Spatially-explicit scenarios on global cropland expansion and available forest land in an integrated modelling framework

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Introduction

The pressure on land as required input in competing uses for agriculture and others fuelled research on global land use and potentials for producing food and non-food commodities while conserving biodiversity and carbon sink functions. Thus, trade-offs in land use due to agricultural land expansion to meet food demand are explicitly and implicitly treated in global land use modelling.

Inputs on the initial stock of crop and non-cropland may result from satellite-based biophysical mappings combined with national inventory data (Ramankutty and Foley 1998, Erb et al. 2007, Klein Goldewijk et al. 2007, Fischer et al. 2002, IMAGE team 2001). Several mapping exercises deal with the spatial extent and patterns of global cropland and grassland but lack accounting for non-agricultural land uses (Ramankutty and Foley 1998, Klein Goldewijk et al. 2007).

Extended land mappings are stimulated by the state-of-the-art Global Agro-Ecological Assessment (GAEZ) methodology on land suitability (Fischer et al. 2002, v. Velthuizen et al. 2007). These exercises exclude land use and cover types (v. Velthuizen et al. 2007) or additionally take population density, proximity parameters and tree cover into account (Bouwman et al. 2006) to allocate land to rainfed crops and pasture according to suitability characteristics. They, however, may still face redundancies in classification. Erb et al. (2007) combines the strength of spatially-explicit mapping and providing consistency with national statistics in land use maps that cover the entire global land stock. The advantage lays in the applicability in non-redundant global land use budgeting.

Empirical climate and soil parameter-based land suitability maps pinpoint less than 25 % (Fischer et al. 2002), 31 % and 33 % (FAO 2002) of the global land stock to be suitable as cropland. Subtracting current cropland leaves 11 % to 21 % of global land to be suitable, i.e. 99 % to more than 180 % of the current cropland (own calculations from Fischer et al. 2002, FAO 2002). About 45 % of potential land is located in forests, 12 % in protected areas and 3 % occupied by human settlements and infrastructure (FAO 2002). About 15 % of the world crop production between 1961 and 1999 are attributed to cropland expansion on average but with major deviations above this figure in regions with a higher share of non-arable land like Sub-Saharan Africa (35 %) and Latin America (46 %) (FAO 2002:38). The share of non-agricultural land shifted to arable and permanent cropland between 1961 and 2003 sums to about 7 % in South-East Asia (own calculations from FAO 2004). In contrast, Europe shows the reverse trend by releasing 1 % of cropland on average (ibid.).

Global economic and integrated land use modelling approaches as compiled by Ronneberger (2006) and Heistermann et al. (2006) use rules to define the initial land base obtained from mappings, databases or in kind of direct outputs from other models. Exemplifying the economic model class, the land base is set up by regional land type data sets from WRI (1992) (partial equilibrium (PE) AgLU model, Sands and Leimbach 2003) or national and subnational statistics on irrigated and rainfed area (PE IMPACT model, Rosegrant et al. 2008), applying rules to, *inter alia*, exclude wilderness (Sands and Leimbach 2003). In a different approach, available land data sets enter as regional aggregate via a land transition matrix (IMAGE 2.2 modelling framework, IMAGE team 2001) into the economic model (Computable General Equilibrium (CGE) GTAP-L model, Burniaux 2002). To determine the rate of land conversion to agriculture, Rosegrant et al. (2008) introduce a growth rate of cropland area as component in crop price-based area response function. Sands and Leimbach (2003) shift land between crop, livestock and forest sectors relative to returns obtained. Burniaux, Lee (2002) and Burniaux (2002) prescribe transitions of sectoral land area by the scenario B2 SRES. The weak point of economic models is missing spatial explicitness and thus the lack of spatial heterogeneity in land endowment.

An example of integrated modelling approaches reveals regional bio-physically-based land classes of the world land stock to set up the stock of allocable land as classes associated with distinct land uses (GIS-based CGE FARM model, Darwin et al. 1996). A different modelling framework (KLUM model and CGE GTAP-EFM model, Ronneberger 2006; Ronneberger et al. 2008) sets up the available land based on harvested area per country taken from the FAO (2004) database. In a third example, the maximal available land for crop production is derived by excluding protected areas and existing agricultural and urban land and setting up the land base as asymptote of the land supply curve for each region (IMAGE modelling framework and CGE GTAP model, Bouwman et al. 2006). Darwin et al. (1996) induce inter- and intra-class land shifts by climate, population growth and trade scenarios. Ronneberger (2006) assumes a constant harvested area over time. In a more elaborated approach the change in the gap between potentially available land and current agricultural land leads to one of four prescribed land conversion types and a change in land prices (Bouwman et al. 2006).

We pursue a spatially-explicit land use-budgeting approach in global available land assessment to overcome overlaps in classification. Redefining the spatially-explicit land base in the Model of Agricultural Production and its Impact on the Environment (MAgPIE) is work in progress which is motivated by gaps in previous approaches – balancing spatial and economic explicitness and using conceptually consistent land use data sets. The implementation of available land and plausible conversion rates in MAgPIE may contribute to the improved modelling of agricultural land expansion paths over time and space. Our objective is to develop rules for determining the spatially-explicit available land for cropland expansion and to implement exogenous land conversion rates in a first step.

The next section introduces the model and gives evidence on our available land and conversion rate elaborations in methodological context and underlying assumptions. Results and the discussion of the model behaviour are provided in section 3. Section 4 offers the conclusions and an outlook.

Methodological framework

The current state of available land and its conversion into cropland in an existing land use optimization model is conceptually advanced by scenarios on global land use types in addition to a scenario on land conversion. The methodological framework on joint spatially-explicit scenarios until 2055 form the backbone for optimization runs.

Current state of available land and conversion rates in MAgPIE

MAgPIE is a spatially-exlicit recursive-dynamic global land use optimization model which, in its current state, minimizes the total costs of agricultural production. It covers the most important agricultural crop and livestock production types in 10 economic regions worldwide at a spatial resolution of three by three degrees taking regional economic conditions and spatially-explicit bio-physical constraints into account (Lotze-Campen et al. 2008).

Land enters as production input in limited supply. Cropland expansion is regarded as one option to adapt production to projected total food consumption (ibid.). Land available for cropland expansion is defined as the total land per cell minus crop and pasture area (ibid.). The initial setup of the static cropland mask relies on Ramankutty and Foley (1998) to start land allocation in decadal time steps. If necessary, cropland expansion is allowed at additional costs. The extent of maximal convertible land per time step is tightened by exogenous scaling parameters. Conversion costs mimic regional-specific relative higher costs for developed regions than developing regions (Lotze-Campen et al. 2008).

Pre-processing input datasets: Concept, assumptions and employed datasets

The employment of available land as production input deserves refinement to explicitly incorporate other land uses. The introduction of proxies of land required in other sectors through available land scenarios and historically-based land conversion scenarios is supposed to be the adequate approach. The global land budget calculation is based on Erb et al. (2007) under assumptions as follows. (1) For the sake of smoothness with historical time-series, the consistent cropland datasets is substituted by a cropland data set produced by Fader et al. (submitted). It comprises rainfed and irrigated areas for 13 crop functional types (cfts) and constitutes a synthesis of previous mapping approaches (Portmann et al. submitted, Portmann et al. 2008, Ramankutty et al. 2008). (2) Urban land is allocated to housing, business and administrative uses and is assumed to represent the most developed, i.e. highest valued type of land use. Thus, conversion to agricultural land is unlikely. The 1.1 % global urban land share (own calculations from Erb et al. 2007) is excluded from conversion. (3) The pasture land is assumed to not be mobile. (4) Forestry and unused land is excluded from potential conversion based on land non-suitability for rainfed crops (Fischer et al. 2002). From an economic perspective, the use of land is assumed to take place from the most to the least suitable land parcel, associated with declining productivity and rising marginal costs of conversion (Bouwman et al. 2006). (5) The land pool is further constrained by land required for nature conservation. We assume, implicitly, high opportunity costs of land conversion to prevent from converting intact and frontier forests (Bryant et al. 1997, Greenpeace 2005). (6) Alternatively, IUCN protected areas (UNEP-WCMC 2007) are non-convertible by political consensus. To avoid redundant and spurious ways of integration, the strictest terrestrial conservation categories I and II are assumed to be covered by the unused, forestry and grazing classes owing to the non-presence of nature reserves, wilderness area and national parks in cropland and urban areas. (7) A hierarchical nested structure is assumed in data integration with land use classes (Erb et al. 2007) at the first level, suitable land (Fischer et al. 2002) at the second level, intact and frontier forest (Bryant et al. 1997, Greenpeace 2005) at the third and tropical forest subset (Olsen et al. 2001) at the fourth level. IUCN areas (UNEP-WCMC 2007) are categorized as third-level inputs. The backbone of data integration is established by data sets as follows (Table 1).

<<Table 1>>

In the data integration procedure second and lower order input datasets are prepared to fit into fractions of cropland, forestry, grazing land, built up (urban) and unused land in the MAgPIE reference grid at 3° resolution, i.e. about 300km*300km grid cell size. This is achieved by aggregation via the area-weighted mean algorithm and harmonization exercises with rules on the handling of missing values, the over- and underestimation of aggregated values and validation checks. Tools primarily used in data integration comprise ARCGIS v. 9.2, R v. 2.6.1. and the C programming language.

The output consists of global datasets at 0.5° and 3° resolution on the fraction of land that is suitable for rainfed crop production in different land use classes by taking into account intact and frontier forests and protected areas.

Scenario on land conversion rates

Decadal land conversion rates have been estimated from the summed historical annual arable and permanent cropland area change taken from statistical time-series datasets for 1961 to 2001 (FAO 2004). Linear trends in regionally aggregated absolute cropland areas over time are assumed which fits well with the statistical data[1]. Declining cropland areas are observable in Europe and the Former Soviet Union. Historical data for North America suggested the use of a quadratic function. In order to simplify calculations we linearly approximate the quadratic function and calculate the average slope per decade. In our land conversion scenario we firstly assume diminishing absolute conversion of non-cropland in the future which is a function of the scenario-dependent available land stock and imitated by a constant percentage rate fixed at the year 1995 level. This is simply the coefficient of the summed annual slope of the cropland expansion to its decadal base area. Thus, we approximate the economic infeasibility of converting the last unit of non-cropland, i.e. non-cropland never gets used up. We secondly assume no land conversion in regions with observed abandonment of cropland, which applies to Europe, Former Soviet Union and North America. In order to cover variability in parameter space we include the standard deviation of residuals from historical data. In MAgPIE, the scenario-dependent percentage rate of change connected to the available land stock prescribes the upper regional constraint of land conversion activity per time step.

[1] indicated by $R^2 = 0.75$ (Former Soviet Union) to $R^2 = 0.98$ (Latin America)

The costs of land conversion are still exogenously provided and are not subject to further refinement at this stage with one exception. Cropland abandonment does not benefit the social planner by negative conversion costs, since no transactions in competitive land markets are simulated but the cultivation of previously unused land.

Elaboration of joint scenarios

The assumptions on integrating datasets facilitate the distinction of available land modules which are deliberately combined in three overarching scenario groups to construct joint scenarios in connection with land conversion rates. Land modules and scenario groups are illustrated in Figure 1.

<<Figure 1>>

Scenario groups thematically refer to (1) two land suitability options at their maximal spatial extent, (2) two exclusion options of frontier and intact forests on suitable land and (3) one option to exclude IUCN areas on suitable land.

We contrast two scenarios: The baseline scenario from scenario group one allows for cropland expansion into non-managed forestry land and unused land in natural vegetation bearing at least marginal suitability (SI 0) which is convertible at the historical rate. Climate change effects are switched off, the trade balance and share of water-saving technology in irrigation are kept at default, and bioenergy is not demanded (see Lotze-Campen et al. 2008). The forest conservation scenario excludes, *ceteris paribus*, tropical intact and frontier forests on at least marginally suitable forestry and unused land. Regional input parameters are depicted in Table 2. Additional scenarios may cover the change in land suitability, the exclusion of IUCN areas for land suitability options at varying rates albeit several combinations of dataset modules may serve for scenario definition.

Available land in land use optimization: Updating space in time

The scenario-based available land determines the allocable land per grid cell in each time step in a recursive-dynamic way as illustrated in the conceptual framework (Figure 2).

<<Figure 2>>

The global land allocation mechanism is designed to incorporate a spatially-explicit and temporal dimension. The set up of land stock takes place in time step t_0 in each grid cell. Through an iterative process the cost optimum at t_0 determines the optimized cropland area, C at t_0, and the optimized remaining land area A at t_0. During optimization the land constraint of land types m, i.e. crop and non-cropland, in cell i, $land\_const_{i,m}$ is binding for the sum of levels of activities x, i.e. crop and conversion activities $x_{i,k}$ (1)

$$\sum_k x_{i,k} * \left(req\_land_{i,k,m} - y\_land_{i,m}\right) \leq land\_const_{i,m} \qquad (1)$$

whereas $req\_land_{i,m}$ constitutes the land requirement and y_land_i is the land delivery from conversion. Land conversion takes place if the marginal costs of production on initial or optimized cropland exceed regional-specific costs of conversion plus the factor requirements for setting up the new production base on an additional hectare of cropland. The marginal costs of production are the summed variable factor requirements complementing one additional hectare of cropland and the costs for required technological change.

The magnitude of land expansion in the allocation procedure is restricted by the upper constraint (2).

$$y\_land_{i,m_{crop}} \leq land\_const_{i,m_{non\_crop}} * (lcr_i + \sigma) \quad (2)$$

It defines the permitted land conversion by means of the land stock and the previously described regional conversion rates lcr_i and the standard deviation of the residuals σ. The subscript *non_crop* comprises the initially or optimized available land respectively.

In each subsequent time step $t_1 \ldots t_m$[2], *C* and the scenario-specific *A* are quantified based on the *C* at $t_{1-1} \ldots t_{m-1}$.

Technically, scenario-based exclusion share parameters are subtracted from the total land share per cell. The time step-wise update of the optimization-depending cropland share triggers the update of the non-agricultural share in analogous manner. Scalar values serve as options to switch on/off combinations of available land and regional conversion rates to in the baseline and forest conservation scenarios. MAgPIE runs in GAMS version 23 using the non-linear solver CONOPT (Drud 1996).

[2]In this paper, 6 time steps for model runs until 2055 are considered.

Projections of land use patterns, technological change and total costs of production

Results pertain to the available land stock, the change of land use patterns, relative total costs and required rates of technological change in three regions harbouring tropical natural forest, Latin America, Sub-Saharan Africa and Pacific Asia.

Land use patterns

Actually converted areas in Sub-Saharan Africa and Latin America account for more than two-third of the totally converted 310 million hectares from 2005 to 2055 (Table 3). However, the projected distribution of cropland use depends on the region-specific average per-hectare production costs that accrue to the social planer for crop-based activities (Lotze-Campen et al. 2008). Additionally, cellular varying crop yields based on bio-physical constraints (Müller et al. 2006) determine the spatially-explicit production costs per ton output which leads to distinct patterns of land use. Figure 3 shows the change in optimized cropland shares between 2005 and 2055 exemplarily illustrated for the baseline.

<<Figure 3>>

The spatially-explicit illustration points to locations of crop production where the trend of clustering is projected. The optimization approach in MAgPIE leads to a clustering of production activities which can be referred to as specialization. Lotze-Campen et al. (2008) confirms that in large regions with low average, unevenly distributed yields production is shifted to the most productive cells. Accordingly in the baseline, highly productive cells are used as cropland up to 100 percent particularly in the Amazon and the Congo basin. Possible gaps between regional food supply and demand due to relatively higher increase in demand than area-loss compensating required yield growth are compensated by trade based on comparative cost advantages (Lotze-Campen et al. 2008). As expected, the variability in cropland conversion is less if forest conversion is prohibited.

The two scenarios approximate different food production strategies of the social planner over time – pursuing either predominantly land expansion or, if land is insufficiently available, agricultural intensification. For each of the regions the relative development of cropland expansion, land abandonment and non-cropland decline is contrasted to the required rate of technological change (Figure 4). Technological change is endogenously treated in MAgPIE as the yield increase needed to bring supply and demand into equilibrium if resource constraints do not permit additional land use activities (Lotze-Campen et al. 2008).

<<Figure 4>>

The effect of the magnitude of available land on diminishing land expansion is demonstrated in all regions. The general projected difference in the slope of converted non-cropland between the scenarios is result of weighting marginal benefits versus marginal costs of land conversion. Specifically, the model behaviour of foregoing the costs for an additional unit of technological change and the corresponding increase in factor requirements is explained by lower marginal costs of production through conversion and corresponding new variable factor inputs. This helps to foster cost-efficiency in global food production.

If forest is conserved the steeper decline of required technological change rates may be explained by the absolute higher level of technological change in the first time step which leads to a compounded interest effect in yield increase in subsequent time steps.

Concerning the forest conversion scenario in Sub-Saharan Africa it is indicated that a fraction of cropland is abandoned over time. This can be due to the comparative cost advantages of other regions and triggered trade after achieving the prescribed regional self-sufficiency rate in food production. However, if forest is allowed to be cut, the highest regional slope in relative cropland expansion coincides with the highest absolute number of converted land (~ 110 million hectares between 2005 and 2055, see Table 3). This fact unveils the pressure on natural forests to be cut for food production in Sub-Saharan Africa if investments in technological change remain insufficient. The effect is likely to be aggravated if additional biomass production for other purposes (energy, timber, etc.) is taken into account.

Required average rates of technological change

Since the scenarios determine food production strategies over time, implications on the magnitude of average technological change and total costs of production until 2055 need clarification.

The average technological change rates give a hint on the magnitude of yield increase necessary to feed a projected global population of more than nine billions in the year 2055. We pinpoint the minimum required yield increase which may be achieved by productivity changes due to rotational effects or raised land productivity connected to increased variable inputs (Figure 5).

<<Figure 5>>

Sub-Saharan Africa's required technological change peaks at ~1.8 percent per annum if forest worth to be conserved is left untouched. Given this number, yields would have more than to double (at ~1.4 percent yield increase per annum) to meet food demand of projected 1.6 billion inhabitants, a 120 percent growth compared to the year 2005. In contrast, Latin America and Pacific Asia (~49 and ~45 percent population growth respectively) require yield increase similar to the global average at ~0.9 percent.

The relatively less average yield increase required in Sub-Saharan Africa to compensate reduced area expansion compared to the remaining two regions (~62 percent compared to 151 and 87 percent in Latin America and Pacific Asia respectively) underlines the positive effect of high investments in early intensification (see Figure 4).

Total costs of agricultural production

The relative total costs of agricultural production are calculated from the cost coefficient of the forest conservation scenario to the baseline for each time step (Figure 6).

<<Figure 6>>

The implications of the two food production strategies comprise varying magnitudes but a similar shape of relative cost development over time. In the forest conservation scenario, the projected higher relative production costs result from weighting more restricted land expansion versus intensification. Lower yields on potentially convertible land translate into higher production costs per ton output, which add on top of conversion costs and are weighted against regional costs of technological change.

The relatively higher but declining total cost relative to the baseline gives evidence that even if the social planner faces high investment costs in the first time steps to intensify crop production, the benefit of not doing so, i.e. the cost reduction from converting forest diminishes. Taking into consideration the value of multiple benefits from conserved forests, e.g. of climate change mitigation effects or preserved biodiversity there may be a net benefit, i.e. relative cost reduction derived from the early intensification strategy. This is true if the foregone net benefits are treated as additional costs in crop production.

Conclusions and outlook

We have presented a work-in-progress version of implemented arguments for plausible land expansion in the model MAgPIE.

Pertaining to the available land input datasets, we conclude that they provide arguments for the stock of convertible land being defined in line with state-of-the-art available land elicitation approaches. Scenarios may be used to specify the bio-physically and normatively set location and time of land conversion which improves the current available land stock and conversion mechanism significantly.

The basic mechanism of land conversion for an exogenously defined available land stock linked to historical conversion rates has been demonstrated. It is concluded that land use patterns are result of trading off land expansion versus agricultural intensification and associated costs.

The effect of declining rates of required yield increase has been projected. It is concluded, that in Sub-Saharan Africa the positive effect of high investments in early intensification is strongest referred to the relative and absolute area of conservable forest due to the highest absolute rates of yield increase. If natural forest conservation in Africa gains priority in international discussions on mitigating climate change, yields would have more than to double until 2055.

Thus, in a next step, the analysis of model sensitivity to conversion rates will be conducted. Subsequent to exogenous historical land conversion rates, the introduction of marginal land conversion cost rates will be the first step to substitute exogenous rates of land conversion based on transition rules. In addition, the opportunity costs of avoided deforestation are calculated to obtain static cost curves over scenarios of gradually conserved forest and time-dynamic costs curves.

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Appendix

Figure 1: Available land modules and scenario groups

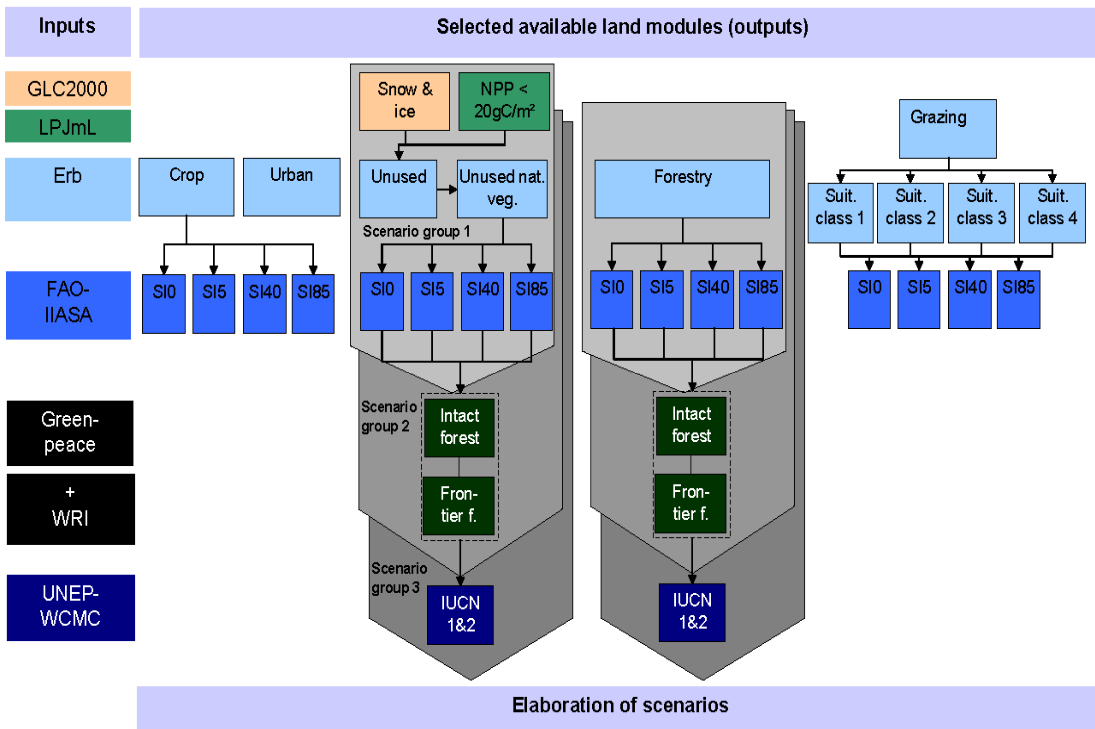

Figure 2: Concept of feedback mechanisms in space and time of allocating existing cropland and available non-cropland to agricultural production

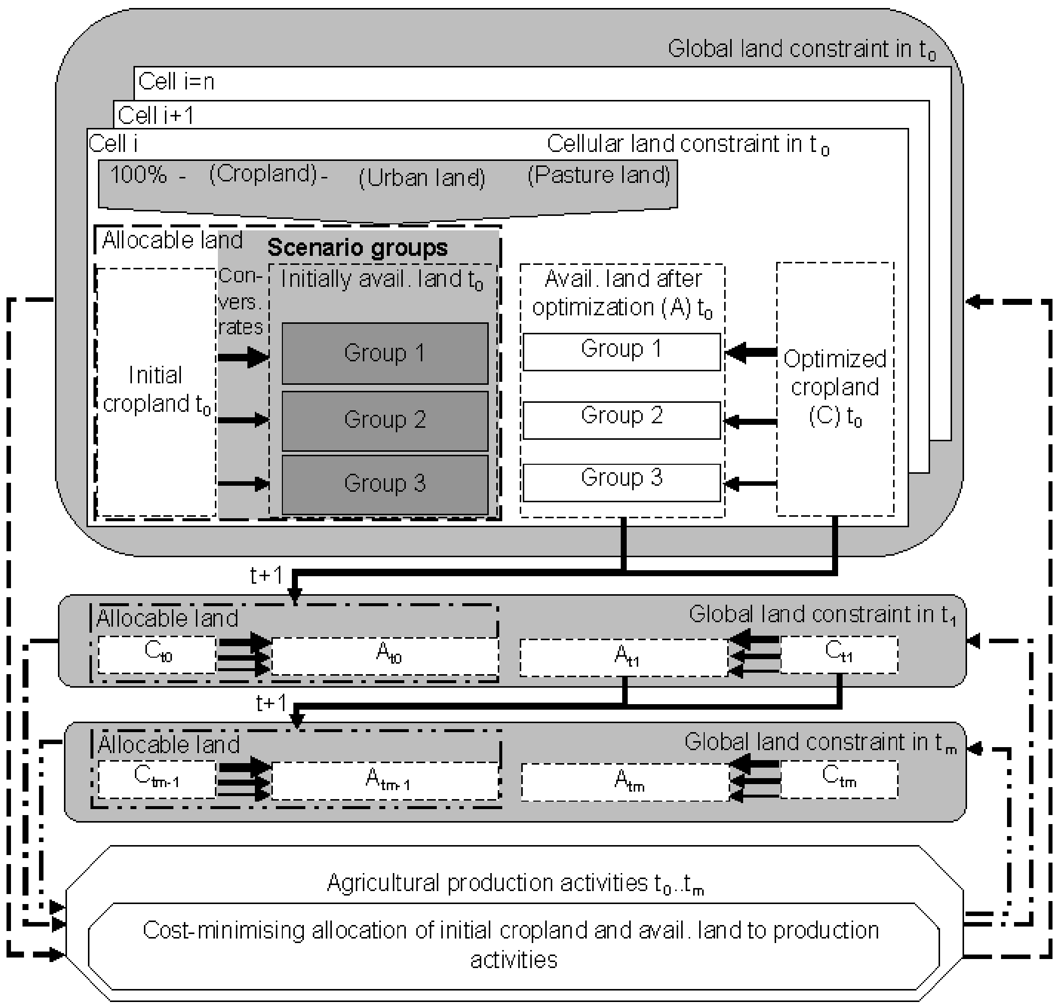

Figure 3: Change in optimized cropland share 2005 to 2055

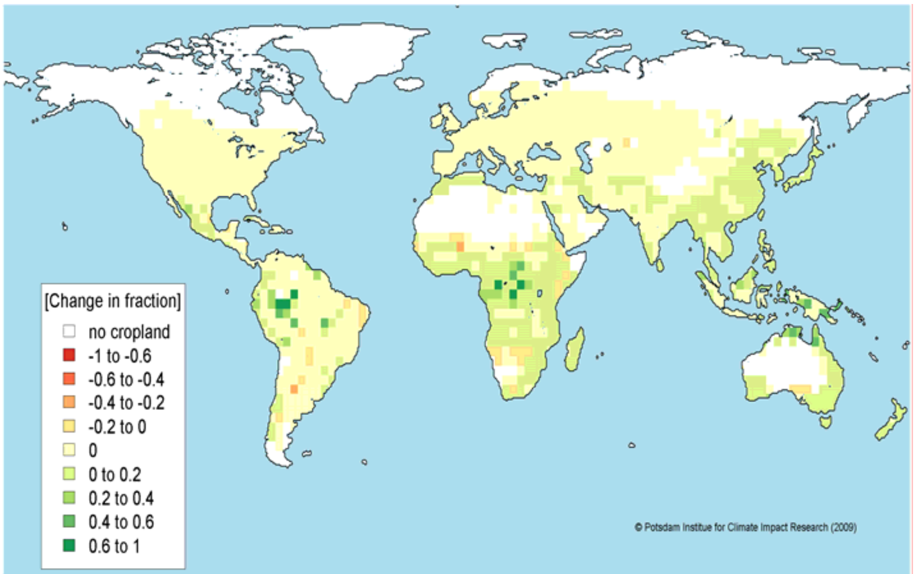

Figure 4: Regional agricultural land use dynamics: Expansion vs. intensification

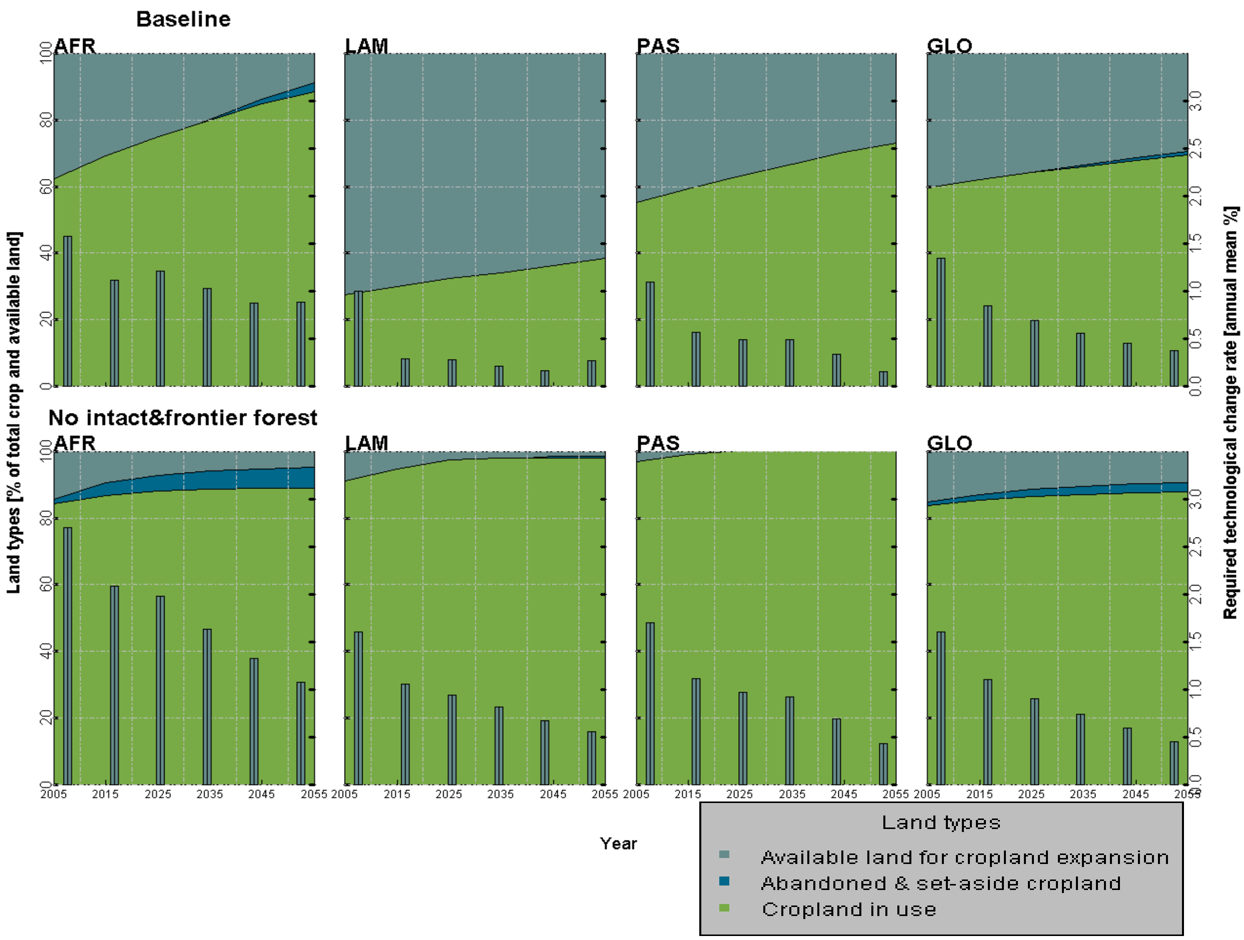

Figure 5: Average required technological change until 2055

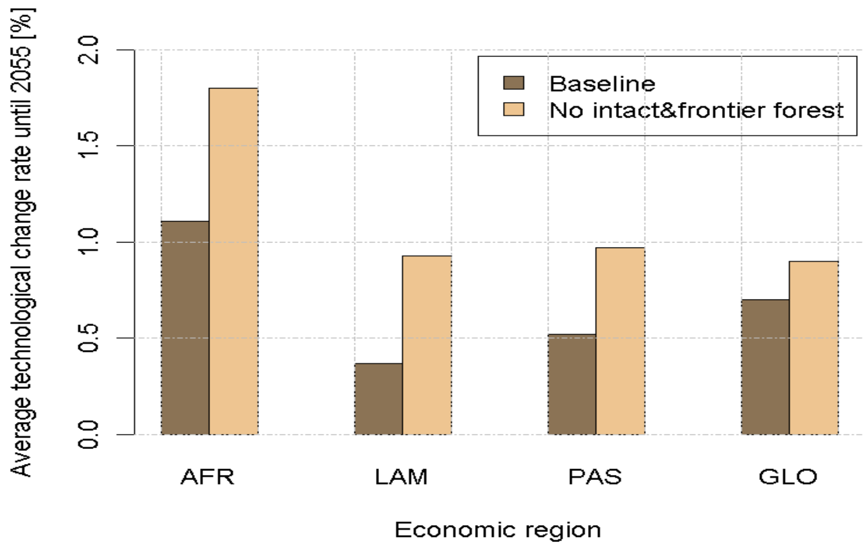

Figure 6: Relative total costs of global agricultural production [Baseline = 100]

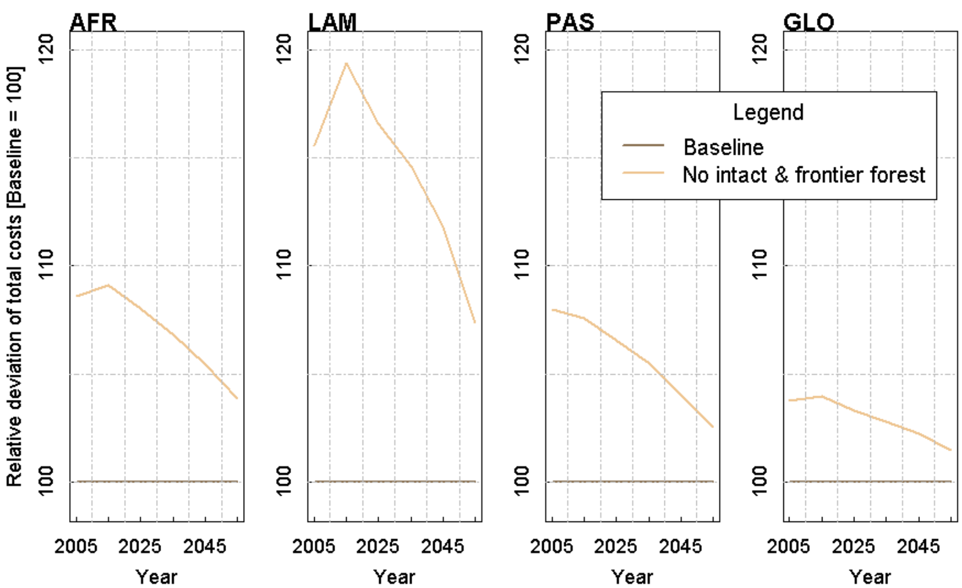

Table 1: Employed geographic datasets

Type of data set	Name of data set	Year	Spatial resolution/ Coverage/ Projection	Cat. used	Institution	Reference
Land use	Land-use data set for the year 2000 consistent with national census data	2000	5 arc min res., geographic projection, 90°/-90° lat, -180°/180° lon	all	Institute of Social Ecology, Klagenfurt University	Erb et al. (2007)
Land suitability	Suitability of global land area for rainfed crops, using max. crop and tech. mix	2002/ 2005	5 arc min res., geographic projection, 90°/-90° lat, -180°/180° lon	SI0, SI5, SI40, SI85	FAO/ IIASA	Fischer et al. (2002), v.Velthuizen et al. (2007)
Protected areas	Protected Areas National – IUCN cat. I to VI	2004	Polygons, geographic projection 90°/ -90° lat, -180°/180° lon	Cat. I&II	UNEP-WCMC	UNEP-WCMC (2007)
Intact forest	World intact forest landscapes map	2005	Polygons, geographic projection, 69°/ -55° lat, -172°/ 178° lon	all	Greenpeace	Greenpeace International, 2005)
Frontier forest	The Last Frontier Forests	1997	Polygons, pseudo-cylindrical equal-area projection, 7984568m/ -6417752, -10138882/ 15316100m	all	WRI	Bryant et al. (1997)
Land use	Rainfed & irrigated cropland and managed grassland	1700-2005	30 arc sec res., 90°/ -90° lat, -180°/180° lon	Cropland 2000	Potsdam- Institute for Climate Impact Research	Fader et al. (submitted)
Land cover	The Global Land Cover Map for the Year 2000	2000	32.1 arc sec. res., geographic projection, 89.991071°/ 56.008928° lat, -180°/ 179.991070° lon	Cat. 37 (Snow)	European Commision Joint Research Centre	European Commision (2003)

Table 2: Available land for cropland expansion, historical conversion rates 1961-2003

Economic region	Initialized cropland (mio. ha)	Scenario-dependent stock of convertible land				Historical cropland conversion (annual mean %) (FAO 2004)
		Baseline (mio. ha)	% of total	No intact & frontier forest (mio ha)	% of total	
World	1315.216	**1063.803**	8.1	324.251	2.5	0.36
AFR	166.670	**154.116**	6.5	45.642	1.9	0.96
CPA	143.400	**28.479**	2.5	19.348	1.7	1.1
EUR	150.236	**8.947**	1.4	8.892	1.4	-0.21
FSU	175.662	**47.447**	2.1	36.208	1.6	-0.28
LAM	149.687	**527.898**	2.6	40.438	2.0	1.19
MEA	29.160	**17.789**	1.6	17.789	1.6	0.58
NAM	190.596	**60.763**	3.3	42.974	2.3	0.19, ~-0.01
PAO	27.813	**80.967**	9.6	67.151	8.0	0.63
PAS	79.263	**93.366**	24.7	11.714	3.1	0.98
SAS	202728	**44032**	8.2	34.095	6.3	0.15

Table 3: Actually converted non-cropland areas in two scenarios 2005-2055

Economic region	Scenario-dependent area of actually converted non-cropland	
	Baseline (mio ha)	No intact & frontier forest (mio ha)
World	310.391	99.824
AFR	110.993	19.752
LAM	99.078	23.522
PAS	39.098	5.858