into account in evaluating REDD measures. In follow-up analysis these topics should be addressed.

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Annex 1: detailed scenario description

Scenario	Land area protected (globally in km²)	Carbon protected (Globally in Gt CO₂)
A	934,408	137
B	2,365,114	280
C	4,490,288	425
D	6,893,088	529
E	8,172,535	653
F	10,203,723	780
G	12,463,634	853
Q	16,986,999	1002
S	23,421,000	1111

Annex 2: regional aggregation

Name	Regions/countries included
NAM	North America (USA and Canada)
CSA	Central and South America
SSA	Sub-Saharan Africa
NAFME	North Africa and the Middle East
EURTUR	Europe and Turkey
FUSSR	Former USSR
INDIA+	India (+ Pakistan Afghanistan, Bangladesh)
CHINA+	China (+ North Korea, South Korea, Japan, Taiwan)
SEA+	Southeast Asia (Indonesia, rest of Southeast Asia)
OCEA	Oceania (Australia, New Zealand)