Schmitz, C., Kreidenweis, U., Lotze-Campen, H., Popp, A., Krause, M., Dietrich, J. P., Müller, C. (2015): Agricultural trade and tropical deforestation: interactions and related policy options. - Regional Environmental Change, 15, 8, 1757-1772

DOI: 10.1007/s10113-014-0700-2

Noname manuscript No.
(will be inserted by the editor)

Agricultural trade and tropical deforestation - Interactions and related policy options

Christoph Schmitz · Ulrich Kreidenweis · Hermann Lotze-Campen · Alexander Popp · Michael Krause · Jan P. Dietrich · Christoph Müller

the date of receipt and acceptance should be inserted later

---

corresponding author: schmitz@pik-potsdam.de, Tel: 0049 (0)331 288 2653, Fax: 0049 (0)331 288 2620

The manuscript contains 6303 words

C. Schmitz
Potsdam Institute for Climate Impact Research (PIK), Climate Impacts and Vulnerabilities (RD2), Potsdam, Germany

U. Kreidenweis
Potsdam Institute for Climate Impact Research (PIK), Sustainable Solutions (RD3), Potsdam, Germany, kreidenweis@pik-potsdam.de

H. Lotze-Campen
Potsdam Institute for Climate Impact Research (PIK), Climate Impacts and Vulnerabilities (RD2), Potsdam, Germany, lotze-campen@pik-potsdam.de,
Department of Agricultural Economics, Humboldt-Universität zu Berlin, Germany

A. Popp
Potsdam Institute for Climate Impact Research (PIK), Sustainable Solutions (RD3), Potsdam, Germany, popp@pik-potsdam.de

M. Krause
Österreichische Bundesforste (OeBf), Austrian Federal Forest Joint Stock Company, Purkersdorf, Austria, michael.krause@bundesforste.at

J.P. Dietrich
Potsdam Institute for Climate Impact Research (PIK), Sustainable Solutions (RD3), Potsdam, Germany, dietrich@pik-potsdam.de

C. Müller
Potsdam Institute for Climate Impact Research (PIK), Climate Impacts and Vulnerabilities (RD2), Potsdam, Germany, cmueller@pik-potsdam.de

Abstract The extensive clearing of tropical forests throughout past decades has been partly assigned to increased trade in agricultural goods. Since further trade liberalisation can be expected, remaining rainforests are likely to face additional threats with negative implications for climate mitigation and the local environment. We apply a spatially explicit economic land-use model coupled to a biophysical vegetation model to examine linkages and associated policies between trade and tropical deforestation in the future. Results indicate that further trade liberalisation leads to an expansion of deforestation in Amazonia due to comparative advantages of agriculture in South America. Globally, between 30 and 60 million ha (5% to 10%) of tropical rainforests would be cleared additionally, leading to 20-40 Gt additional CO_2 emissions by 2050. By applying different forest protection policies, those values could be reduced substantially. Most effective would be the inclusion of avoided deforestation into a global emissions trading scheme. Carbon prices corresponding to the concentration target of 550 ppm would prevent deforestation after 2020. Investing in agricultural productivity reduces pressure on tropical forests without the necessity of direct protection. In general, additional trade-induced demand from developed and emerging countries should be compensated by international efforts to protect natural resources in tropical regions.

Keywords land-use change · trade liberalisation · tropical deforestation · forest protection · agricultural productivity growth

1 Introduction

Throughout the past three decades tropical deforestation has contributed between 12% and 25% to worldwide greenhouse gas emissions (Houghton, 2003; Fearnside and Laurance, 2003; van der Werf et al., 2009). Total net release of carbon from forest change in the 1990s varied according to different methodology and data sources between 0.5 and 2.2 PgC per year, having increased considerably since the 1950s (Ramankutty et al., 2006). A more recent study estimates average net emissions from tropical land-use change at 1.5 PgC per year in the 1990s and 1.1 PgC per year between 2000 and 2007 (Pan et al., 2011). Besides generating carbon emissions, deforestation leads to socio-economic damages for the local population (Barraclough and Ghimire, 2000), reduced water cycling (Fearnside, 2005), increased flood risk (Bradshaw et al., 2007), disruptions to the local climate (Costa and Foley, 2000) and severe loss of biodiversity (Gorenflo and Brandon, 2005). From FAO country studies it is assessed that since the 1980s on average around 13 million ha of forest area has been lost every year (Ramankutty et al., 2006; FAO, 2010).

Cropland expansion is considered to be one of the key drivers behind tropical deforestation. Commercial and subsistence agriculture are related to about three-quarters of deforestation (Hosonuma et al., 2012). Another study about deforestation in Brazil based on satellite data indicated that up to 23% is triggered by cropland expansion and 66% by pasture expansion (Morten et al., 2006). By using the Landsat database from FAO, Gibbs et al. (2010) revealed that between 1980 and 2000 about 55% of new agricultural land in the Pan-Tropics came from intact forests and about 30% from disturbed forests. Especially in South America, large-scale and enterprise-driven agriculture fuelled by rising consumer demand is a major cause (Parker et al., 2009). In contrast, in Central Africa, extraction of natural resources (e.g. timber) and in Pacific Asia pressure from commercial agricultural plantations are seen as the main driving forces behind the forest loss (Lambin et al., 2001). Although some recent sources have referred to a decreasing deforestation rate (Kauppi et al., 2006; FAO, 2010), the remaining rainforest worldwide is in severe danger due to increasing demand for food and other agricultural products (Gibbs et al., 2010).

Besides the general rise in agricultural demand, several studies point out that further trade liberalisation is and will be an important factor for deforestation activities. Barbier (2000) demonstrated this relationship with case studies from Ghana and Mexico. In Brazil, improved access to international markets has pushed soy and beef production causing a surge in deforestation (Fearnside, 2005; Nepstad et al., 2006). Based on satellite data DeFries et al. (2010) concluded that forest loss is largely driven by urban population growth and international exports of agricultural products. Other studies have used a global modelling approach to analyse future effects of trade liberalisation. Verburg et al. (2009) and Schmitz et al. (2012) have shown that the rates of tropical deforestation and global greenhouse gas emissions are likely to rise with increased trade liberalisation in the future. Similar studies have emphasised that liberalising trade leads only to small land use shifts in Europe but dramatic shifts in developing regions with negative implications for the environment (van Meijl et al., 2006; Eickhout et al., 2010).

To induce climate change mitigation and reduce further deforestation different policies are available (Forner et al., 2006; Kolstad et al., 2014). These include direct regulatory approaches, economic incentives, or government provision of technology to tackle the problem. Direct regulation is mainly applied to protected areas (PAs); it has been shown to be effective (Nelson and Chomitz, 2011; Beresford et al., 2013) and is linked to the recent slowdown of deforestation in the Amazonian rainforest (Soares-Filho et al., 2010). Economic incentives include classic measures like taxes or subsidies but also tradable emissions allowances. Pricing greenhouse gas emissions from the land-use sector has been proposed as one promising approach and has been analysed extensively through the application of large-scale integrated land-use models (Kindermann et al., 2008; Wise et al., 2009; Thomson et al., 2010). The sequestration and storage of carbon in vegetation can also be rewarded by Payments for Ecosystem Services (PES). Rewarding measurable, below-baseline emissions, is also the idea behind the REDD scheme (Reducing Emissions from Deforestation and Degradation) currently discussed under the United Nations Framework Convention on Climate Change (UNFCCC). Governments could also invest in yield increasing Research & Development that lowers the pressure on expansion into forests. Whether this is a promising strategy has been under discussion for several years.

The Borlaug hypothesis, named after the father of the Green Revolution Norman Borlaug, suggests that yield increases lead to a lower spatial need for production, and thus have and will save natural ecosystems such as forests. In contrast, according to Jevon's paradox, at the local forest frontiers, new technologies can be labour saving, thus freeing workforce for expanding agriculture. (Angelsen, 2001; Hertel, 2012)). Byerlee et al. (2014), however, conclude in their recent literature review that at a global level, investment in R&D to improve productivity remains one of the best ways to reduce pressure on increasingly scarce land resources and conserve natural ecosystems.

Previous studies have either focused on trade liberalisation or on forest-protection measures but none have looked at the important interplay between these. We here integrate both effects and consider explicitly the interaction between trade liberalisation and deforestation. We apply the economic land-use model MAgPIE ("Model of Agricultural Production and its Impact on the Environment"), which takes global and regional interactions into account and simulates spatially explicit land-use patterns. MAgPIE uses endogenously derived technological change and land expansion rates, which make it unique in the field of land-use modelling. Biophysical processes and inputs are considered through the link with the global vegetation-hydrology model LPJmL. The main goal of our study is to investigate consequences of different trade volume scenarios and forest protection policies on land-use change, carbon emissions, net exports, and technological change rates over the coming five decades. As forest protection scenarios, we assume an expansion of protected areas, different carbon price scenarios and one case in which agricultural productivity in forest regions is increased through higher investments in Research & Development and infrastructure. The latter is used to highlight the important interplay between land expansion and technological change (Lotze-Campen et al., 2010; Dietrich et al., 2013; Popp et al., 2012). We start by explaining the model framework with the implementation of trade and forest and by describing the applied scenarios. Following this, we present results of the analysis which are, finally, compared and discussed.

2 Methods

2.1 General Model Description

For the analysis we use the recursive dynamic optimisation model MAgPIE ("Model of Agricultural Production and its Impact on the Environment"). In the following, we briefly present the main model features for this study. For further details we refer to the extensive model documentation (Lotze-Campen et al., 2008, 2010; Popp et al., 2010, 2011; Schmitz et al., 2012) and the mathematical description, which is attached as supplementary material.

Figure 1 presents a simplified flow chart of the inputs for MAgPIE. The model reflects three layers: global, regional (reflected by ten world regions, see Figure 1) and cellular layers (based on 0.5 degree resolution). MAgPIE simulates time steps of 10 years (starting in 1995) and uses in each period the optimal land-use pattern from the previous period as a starting point. Required calories in the demand categories are derived through a cross-country regression based on a medium population scenario (UN, 2011) and a medium income-growth scenario (projections based on Heston et al. (2011)). With the implementation of international trade it is determined how many calories are produced domestically and how many are imported. In MAgPIE, trade can be either fixed, if it is allocated according to historic self-sufficiency rates (1995 values from FAO (2011a)), or liberalised, which means that regions with comparative advantages produce more at the expense of less competitive regions. The share of the two options is determined by the trade balance reduction factor $p_t b$ (see Figure 1). More details on the trade implementation are described in Schmitz et al. (2012). The resulting calories are produced by 16 crop groups (temperate cereals, maize, tropical cereals, rice, soybean, rapeseed, groundnut, sunflower, oil palm, pulses, potato, cassava, sugar beet, sugar cane, cotton, others) and 5 livestock types (ruminant meat, pig meat, poultry meat, egg, milk) in the particular regions.

Further inputs to MAgPIE are socio-economic data, mainly costs, which define the cost minimisation objective function. In the baseline version of the model four categories of costs arise: 1) Production costs are taken from GTAP (Narayanan and Walmsley, 2008) and contain factor costs for labour, capital, and intermediate inputs. 2) Technological change is endogenously implemented in MAgPIE. That means the model decides (based on an investment regression) how much additional technological change is required and cost effective. Costs are based on investments in agricultural Research & Development as well as infrastructure investments (Dietrich et al., 2013). They rise exponentially with the state of agricultural development of a region (Dietrich et al., 2012). The endogenous implementation allows MAgPIE to project future yield increases and the costs involved. 3) Land expansion involves costs for preparation of new land and basic infrastructure investments (Krause et al., 2012). Land conversion costs are based on country-level marginal access costs generated by the Global Timber Model (GTM) (Sohngen et al., 2009). Regarding the conversion of intact and frontier forests (IFF) we base our cost parameterisation on reference values from case studies. Merry et al. (2002) analysed forest transition in Latin America with a case study of Bolivia and calculated conversion costs of 600 to 700 US$/ha. Similar costs accrue in Indonesia where the value for converting rainforest to cropland is 550 US$/ha(Simorangkir, 2007). Another case study from Latvia, however, reveals considerably higher costs of 1,500 US$/ha (Lazdins et al., 2009). In developed countries this value (based on marginal access costs) increases even further up to 7,500 US$/ha (Sohngen et al., 2009). The large variation in costs is due to topography, forest type, soil conditions, applied technology, and the governmental system. As a base value we assume 1,000 US$/ha for tropical land conversion. We applied a sensitivity

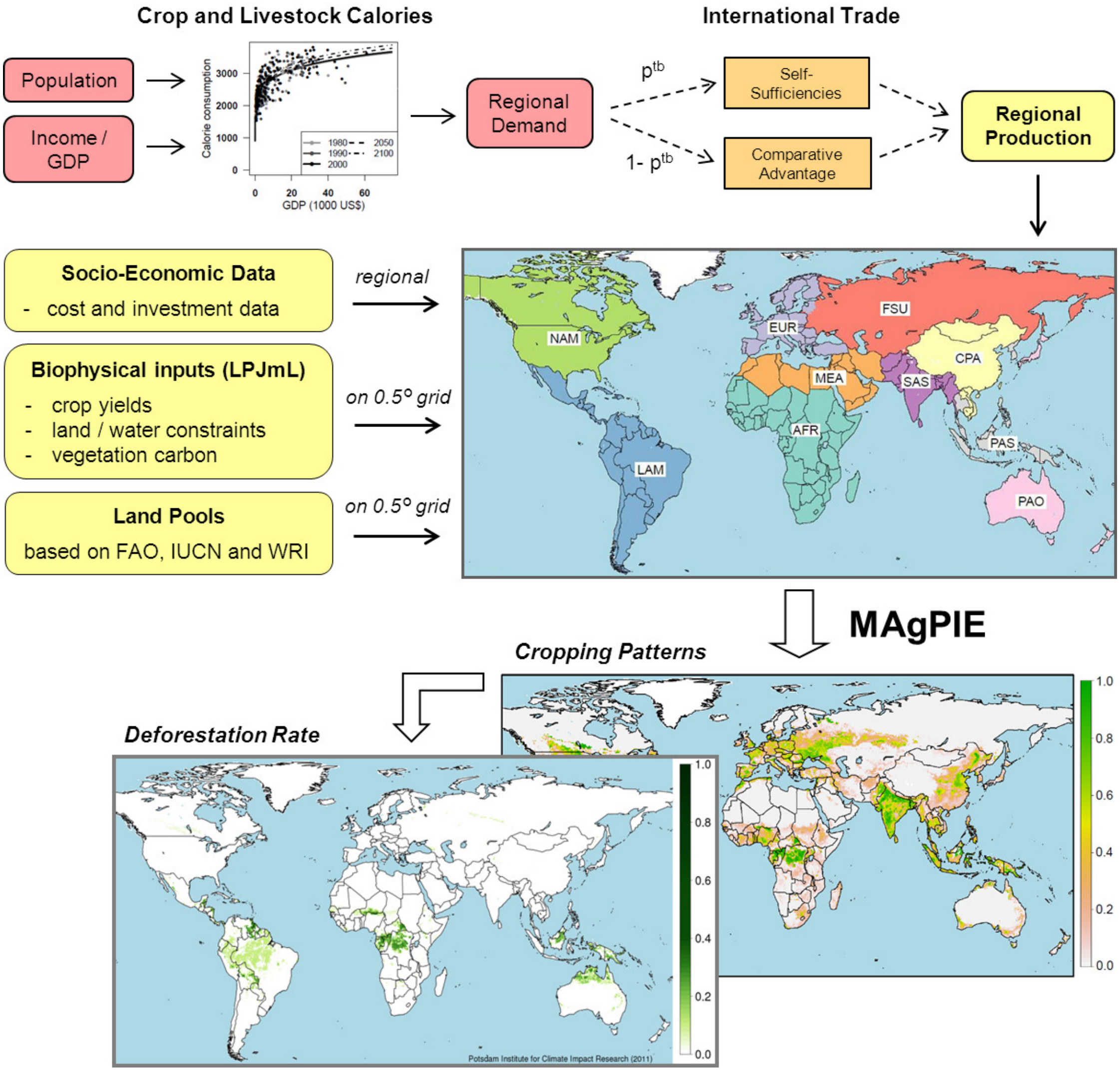

Fig. 1 Simplified MAgPIE flow chart of key processes highlighted in this study (demand and trade implementation, land pools and spatially explicit land-use change). With exogenous data about population and GDP development, we calculate regional demand and the livestock share. The former is then translated to regional production depending on the international trade scenario. Further inputs for MAgPIE are socio-economic data like production costs, biophysical inputs from LPJmL and land-type data based on various sources (FAO, IUCN and WRI). After optimisation of MAgPIE, possible outputs are cropping patterns of different crops or maps with deforestation rates. MAgPIE divides the world into ten regions: AFR = Sub-Sahara Africa, CPA = Centrally Planned Asia (incl. China), EUR = Europe (incl. Turkey), FSU = Former Soviet Union, LAM = Latin America, MEA = Middle East and North Africa, NAM = North America, PAO = Pacific OECD (Australia, Japan and New Zealand), PAS = Pacific Asia, SAS = South Asia (incl. India).

analysis of this parameter by varying it in 200 US$ steps from 200 US$ to 1,800 US$ (see Figure 9). 4) Intraregional transport costs for every commodity unit reflect the distance to intraregional markets and the quality of the infrastructure. Data for transport costs are derived from GTAP (Narayanan and Walmsley, 2008) and travel time to the nearest city is reflected by a 30 arc-second resolution data set (Nelson, 2008). For long-term investments, like land conversion or R&D, we assume an annual discount rate of 7%, which reflects the opportunity costs of capital at the global level (IPCC (2007), chapter 2.4.2.1).

For the representation of biophysical processes, MAgPIE is linked to the global biophysical vegetation-hydrology model LPJmL (Bondeau et al., 2007). LPJmL endogenously models the dynamic processes linking climate and soil conditions, water availability and plant growth, and takes the impacts of CO_2, temperature and radiation on yield directly into account. The link to MAgPIE is generated via rainfed and irrigated yields for different crops, rainfed and irrigated land-use fractions (Fader et al., 2010), water inputs, like irrigation requirements and water availability (Rost et al., 2008), and the carbon content of the various vegetation types. These outputs from LPJmL are used in a 0.5 degree resolution in MAgPIE. The same resolution is used for the determination of land types per grid cell. The different land pools are taken from a consistent land-use database developed by Krause et al. (2009) which is based on Erb et al. (2007) and integrates crop suitability indicators (van Velthuizen et al., 2007), intact and frontier forest types (Bryant et al., 1997; Potapov et al., 2008), and protected areas (UNEP-WCMC, 2006). Intact and frontier forests can also be denoted as undisturbed natural forests. Together with other natural vegetation not defined as grazing land or forest (around 122 million ha), it constitutes the land pool that is made available for cropland expansion (around 734 million ha). The remaining land pools, like pasture and managed

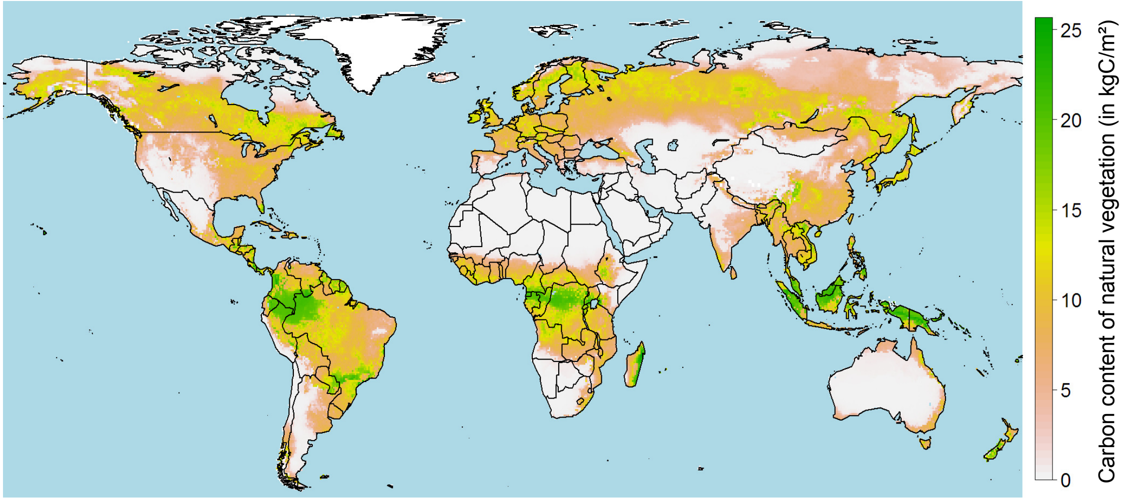

Fig. 2 Grid-cell specific carbon content (0.5 degree) of natural vegetation (in kgC/m^2) from LPJmL (average from 1990-1999) used in MAgPIE

forests, are not regarded for cropland expansion. When land-use change occurs and land is converted to a different type (e.g. forest to cropland), MAgPIE accounts for carbon emissions by taking the differences in LPJmL-derived carbon stocks between the two land pools. The used LPJmL model version is able to capture changes in above- and belowground vegetation carbon (see Figure 2) but not in soil carbon. Related carbon emissions are reported as CO_2-equivalent emissions after each time step.

2.2 Scenario Design

The aim of this study is to investigate interactions between international trade policy and forest protection measures (Table 1) and their consequences on tropical deforestation patterns.

Concerning trade policy, our analysis largely follows the policy scenario of the predecessor study (Schmitz et al., 2012), except that trade liberalisation starts in 2015 (instead of 2005). Hence, our reference case keeps the trade pat-

Table 1 Scenario Definition

Policies	**Trade policy**	**Forest policy**		
Scale	*global*	*AFR*	*LAM*	*PAS*
Reference Scenario [*reference*]	constant	- basic forest protection -		
Trade Scenarios:				
(a) no forest policy [*nopol*]	liberalisation	- basic forest protection -		
(b) Increasing forest protection over time [*time*]	liberalisation	until 2040	until 2030	until 2030
(c) Low CO_2 price [*lowprice*]	liberalisation	- low CO_2-Price -		
(d) CO2-price to achieve 550 ppm [*550ppm*]	liberalisation	- high CO_2-Price -		
(e) Additional investment in TC [*TC*]	liberalisation	- 1% TC p.a. -		

Table 2 Forest protection rate in the past (2000-2010) and assumed rates for the future (2010-2050) in the trade scenario *time*

Scenario	**Region**	**2000-10**	**2010-20**	**2020-30**	**2030-40**	**2040-50**
Basic protection	*AFR*	8%	8%	8%	8%	8%
(observed)	*LAM*	25%	25%	25%	25%	25%
	PAS	12%	12%	12%	12%	12%
Protection over time	*AFR*	8%	31%	54%	77%	100%
(assumed)	*LAM*	25%	50%	75%	100%	100%
	PAS	12%	41%	70%	100%	100%

terns fixed over time, whereas the trade scenarios assume further progress in the Doha Development Round [1], leading to liberalisation efforts comparable to situations in the 1980s and 1990s, when large global liberalisation efforts were undertaken. Based on Dollar and Kraay (2004) and Conforti and Salvatici (2004), we assume that trade barriers are continuously reduced by 10% each decade. The trade policy is the same in all five trade scenarios, but the scenarios differ according to their forest policy (Table 1). Whereas the scenario *nopol* assumes no forest protection measures in order to highlight the differences of the trade effect compared to the reference case, the other four scenarios assume different global and regional policy measures to reduce deforestation.

---

[1] The Doha Development Round is the latest round of trade negotiations of the World Trade Organisation (WTO). It was launched in 2011 with the aim of improving the access to global markets. For more information on the stage and agenda of the Doha Round, see Martin and Mattoo (2011).

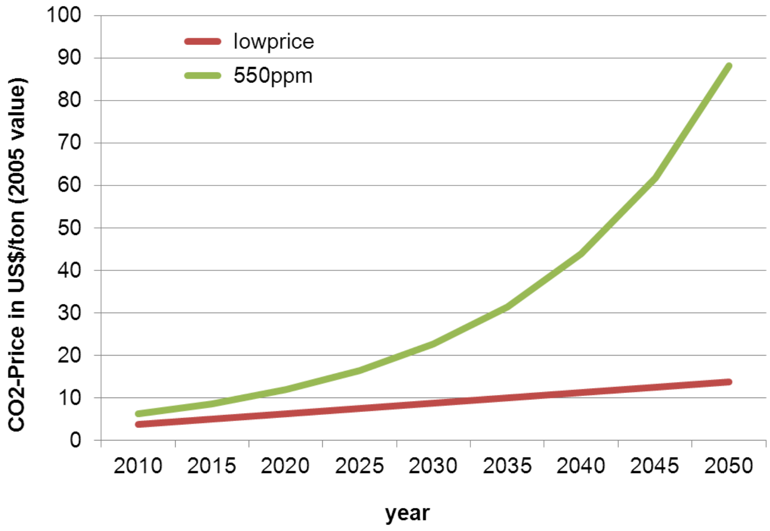

Fig. 3 Modelled CO_2-Price (in US$/tonne) for the *lowprice* and *550ppm* scenario until 2050

As a first scenario, we introduce policies to restrict deforestation and to implement protected areas (PAs). Based on Soares-Filho et al. (2006) we consider a defined share of intact and frontier forest as protected and increase this share over time (*time* scenario). For the three main tropical IFF regions we assume a different time span (2040 in AFR and 2030 in LAM and PAS) until full forest protection is achieved depending on awareness level and governmental structures (Table 2). For comprehensibility reasons and to depict the whole range of possible outcomes we allow for no deforestation in these protected areas.

As a further scenario set-up, we introduce a CO_2 price as climate mitigation policy, which has to be paid in cases of deforestation and increases the costs of land conversion. In contrast to other approaches, which use constant carbon prices over time (e.g. Kindermann et al. (2008)), our price assumption rises over time. We differentiate two cases. First, we reflect a low price scenario (*lowprice*), in which the price per tonne of CO_2 starts at 5 US$ and rises continuously to 12.5 US$ (Figure 3). In 2013 an average of 4.9 US$ was paid per tonne of CO_2 on the voluntary offset market (Peters-Stanley and Gonzalez, 2014). In a second CO_2 price scenario, called *550ppm*, we consider the other case, in which CO_2 emissions from deforestation are included in a potential global carbon market. The CO_2 price is in this case based on modelling results from the ReMIND model for the Energy Modeling Forum (EMF-24) (Luderer et al., 2012), which assumes a maximum concentration of greenhouse gas emissions of 550 ppm (Figure 3).

Finally, the last scenario assumes that the three forest regions, Latin America (LAM), Sub-Sahara Africa (AFR) and Pacific Asia (PAS) receive financial means to increase their yields by 1% per year. This kind of exogenous technological change (TC) is a special case since no direct intervention of forest protection is assumed and only indirect effects on the forest area will be obtained. At the same time, the countries are allowed to invest in TC on top of that external investment. The hypothesis behind this scenario is that higher investments in TC can reduce the rate of forest destruction without any forest protection.

Table 3 Intact and Frontier Forest (IFF) in 2050, deforestation area (2010-2050), associated CO_2 emissions and the net average carbon emissions of deforested area in the different scenarios

Region	**Result**	**Unit**	**reference**	**nopol**	**time**	**lowprice**	**550ppm**	**TC**
Latin America (LAM)	IFF in 2050	10^6 ha	339.5	299.7	388.5	411.1	459.6	343.3
	Deforestation (2010-50)	10^6 ha	140.5	180.3	91.5	68.9	20.4	136.7
	CO_2 emissions (2010-50)	Gt CO_2	60.0	84.5	42.9	27.3	5.5	58.3
	Average carbon emissions	kgC/m^2	11.7	12.8	12.8	10.8	7.4	11.6
Sub-Sahara Africa (AFR)	IFF in 2050	10^6 ha	0.7	0.9	9.2	34.5	63.6	1.1
	Deforestation (2010-50)	10^6 ha	63.7	63.5	55.2	29.9	0.8	63.3
	CO_2 emissions (2010-50)	Gt CO_2	40.8	40.5	36.2	17.0	0.5	38.8
	Average carbon emissions	kgC/m^2	17.5	17.4	17.9	15.5	15.4	16.7
Pacific Asia (PAS)	IFF in 2050	10^6 ha	31.2	35.0	50.3	47.1	45.2	49.4
	Deforestation (2010-50)	10^6 ha	24.3	20.5	5.2	8.4	10.3	6.1
	CO_2 emissions (2010-50)	Gt CO_2	10.9	9.9	2.6	0.9	2.1	2.8
	Average carbon emissions	kgC/m^2	12.2	13.2	13.6	2.9	5.6	12.5

3 Results

3.1 Tropical Deforestation and Carbon Emissions

Table 3 provides an overview showing the potential area of tropical intact and frontier forest (IFF) in the three forest regions in 2050 as well as the change between 2010 and 2050 under the different scenarios. The concentration of IFF in Latin America ($\sim$ 80%) is also reflected in the deforestation patterns, as the region sees the highest forest loss in all scenarios. Since a much smaller share of tropical IFF is located in Central Africa ($\sim$ 10%) and South-East Asia ($\sim$ 9%), deforestation is quite small in absolute terms, but percentual changes in IFF are much higher than in LAM (in Central Africa up to 99% depending on the scenario).

In Latin America around 140 million ha of IFF is deforested between 2010 and 2050 in the reference case, leading to 60 Gt CO_2 emissions. With additional trade liberalisation this value grows to 180 million ha and about 85 Gt CO_2 emissions. The forest protection scenario (*time*) and the two price scenarios (*lowprice* and *550ppm*) lead to lower deforestation rates than in the reference case and to almost no emissions after 2040 (Figure 4). With exogenous TC, additional CO_2 emissions can be reduced to a similar level to that of the reference case (60 Gt CO_2). Most effective is the integration of deforestation in a potential carbon market (*550ppm* scenario), leading to a total IFF loss of only 20.4 million ha and corresponding emissions of 5.5 Gt CO_2. In the *lowprice* scenario deforestation is reduced to 69 million ha and with full forest protection until 2030 around 92 million ha will still be cleared prior to 2030.

For the Central African rainforest the picture looks different. Almost all IFF will be gone under the $reference$, the *nopol* and the TC scenarios (around 63 million ha). This leads to relatively more CO_2 emissions (40 Gt), since the average carbon content in AFR is higher than in the deforested area in LAM. Full forest protection until 2040 saves 9.2 million ha of IFF, the *lowprice* scenario saves around 35 million ha and the *550ppm* scenario saves almost the whole IFF (64 million ha). In Pacific Asia, deforested area decreases under trade liberalisation. Additionally, in contrast to the other regions, the *time* and TC scenarios are most effective by conserving around 50 million ha of the original 55.5 million. Additionally, the lower CO_2 price saves 2 million ha more than the higher price scenario (*550ppm*).

The net average carbon emissions per deforested hectare in all scenarios is highest in Central Africa (Table 3), where the northern part of the rainforest has the highest carbon densities (see Figure 2). In South America average carbon intensity is lower, since mostly cells at the border with a lower carbon content are affected by deforestation (see Figure 5). As the model minimises costs, considering a CO_2 price for released carbon (as in the *lowprice* and *550ppm* scenarios) includes an additional decision criteria to the objective function. In these scenarios, we observe a substantial reduction in the aver-

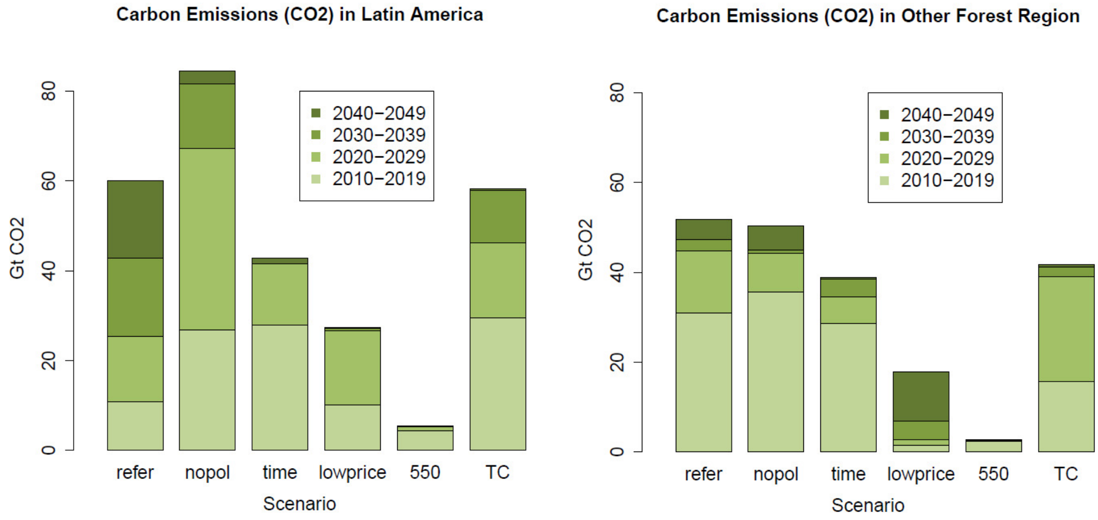

Fig. 4 CO_2 Emissions (in Gt) from tropical deforestation over time and for the two forest regions (LAM and OFR)

age per hectare carbon emissions since the model has an explicit incentive to minimise carbon release by choosing low carbon cells for land conversion.

For presentation purposes we have aggregated the model results into four regions. Latin America is treated separately due to its importance for IFF and the agricultural sector. Sub-Sahara Africa and Pacific Asia are grouped in the category "Other-tropical-Forest Regions" (OFR). For net export and technological change rates, the remaining regions are grouped together as Non-tropical-Forest Developing Countries (NFDC) (mainly China, India, Russia, and the Middle East) and OECD countries. The pace of deforestation varies substantially between scenarios (Figure 4). Forest clearance in LAM is much faster under the nopol scenario than under the reference scenario (drawing level with the 2030 baseline values in 2020 and exceeding the 2050 baseline in 2030). Including a low CO_2 price reduces emissions in LAM until 2050 to a level compared to the *nopol* scenario in 2020. In OFR, we obtain that in some scenarios (reference, *nopol*, *lowprice*) deforestation is higher in the last

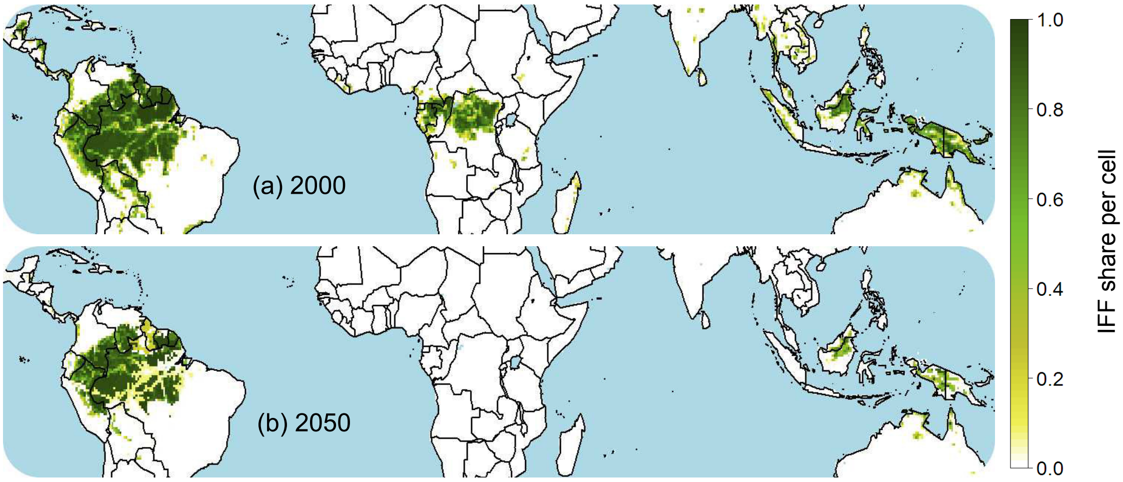

Fig. 5 Share of tropical intact and frontier forest per grid cell in the reference case in the years 2000 and 2050

time step than in the penultimate time step. In the other scenarios almost no deforestation takes place after 2040 due to full protection (*time*), high CO_2 prices (*550ppm*) or high agricultural productivity (*TC*).

In the following, we present grid-specific maps, which support the understanding of local dynamics. Figure 5a presents the tropical intact and frontier forest (IFF) in the year 2000. The tropical IFF forest is mainly located in Amazonia, Central Africa (mainly DR Congo, Cameroon, Gabon and Congo) and South-East Asia (mainly Malaysia, Indonesia, the Philippines and Papua New Guinea). Compared to the state in 2000, Figure 5b highlights the potential area of IFF in 2050 for the reference case. The Amazonia rainforest is considerably reduced especially at the borders in the south and west, but also within the forest, where infrastructure exists. The situation in Central Africa is even more intense, since in the reference case almost all IFF area would be cleared. In Pacific Asia forest area is reduced significantly in some locations, up to a complete loss of IFF.

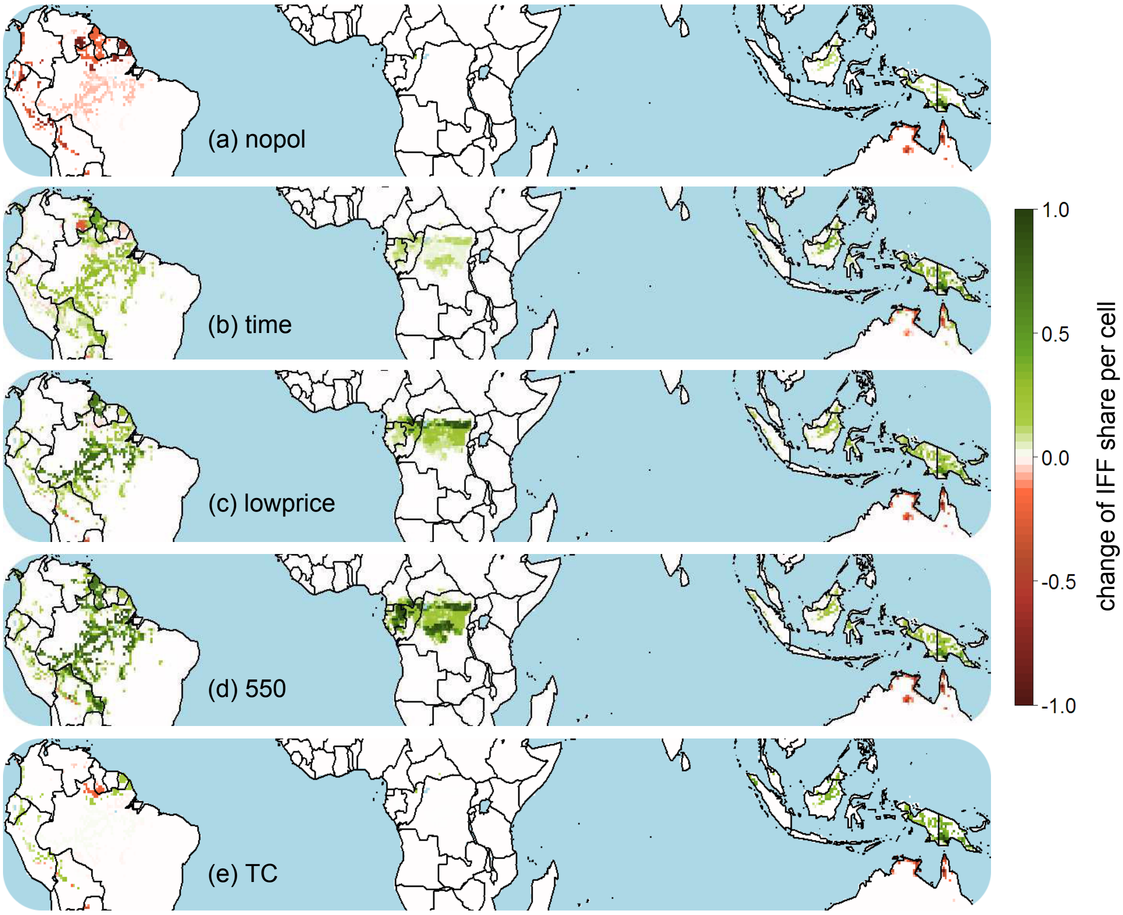

Fig. 6 Change of intact and frontier forest share per grid cell in the five trade scenarios compared to the reference case in 2050 (Red cells diplay additional deforestation, green cells display less deforestation)

To analyse the importance of trade liberalisation and forest protection measures in a spatially-explicit way, we investigate the scenarios' differences to the baseline setting in 2050 with difference maps (Figure 6). Positive values indicate a higher share of IFF in the scenarios and a negative value indicates further deforestation. The effects of trade liberalisation on deforestation rates are shown in Figure 6a (*reference* in 2050 minus *nopol* in 2050). In Latin America, the northern part of Amazonia and some border areas in the west are most negatively affected by trade liberalisation. Additionally, the interior close to existing infrastructure faces slight increases in deforestation. In Africa nothing changes as the whole forest would be gone in both scenarios, whereas Pacific Asia has lower and North Australia higher deforestation rates. Analysing the effects of forest protection measures, we show that deforestation in LAM is very sensitive to forest protection. If parts of the rainforest are protected with an increasing rate (Figure 6b), it mostly helps interior areas of the forest. Only some cells in the north of the forest are still deforested but to a lower extent than without protection policy. Both CO_2 price scenarios lead to much lower deforestation rates in the interior of the forest. In the *550ppm* scenario this is most effective in the south (Figure 6d). Finally, in the *TC* scenario almost no differences can be detected compared to the reference case with respect to South America, except for some border cells in the north and west. In Africa, the CO_2 price scenarios have the biggest effect on deforestation, protecting the northern part and in the *550ppm* scenario also the southern and western part. The expansion of protected areas (*time* scenario) has only small effects on deforestation patterns and investments in agricultural productivity (*TC* scenario) have no effects on deforestation as the whole forest is still cleared for agriculture. In Pacific Asia, all forest protection measures have positive effects with highest forest savings in Papua New Guinea.

3.2 Net export and Technological Change Rates

The analysis of net export rates indicates regions with comparative advantages in agricultural production. Figure 7 illustrates net export rates for cereals, oilcrops, sugar, and meat in the reference case and the trade scenarios.

In general, under trade liberalisation, Latin America exports more of every commodity compared to the reference scenario. In case of cereals, LAM turns from a net importer to a net exporter. Under forest protection, LAM becomes

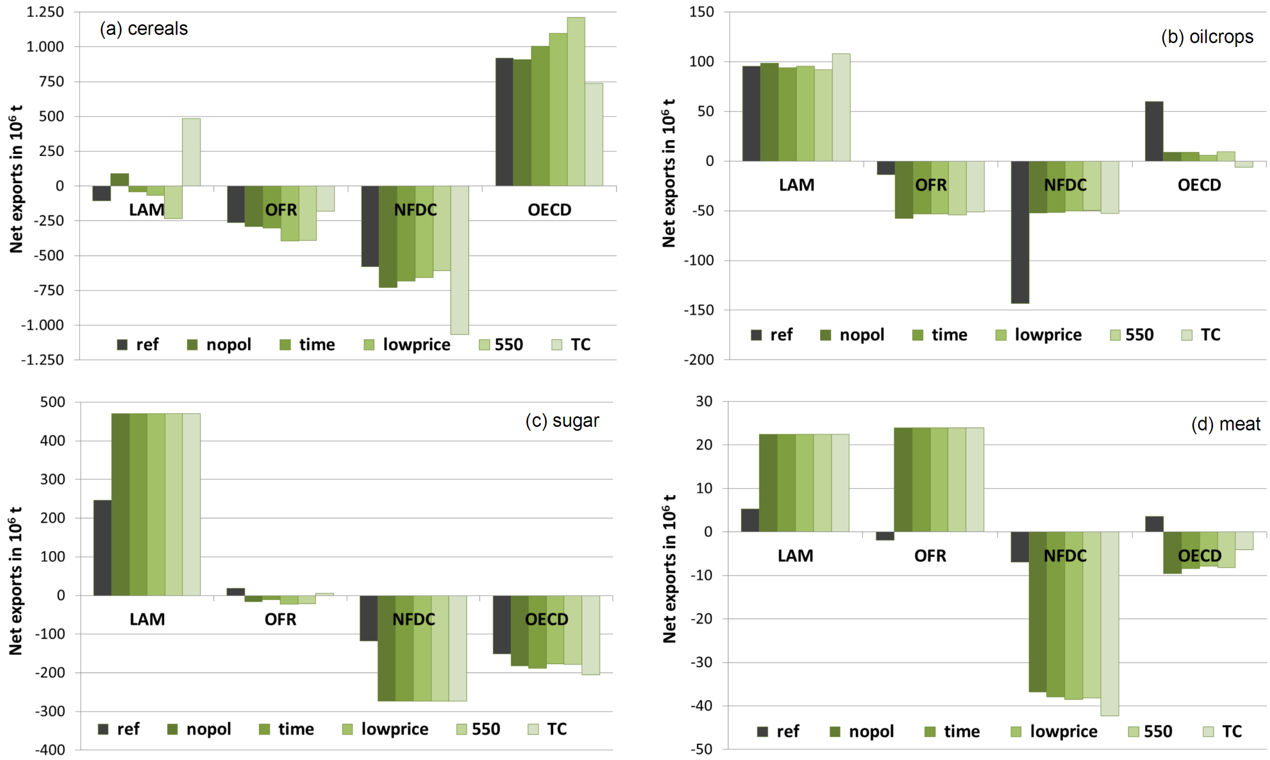

Fig. 7 Aggregated net exports (2010-2050) for the traded commodities (cereals, oilcrops, sugar and meat) in Latin America (LAM), Other Forest Regions (OFR), Non-tropical-Forest Developing Countries (NFDC) and OECD countries

a net importer again whereas the *TC* scenario generates the highest cereal net exports. Other commodities are less (oilcrops) or not at all (sugar, meat) affected by various forest protection policies and remain on a high export level. Trade liberalisation allows Non-tropical-Forest Developing Countries (NFDC) to reduce their imports in oilcrops at the expense of OECD countries, which face a drop in export levels. The rise in sugar exports in LAM leads to additional imports in NFDC and OECD countries. Concerning meat, the overall extent of trade is rather low in 2050. Regions with tropical IFF increase their exports in livestock, whereas NFDC increase imports and OECD countries turn from exporters to importers.

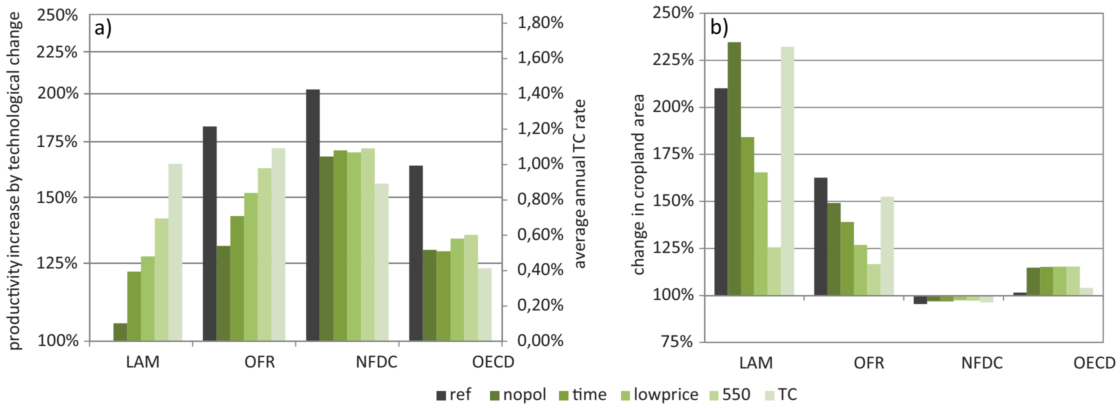

Fig. 8 a) Productivity increase by technological change and respective annual TC rates and b) increase in cropland of food and fodder crops in Latin America (LAM), Other Forest Regions (OFR), Non-tropical-Forest Developing Countries (NFDC) and OECD countries

Technological change (TC) rates are endogenously derived by MAgPIE (Dietrich et al., 2012, 2013), indicating the need for investments in technological development of the agricultural sector per region. In LAM, no investment into TC is observed in the reference case, production increase is mainly the result of an increase in cropland at the expense of tropical rainforests (Figure 8). In turn, in all other regions, TC rates decrease with trade liberalisation compared to the reference case. Among the trade liberalisation scenarios, TC rates are lowest in the *nopol* scenario in LAM (0.1%) and OFR (0.54%) and highest where 1% annual Technological Change is provided at no costs (*TC* scenario). These high TC rates, however, do not change cropland area in these two regions a lot, but slightly reduce the expansion of cropland in OECD countries. In general, forest protection increases the need for TC in regions rich in intact and frontier forests, if growing food demand is to be fulfilled.

3.3 Sensitivity Analysis

Our model results depend largely on exogenous parameters. In order to verify the results we regularly perform sensitivity tests with the crucial parameters.

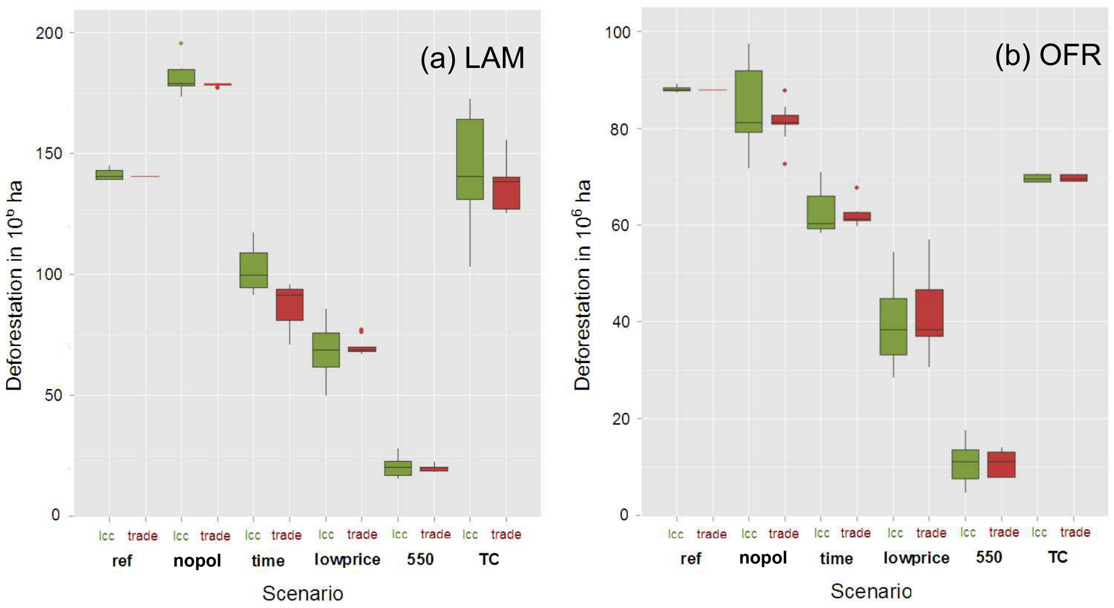

Fig. 9 Sensitivity of intact and frontier forest (IFF) area in LAM (Latin America) and OFR (Other Forest Regions) in 2050. For the analysis, land conversion costs (*lcc*) are varied in 200 US$/ha - steps from 200 US$/ha to 1,800 US$/ha (green boxplots) and the trade balance reduction (*trade*) is varied in 2.5% steps (up to 10%) around the current setting (red boxplots). The boxplots display minimum, lower quartile, median, upper quartile and maximum values.

For this study we have chosen land conversion costs (lcc) and the trade balance reduction factor, which triggers the amount of trade liberalisation. In the first case we vary lcc from 200 US$/ha to 1800$/ha in 200 US$/ha steps in each scenario, which amounts to 54 model runs. The same amount of model runs is required for the second sensitivity test, in which we vary the trade balance reduction factor by 2.5%, 5%, 7.5% and 10% below and above current values in each time step.

Resulting boxplots display the variation (minimum, lower quartile, median, upper quartile and maximum) in deforestation area of land conversion costs in green and the trade balance reduction in red for each scenario and the forest regions (LAM and OFR) (Figure 9). We obtain a quite heterogeneous picture with the general trend that the model outcome appears to be much more sensitive towards variations in land conversion costs than in trade liberalisation. However, in most cases the rank order between scenarios is not affected, except two cases: The TC scenario in LAM and the *nopol* scenario in ORF appear to be either higher or lower in deforestation than the reference case depending on the chosen land conversion costs.

4 Discussion

In the preindustrial period, demand for agricultural land, fuelled by population growth, was the main driver for deforestation in temperate zones (Simmons, 1987). After the industrial revolution the situation started to change and the rising wealth of industrialised countries initiated a domestic forest transition (Meyfroidt and Lambin, 2011). However, globalisation and increasing demand for goods in developed countries has shifted parts of the production to land-rich developing countries, leading to tropical deforestation (Lambin et al., 2001). This relation, also referred to as the virtual trade in land (Würtenberger et al., 2006), is triggered by the costs of trade (like tariffs, transport and information costs), which have been substantially reduced during the past century (Feenstra, 1998; Jacks et al., 2008). Since it is likely that this trend will continue (Josling, 2010), further deforestation is likely to lead to considerable damage to local environments and populations, as well as to the climate system. It is therefore relevant to examine how future growth in trade will affect deforestation rates and how different forest protection policies might influence the interplay between land expansion and trade competitiveness.

With the spatially explicit land-use model MAgPIE we analyse effects of trade liberalisation and different forest protection policies. Compared to other global land-use models it has the advantage that technological change and land expansion are implemented in an endogenous and competitive way. Associated investment costs are optimised together with production and transport costs on a global level. Biophysical inputs are derived from the process-driven vegetation-hydrology model LPJmL. In this study we do not explicitly consider future scenarios of bioenergy demand, since that has been done in separate studies with the ReMIND-MAgPIE model system (Popp et al., 2011, 2012). As these and other studies (e.g. Gibbs et al. (2008)) have shown, bioenergy production only saves carbon, if the associated additional agricultural production does not come at the expense of forest land or alternatively, is achieved by agricultural productivity gains.

Nor do we here explicitly consider different governmental systems and political situations in the regions, and how this would influence investments in agriculture. A further drawback of the model is the current lack of a link between pasture and cropland expansion. As the interaction between these elements is crucial, future model development will concentrate on this link to improve the accuracy of model outcomes.

Our simulation results for 2000 to 2010 are in good agreement with observation data (FAO, 2011b). For instance, in the case of Latin America, we simulate an average annual deforestation rate of 3 million ha of intact and frontier forest (IFF) compared to 4.25 million ha observed by FAO in this period. However, since FAO considers the whole unmanaged forest, the deforested IFF area in FAO statistics should be lower and much closer to our value. Nepstad et al. (2009) report an annual value of around 2 million ha (1996-2005), only for the Brazilian Amazon. In contrast, in Central Africa (4.5 vs. 3.4) our values are moderately higher and in Pacific Asia (2.7 vs 0.9) significantly higher than FAO observations. The large gap in Pacific Asia can be partly explained by recent reforestation efforts in this region (Lamb, 2011), which are considered in FAO statistics but are not relevant for our definition of IFF.

Overall, our results show that in the main forest regions, Latin America, Sub-Sahara Africa, and Pacific Asia, cropland area would significantly increase over time under constant trade and forest protection. With growing trade liberalisation the most prominent region in terms of IFF area, Latin America, would clear an additional 40 million ha of forest area, leading to 25 Gt additional CO_2 emissions by 2050. At the same time, due to its comparative advantage, Latin America is the only region which requires higher technological change (TC) rates than in the reference case and expands its exports in each of the four major traded commodities (cereals, oilcrops, sugar, and meat). In contrast, Sub-Sahara Africa reduces its production level due to trade liberalisation. However, this decrease has no influence on the level of deforestation and is purely triggered by lower investments in technological change. In the $reference$ and *nopol* scenarios the low forest protection of the past in Africa is assumed to continue. This leads to dramatic forest loss in Central Africa in these scenarios. Although the disappearance of the whole tropical rainforest seems unrealistic, it gives an indication that especially the forests of Central Africa are likely to come under huge pressure in the future if no policy intervention is undertaken. Countries in Pacific Asia decrease their deforestation rate under liberalisation compared to the reference case. The main reason for this is that these countries have low comparative advantages in most agricultural commodities, which leads to further imports under liberalisation. However, the pace of deforestation there still increases with liberalisation, leading to higher rates until 2020. Land-scarce regions like the Middle East, North Africa, and South Asia are projected to see the highest growth in imports. With increasing liberalisation there is less pressure to increase productivity in these regions, resulting in significantly lower investment in technological advances.

Reducing emissions from land-use change requires intervention to protect forests. We combined trade scenarios with different forest protection measures, divided into direct regulations, market instruments, and compensation payments. Only in Latin America, forest protection leads to higher investment in TC. Except for some slight reductions, net export rates stay constant due to higher agricultural productivity. Hence, forest regions do not lose their competitive advantage as a consequence of forest protection.

As a direct regulation we increased protected areas (PAs) over time. We chose the rather extreme scenario of full forest protection in order to depict the whole range of possible outcomes. Soares-Filho et al. (2010) tried to quantify the impact of PAs in the Amazonian rainforest and concluded that 37% of the recent decline in deforestation was due to new PAs and 44% due to lower agricultural activity. In another study they estimated a reduction in deforestation of around 100 million ha by comparing a business-as-usual case with a strict governance scenario (involving an expansion of PAs and other legal protection enforcement) (Soares-Filho et al., 2006). Our continuously increasing rate of PAs in Latin America (*time* scenario) follows their governance scenario as far as possible and achieves savings of almost 90 million ha compared to a scenario without any further forest protection (*nopol*). Nepstad et al. (2009) even discussed the possibility of ending deforestation by 2020 (which is confirmed by our *550ppm* scenario), based on the assumed continuation and extension of recent efforts, like expansion of PAs, externally-financed funds and regulation efforts by the agri-business sector. However, if not monitored or applied globally, protecting forests in one place can lead to displacement of land use to other regions (Soares-Filho et al., 2010; Meyfroidt et al., 2010) and resulting carbon leakage (Wunder, 2008). Although we have not directly analysed this mechanism, we observe some non-continuous effects between different time steps and scenarios. For instance, in ORF between 2030 and 2040 deforestation is higher in the scenarios *time* and *lowprice* compared to the *nopol* scenario, whereas it is the other way round for LAM. Since agricultural area is not allowed to expand into IFF in LAM and PAS in this time step, agricultural area in Central Africa expands at the expense of IFF area. The establishment of protected areas should, therefore, be an international effort in order to avoid leakage effects and to support the political will in target countries (Soares-Filho et al., 2006).

As a representative policy for market instruments, we included a CO_2 price as a climate mitigation policy for avoided deforestation. With a price sufficiently high to reach the 550ppm concentration target, total emissions related to deforestation are below 10 Gt CO_2 by 2050. This rather sensitive behaviour is in line with other studies. The MiniCAM model is even more sensitive towards a CO_2 price by generating no land use related carbon emissions in a *550ppm* scenario (Wise et al., 2009). Its successor, the GCAM model, calculates deforestation levels under a 526ppm scenario amounting to around 30 Gt emissions between 2020 and 2050 (Thomson et al., 2010). Finally, the study by Kindermann et al. (2008) provides a comparison of three different models, GTM, DIMA and GCOMAP, by calculating marginal abatement cost curves. They show that with assumed constant carbon prices, deforestation in Latin America is fully avoided in 2020 with a CO_2 price of between 30 and 40 US$/tonne. In our study, this is already achieved with prices of 12 to 20 US$/tonne. With regard to climate mitigation, the inclusion of CO_2 prices has the advantage over other measures that the carbon intensity per unit of land is explicitly considered. As a consequence carbon-rich vegetation is valued higher and land expansion moves to places where forests and other natural vegetation contain relatively less carbon.

Lastly, we applied a scenario of indirect forest protection in order to investigate the effect of additional growth in agricultural productivity on deforestation (*TC* scenario). Results suggest that investment in technological change could potentially reduce the pressure on tropical rainforests. However, it has to be noted that an additional yield growth of 1% per year requires huge investment in the agricultural sector (Dietrich et al., 2013) and that this yield increase would not be sufficient to prevent deforestation completely. As shown by others as well, additional and complementary measures are needed (Wise et al., 2009; Thomson et al., 2010). In this context, Angelsen (2010) points out that local yield increases may encourage local deforestation and that, therefore, agriculture in low-forest areas should be supported instead of agriculture close to the forest frontier.

5 Conclusion

From our analysis we draw several conclusions. First, more trade liberalisation leads to a substantial increase in tropical deforestation in Latin America, driven by the strong growth in agricultural exports. Therefore, global liberalisation efforts, for instance by the World Trade Organization (WTO), should not be undertaken without considering global forest protection measures.

Second, policies to protect forest area do not necessarily lead to losses in trade competitiveness, since the reduced land availability is compensated in most cases by higher technological change rates. This contradicts often expressed concerns that policies to protect forests reduce economic growth or international competitiveness (Banerjee et al., 2009).

Third, pricing CO_2 emissions from deforestation could effectively conserve large parts of the tropical rainforests, avoid over 100 Gt of carbon emissions, and also preserve some of the most biodiverse ecosystems. Voluntary payments for avoided deforestation, as discussed under REDD+ can provide the same incentive.

Fourth, developed countries accelerate tropical deforestation due to their agricultural demand and should be aware of their responsibility regarding the virtual trade in land. Awareness of this problem has risen in recent years, and first attempts to tackle it have been made. The European Union, for instance, has set sustainability standards for biofuels. But also a decreasing demand for agricultural products by the global North would reduce the pressure on tropical forests.

Acknowledgements

We thank our colleagues in the land-use research group of PIK for many valuable discussions. We gratefully acknowledge financial support by the German BMBF projects "Hydrothermal carbonization of biomass" and "GLUES Global Assessment of Land Use Dynamics on Greenhouse Gas Emissions and Ecosystem Services" and the EU FP7 project "Visions of Land Use Transitions in Europe (VOLANTE)". Finally, we thank Alison Schlums for proofreading. The authors declare that there is no conflict of interest.

References

Angelsen, A. and D. Kaimowitz (2001), Introduction: the Role of Agricultural Technologies in Tropical Deforestation, *In:* A. Angelsen and D. Kaimowitz (eds.), Introduction: the Role of Agricultural Technologies in Tropical Deforestation, CABI Publishing, Oxon, UK and New York, USA.

Angelsen, A. (2010), Policies for reduced deforestation and their impact on agricultural production, *Proceedings of the National Academy of Sciences 107(46)*, 19639–19644. doi: 10.1073/pnas.0912014107

Banerjee, O., A.J. MacPherson and J. Alavalapati, J. (2009), Toward a Policy of Sustainable Forest Management in Brazil : A Historical Analysis, *Journal of Environment & Development 18(2)*, 130–153. doi: 10.1177/1070496509333567

Barbier, E.B. (2000), Links between economic liberalization and rural resource degradation in the developing regions, *Agricultural Economics 23(3)*, 299–310. doi: 10.1016/S0169-5150(00)00091-8

Barraclough, S. and K. Ghimire (2000), Agricultural expansion and tropical deforestation, Earthscan, London (2000).

Beresford, A.E., G.W. Eshiamwata, P.F. Donald, A. Balmford, B. Bertzky, A.B. Brink, L.D.C. Fishpool, P. Mayaux, B. Phalan, D. Simonetti and G.M. Buchanan (2013), Protection Reduces Loss of Natural Land-Cover at Sites of Conservation Importance across Africa, *PLoS ONE 8(5)*, e65370. doi: 10.1371/journal.pone.0065370

Bondeau, A., P. Smith, S. Zaehle, S. Schaphoff, W. Cramer, D. Gerten, H. Lotze-Campen, C. Müller, M. Reichstein and B. Smith (2007), Modelling the role of agriculture for the 20th century global terrestrial carbon balance, *Global Change Biology 13(3)*, 679–706. doi: 10.1111/j.1365-2486.2006.01305.x

Bradshaw, C.J.A., N.S. Sodhi, K. Peh and B.W. Brook (2007), Global evidence that deforestation amplifies flood risk and severity in the developing world, *Global Change Biology 13(11)*, 2379–2395. doi: 10.1111/j.1365-2486.2007.01446.x

Bryant, D., D. Nielsen and L. Tangley (1997), The Last Frontier Forests - Ecosystems and Economies on the Edge, World Resources Institute (WRI), Washington DC.

Byerlee, D., J. Stevenson and N. Villoria (2014), Does intensification slow crop land expansion or encourage deforestation?, *Global Food Security 3(2)*, 92–98. doi: 10.1016/j.gfs.2014.04.001

Conforti, P. and L. Salvatici (2004), Agricultural trade liberalisation in the Doha round - Alternative scenarios and strategic interactions between developed and developing countries, *FAO Commodity and Trade Policy Research Working Paper 10.*

Costa, M.H. and J.A. Foley (2000), Combined Effects of Deforestation and Doubled Atmospheric CO2 Concentrations on the Climate of Amazonia, *Journal of Climate 13*, 18–34. doi: 10.1175/1520-0442(2000)013<0018:CEODAD>2.0.CO;2

DeFries, R.S., T. Rudel, M. Uriarte and M. Hansen (2010), Deforestation driven by urban population growth and agricultural trade in the twenty-first century, *Nature Geoscience 3*, 178–181. doi: 10.1038/NGEO756

Dollar, D. and A. Kraay (2004), Trade, Growth and Poverty, *The Economic Journal 114*, 22–49. doi: 10.1111/j.0013-0133.2004.00186.x

Dietrich, J.P., C. Schmitz, C. Müller, M. Fader, H. Lotze-Campen and A. Popp (2012), Measuring agricultural land-use intensity - A global analysis using a model-assisted approach, *Ecological Modelling 232*, 109–118. doi: 10.1016/j.ecolmodel.2012.03.002

Dietrich, J.P., C. Schmitz, H. Lotze-Campen, A. Popp and C. Müller (2013), Forecasting technological change in agriculture - An endogenous implementation in a global land use model, *Technological Forecasting and Social Change* (In Press), DOI: http://dx.doi.org/10.1016/j.techfore.2013.02.003.

Eickhout, B., H. van Meijl, A. Tabeau and E. Stehfest (2010), The impact of environmental and climate constraints on global food supply, *In:* T.W. Hertel, S.K. Rose and R.S.J. Tol, Editors, Economic Analysis of Land Use in Global Climate Change Policy, Routledge, New York, 2009.

Erb, K.-H., V. Gaube, F. Krausmann, C. Plutzar, A. Bondeau and H. Haberl (2007), A comprehensive global 5 min resolution land-use data set for the year 2000 consistent with national census data, *Journal of Land Use Science 2(3)*, 191–224. doi: 10.1080/17474230701622981

Fader, M., S. Rost, C. Müller, A. Bondeau and D. Gerten (2010), Virtual water content of temperate cereals and maize: Present and potential future patterns, *Journal of Hydrology 384(3–4)*,218–231. doi: 10.1016/j.jhydro1.2009.12.011

FAO (2010), Global Forest Resources Assessment 2010, Main Report, Food and Agriculture Organization of the United Nations, FAO Forestry Paper 163, Rome.

FAO (2011a), FAOSTAT - Food and Agriculture Organization of the United Nations Statistics Division, Last Access: 12/10/2011 *: http://faostat.fao.org/.*

FAO (2011b), State of the World's Forests 2011, Food and Agriculture Organization of the United Nations, Rome.

Fearnside, P.M and W.F. Laurance (2003), Comment on "Determination of deforestation rates of the world's humid tropical forests", *Science 299*, 1015. doi: 10.1126/science.1078714

Fearnside, P.M (2005), Deforestation in Brazilian Amazonia: History, Rates, and Consequences, *Conservation Biology 19(3)*, 680–688. doi: 10.1111/j.1523-1739.2005.00697.x

Feenstra, R.C. (1998), Integration of Trade and Disintegration of Production in the Global Economy, *The Journal of Economic Perspectives 12(4)*, 31–50. doi: 10.1257/jep.12.4.31

Forner, C., J. Blaser, F. Jotzo and C. Robledo (2005), Keeping the forest for the climate's sake: avoiding deforestation in developing countries under the UNFCCC, *Climate Policy 6(3)*, 275–294. doi: 10.1080/14693062.2006.9685602

Gibbs, H.K., M. Johnston, J.A. Foley, T. Holloway, C. Monfreda, N. Ramankutty and D. Zaks (2008), Carbon payback times for crop-based biofuel expansion in the tropics: the effects of changing yield and technology, *Environmental Research Letters 3*, 034001. doi: 10.1088/1748-9326/3/3/034001

Gibbs, H.K., A.S. Ruesch, F. Achard, M.K. Clayton, P. Holmgren, N. Ramankutty and J.A. Foley (2010), Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s, *Proceedings of the National Academy of Sciences 107(38)*, 16732–16737. doi: 10.1073/pnas.0910275107

Gorenflo, L.J. and K. Brandon (2005), Agricultural Capacity and Conservation in High Biodiversity Forest Ecosystems, *AMBIO: A Journal of the Human Environment 34(3)*, 199–204. doi: 10.1639/0044-7447(2005)034[0199:ACACIH]2.0.CO;2

Hertel, T.W. (2012), Implications of Agricultural Productivity for Global Cropland Use and GHG Emissions: Borlaug vs. Jevons, *GTAP Working Paper 69.*

Heston A., R. Summers and B. Aten (2011), Penn World Table Version 7.0, *Center for International Comparisons of Production, Income and Prices at the University of Pennsylvania, May 2011.*

Hosonuma, N., M. Herold, V. De Sy, R.S. De Fries, M. Brockhaus, L. Verchot, A. Angelsen and E. Romijn (2012), An assessment of deforestation and forest degradation drivers in developing countries, *Environmental Research Letters 7(4)*, 004009. doi: 10.1088/1748-9326/7/4/044009

Houghton, R.A. (2003), Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000, *Tellus B 55(2)*, 378–390. doi: 10.1034/j.1600-0889.2003.01450.x

IPCC (2007), Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, B. Metz, O.R. Davidson, P.R. Bosch, R. Dave and L.A. Meyer (eds.), Cambridge University Press.

Jacks, D.S., C.M. Meissner and D. Novy (2008), Trade Costs 1870-2000, *The American Economic Review 98(2)*, 529–534. doi: 10.1257/aer.98.2.529

Josling, T. (2010), Looking ahead to 2050 - Evolution of agricultural trade policies, *In:* A. Sarris and J. Morrison (eds.), The evolving structure of world agricultural trade: implications for trade policy and trade agreements, FAO, Rome.

Kauppi, P.E., J.H. Ausubel, J. Fang, A.S. Mather, R.A. Sedjo and P.E. Waggoner (2006), Returning forests analyzed with the forest identity, *Proceedings of the National Academy of Sciences 103(46)*, 17574–17579. doi: 10.1073/pnas.0608343103

Kindermann, G., M. Obersteiner, B. Sohngen, J. Sathaye, K. Andrasko, E. Rametsteiner, B. Schlamadinger, S. Wunder and R. Beach (2008), Global cost estimates of reducing carbon emissions through avoided deforestation, *Proceedings of the National Academy of Sciences 105(30)*, 10302–10307. doi: 10.1073/pnas.0710616105

Kolstad, C., K. Urama, J. Broome, A. Bruvoll, M.C. Olvera, D. Fullerton, C. Gollier, W.M. Hanemann, R. Hassan, F. Jotzo, M.R. Khan, L. Meyer,

L. Mundaca, P. Aghion, H. Allcott, G. Betz, S. Borenstein, A. Brennan, S. Caney, D. Farber, A. Jaffe, G. Luderer, A. Ockenfels and A. Popp (2008), Social, Economic and Ethical Concepts and Methods, *In:* IPCC (eds.), Climate Change 2014: Mitigation of Climate Change.

Krause, M., H. Lotze-Campen and A. Popp (2009), Spatially-explicit scenarios on global cropland expansion and available forest land in an integrated modelling framework, *Selected and reviewed paper at the 27th IAAE Conference in Beijing, China, August 16-22, 2009.*

Krause M., H. Lotze-Campen, A. Popp, J.P. Dietrich and M. Bonsch (2012), Conservation of undisturbed natural forests and economic impacts on agriculture, *Land Use Policy 30*, 344–354. doi: 10.1016/j.landusepol.2012.03.020

Lamb, D. (2011), Regreening the Bare Hills - Tropical Forest Restoration in the Asia-Pacific Region, *World Forests VIII*, Springer. doi: 10.1007/s10745-011-9436-5

Lambin, E.F., B.L. Turner, H.J. Geist, S.B. Agbola, A. Angelsen, J.W. Bruce, O.T. Coomes, R. Dirzo, G. Fischer, C. Folke, P.S. George, K. Homewood, J. Imbernon, R. Leemans, X. Li, E.F. Moran, M. Mortimore, P.S. Ramakrishnan, J.F. Richards, H. Skanes, W. Steffen, G.D. Stone, U. Svedin, T.A. Veldkamp, C. Vogel and J. Xu (2010), The causes of land-use and land-cover change: moving beyond the myths, *Global Environmental Change 11(4)*, 261–269. doi: 10.1016/S0959-3780(01)00007-3

Lazdins, A., H. von Hofsten, L. Dagnija and V. Lazdans (2008), Productivity and costs of stump harvesting for bioenergy production in Latvian conditions, *Engineering for Rural Development 2009*, 194–201.

Lotze-Campen, H., C. Müller, A. Bondeau, A. Jachner, A. Popp and W. Lucht (2008), : Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical programming approach, *Agricultural Economics 39*, 325–338. doi: 10.1111/j.1574-

0862.2008.00336.x

Lotze-Campen, H., A. Popp, T. Beringer, C. Müller, A. Bondeau, S. Rost and W. Lucht (2010), Scenarios of global bioenergy production: The trade-offs between agricultural expansion, intensification and trade, *Ecological Modelling 221*, 2188–2196. doi: 10.1016/j.ecolmodel.2009.10.002

Luderer, G., R. Pietzcker, E. Kriegler, M. Haller and N. Bauer (2012), Asia's Role in Mitigating Climate Change: A Technology and Sector Specific Analysis with ReMIND-R, *Energy Economics (under review)*. doi: 10.1016/j.eneco.2012.07.022

Martin, W. and A. Mattoo (2011), Unfinished Business? - The WTO's Doha Agenda, World Bank Report in cooperation with the Centre for Econmic Policy Research, Washington DC, available at URL: http://go.worldbank.org/S9GA0D7RY0.

Merry, F.D., P.E. Hildebrand, P. Pattie and D.R. Carter, (2002), An analysis of land conversion from sustainable forestry to pasture: a case study in the Bolivian Lowlands, *Land Use Policy 19*, 207–215. doi: 10.1016/S0264-8377(02)00015-7

Meyfroidt, P., T.K. Rudel and E.F. Lambin (2010), Forest transitions, trade, and the global displacement of land use, *Proceedings of the National Academy of Sciences 107(49)*, 20917–20922. doi: 10.1073/pnas.1014773107

Meyfroidt, P. and E.F. Lambin (2011), Global Forest transitions: Prospects for an End to Deforestation, *Annual Review of Environment and Resources 36*, 343–371. doi: 10.1146/annurev-environ-090710-143732

Morton, D.C., R.S. DeFries, V.E. Shimabukuro, L.O. Anderson, E. Arai, F. Espirito-Santo, R. Freitas and J. Morisette (2006), Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon, *Proceedings of the National Academy of Sciences 103(39)*, 14637–14641. doi: 10.1073/pnas.0606377103

Narayanan, B. and T.L. Walmsley (2008), Global Trade, Assistance, and Production: The GTAP 7 Data Base, *Center for Global Trade Analysis, Purdue University.*

Nelson, A. (2008), Estimated travel time to the nearest city of 50,000 or more people in year 2000, *Global Environment Monitoring Unit - Joint Research Centre of the European Commission, Ispra Italy. URL: http://bioval.jrc.ec.europa.eu/products/gam/ (accessed 30/07/2011).*

Nelson, A. and K.M. Chomitz (2011), Effectiveness of Strict vs. Multiple Use Protected Areas in Reducing Tropical Forest Fires: A Global Analysis Using Matching Methods, *PLoS ONE 6(8)*, e22722. doi: 10.1371/journal.pone.0022722

Nepstad, D.C., C.M. Stickler and O.T. Almeida, (2006), Globalization of the Amazon Soy and Beef Industries: Opportunities for Conservation, *Conservation Biology 20(6)*, 1595–1603. doi: 10.1111/j.1523-1739.2006.00510.x

Nepstad, D., B.S. Soares-Filho, F. Merry, A. Lima, P. Moutinho, J. Carter, M. Bowman, A. Cattaneo, H. Rodrigues, S. Schwartzman, D.G. McGrath, C.M. Stickler, R. Lubowski, P. Piris-Cabezas, S. Rivero, A. Alencar, O. Almeida and O. Stella (2009), The End of Deforestation in the Brazilian Amazon, *Science 326(5958)*, 1350–1351. doi: 10.1126/science.1182108

Pan, J., R.A. Birdsey, J. Fang, R. Houghton, P.E. Kauppi, W.A. Kurz, O.L. Philips, A. Shvidenko, S.L. Lewis, J.G. Canadell, P. Ciais, R.B. Jackson, S.W. Pacala, A.D. McCuire, S. Piao, A. Rautiainen, S. Sitch and D. Hayes (2011), A large and persistent carbon sink in the World's Forests, *Science 333(6045)*, 988–993. doi: 10.1126/science.1201609

Parker, C., A. Mitchell, M. Trivedi, N. Mardas and K. Sosis (2009), The Little REDD+ Book - An updated guide to governmental and non-governmental proposals for reducing emissions from deforestation and degradation, *Global Canopy Programme*, Oxford, UK.

Peters-Stanley, M. and G. Gonzalez (2014), Sharing the Stage. State of the Voluntary Carbon Markets 2014, *Forest Trends Ecosystem Marketplace 1.*

Popp, A., H. Lotze-Campen and B. Bodirsky (2010), Food consumption, diet shifts and associated non-CO2 greenhouse gases from agricultural production, *Global Environmental Change 20*, 451–462. doi: 10.1016/j.gloenvcha.2010.02.001

Popp, A., J.P. Dietrich, H. Lotze-Campen, D. Klein, N. Bauer, M. Krause, T. Beringer, D. Gerten and O. Edenhofer (2011), The economic potential of bioenergy for climate change mitigation with special attention given to implications for the land system, *Environmental Research Letters 6(3)*, 034017. doi: 10.1088/1748-9326/6/3/034017

Popp A., M. Krause, J.P. Dietrich, H. Lotze-Campen, M. Leimbach, T. Beringer and N. Bauer (2012), Additional CO2 emissions from land use change - Forest conservation as a precondition for sustainable production of second generation bioenergy., *Ecological Economics 74*, 64–70. doi: 10.1016/j.ecolecon.2011.11.004

Potapov, P., A. Yaroshenko, S. Turubanova, M. Dubinin, L. Laestadius, C. Thies, D. Aksenov, A. Egorov, Y. Yesipova, I. Glushkov, M. Karpachevskiy, A. Kostikova, A. Manisha, E. Tsybikova and I. Zhuravleva (2008), Mapping the world's intact forest landscapes by remote sensing, *Ecology and Society 13(2).*

Ramankutty, N., H.K. Gibbs, F. Archard, R. deFries, J.A. Foley and R.A. Houghton (2006), Challenges to estimating carbon emissions from tropical deforestation, *Global Change Biology 13(1)*, 51-66. doi: 10.1111/j.1365-2486.2006.01272.x

Rost, S., D. Gerten, A. Bondeau, W. Lucht, J. Rohwer and S. Schaphoff (2008), Agricultural green and blue water consumption and its influence on the global water system, *Water Resources Research 44*, W09405. doi:

10.1029/2007WR006331

Schmitz, C., A. Biewald, H. Lotze-Campen, A. Popp, J.P. Dietrich, B. Bodirsky, M. Krause and I. Weindl (2012), Trading more Food - Implications for Land Use, Greenhouse Gas Emissions and the Food System, *Global Environmental Change 22(1)*, 189–209. doi: 10.1016/j.gloenvcha.2011.09.013

Simmons, I.G. (1987), Transformation of the land in pre-industrial time, *In:* M.G. Wolman and F.G.A. Fournier (eds.), Land Transformation in Agriculture, *John Wiley and Sons*, Chichester, UK, 45–77.

Simorangkir, D. (2007), Fire use: Is it really the cheaper land preparation method for large-scale plantations?, *Mitigation and Adaptation Strategies for Global Change 12*, 147–164. doi: 10.1007/s11027-006-9049-2

Soares-Filho, B.S., D.C. Nepstad, L.M. Curran, G.C. Cerqueira, R.A. Garcia, C.A. Ramos, E. Voll, A. McDonald, R. Lefebvre and P. Schlesinger (2006), Modelling conservation in the Amazon basin, *Nature*, *440*, 520–523. doi: 10.1038/nature04389

Soares-Filho, B.S., P. Moutinho, D.C. Nepstad, A. Anderson, H. Rodrigues, R.A. Garcia, L. Dietzsch, F. Merry, M. Bowman, L. Hissa, R. Silvestrini, and C. Maretti (2010), Role of Brazilian Amazon protected areas in climate change mitigation, *Proceedings of the National Academy of Sciences*, *107(24)*, 10821–10826. doi: 10.1073/pnas.0913048107

Sohngen, B., C. Tennity, and M. Hnytka (2009), Global forestry data for the economic modeling of land use, *In:* Hertel, T.W.; Rose, S.; Tol, R.S.J. (Eds.), Economic analysis of and use in global climate change policy, Routledge, New York. pp 49- 71.

Thomson, A.M., K.V. Calvin, L.P. Chini, G. Hurtt, J.A. Edmonds, B. Bond-Lamberty, S. Frolking, M.A. Wise and A.C. Janetos (2010), Climate Mitigation and the Future of Tropical Landscapes, *Proceedings of the National Academy of Sciences*, *107(46)*, 19633–19638. doi: 10.1073/pnas.0910467107

UN (2011). World Population Prospects: The 2010 Revision, *United Nations, Department of Economic and Social Affairs, Population Division, CD-ROM Edition.*

UNEP-WCMC (United Nations Environment Programme World Conservation Monitoring Centre) (2006): World Database on Protected Areas (WDPA), CD-ROM, Cambridge, U.K, available at URL: http://sea.unep-wcmc.org/wdbpa/.

van Meijl, H., T. van Rheenen, A. Tabeau and B. Eickhout (2006), The impact of different policy environments on agricultural land use in Europe, *Agriculture, Ecosystems and Environment*, *114*, 21–38. doi: 10.1016/j.agee.2005.11.006

van Velthuizen, H., B. Huddleston, G. Fischer, M. Salvatore, E. Ataman, F.O. Nachtergaele, M. Zanetti, M. Bloise, A. Antonicelli, J. Bel, A. De Liddo, P. De Salvo and G. Franceschini (2007): Mapping biophysical factors that influence agriculturalproduction and rural vulnerability, *Environment and Natural Resources Series*, *11*, FAO, Rome.

van der Werf, G.R., D.C. Morton, R.S. DeFries, J.G.J. Olivier, P.S. Kasibhatla, R.B. Jackson, G.J. Collatz and J.T. Randerson (2009), CO_2 emissions from forest loss, *Nature Geoscience*, *2(11)*, 737–738. doi: 10.1038/ngeo671

Verburg, R., E. Stehfest, G. Woltjer and B. Eickhout (2009), The effect of agricultural trade liberalisation on land-use related greenhouse gas emissions, *Global Environmental Change*, *19*, 434–446. doi: 10.1016/j.gloenvcha.2009.06.004

Wise, M., K. Calvin, A. Thomson, L. Clarke, B. Bond-Lamberty, R. Sands, S.J. Smith, A. Janetos, J. Edmonds (2009), Implications of Limiting CO2 Concentrations for Land Use and Energy, *Science*, *324*, 1183–1186. doi: 10.1126/science.1168475

Würtenberger, L., T. Koellner and C.R. Binder (2007), Virtual land use and agricultural trade: Estimating environmental and socio-economic impacts, *Ecological Economics*, *57(4)*, 679–697. doi: 10.1016/j.ecolecon.2005.06.004

Wunder, S. (2008), How do we deal with leakage?, *In:* Angelsen, A. (ed.) Moving ahead with REDD: issues, options and implications, 65-75. CFIOR, Bogor, Indonesia.