Global cropland conversion in a spatially-explicit scenario on available land in an integrated modelling framework

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Introduction

The pressure on land as required input in competing uses for agricultural crop production 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 cropland expansion to meet food demand are explicitly and implicitly treated in global land use modelling. The physical global land stock sets up the prerequisite for elaborating the economically available agricultural land and commonly enters models as pre-processed inputs. They are used to allow land allocation mechanisms to endogenize land shifts at the agricultural – non-agricultural interface, or, excluding pasture land, at the crop – non-cropland interface. Inputs on the initial stock of crop and non-cropland for land allocation modelling exercises may result from satellite-based biophysical mappings combined with national inventory data from databases, e.g. by FAO or USDA (Ramankutty, Foley 1998, Erb et al. 2007, Klein Goldewijk et al. 2007, Bouwman et al. 2006, Fischer et al. 2002, Image team 2001). Several mapping exercises deal with the spatial extent and patterns of global cropland and grassland (Ramankutty, Foley 1998, Klein Goldewijk 2001, Klein Goldewijk et al. 2007). About 11.2 % to 13.7 % cropland and 25.7 % to 26.3 % grassland share could be excluded from the global land stock but lack accounting for non-agricultural land uses.

Extended land cover and available agricultural 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 subtract built-up area, barren land, forest cover, protected areas, and irrigation area (v. Velthuizen et al. 2007) or additionally take population density, proximity parameters and tree cover into account (Bouwman et al. 2006) to allocate and to rainfed crops and pasture according to suitability characteristics. These approaches, however, may still face redundancies in classification. In contrast, statistical databases on land available for cropland expansion lack spatial explicitness (FAO (2002). 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 % (Ramankutty et al. 2002) 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, Ramankutty et al. 2002, FAO 2002). Fischer et al. (2002) separate 1,800 mio. ha and 765 mio. ha cultivable land with 20 % and 35 % share of moderately suitable land[1] in developing [2]and developed countries respectively. About 45 % of potential land is located in forests, 12 % in protected areas and 3 % occupied by

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[1] Expressed as area-weighted Suitability Index (SI) on land productivity.

[2] The very suitable to moderately suitable land share for expansion of cultivated land located in Sub-Saharan Africa and South and Central America sums up to more than 70 % of the additional cultivable land.

human settlements and infrastructure (FAO 2002). The global net clearance of forests amounts to 100 mio. ha from 1990 to 2000 and is primarily due to the expansion of cropland and may partially be attributed to the availability of suitable land in forest ecosystems in South America (35 %) (Fischer et al. 2002). About 15 % of the world crop production between 1961 and 1999 are attributed to cropland expansion 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 2005). In contrast, Europe shows the reverse trend by releasing about 2 % of cropland on average. The trend in both of the regions coincides with the development of productivity-increasing technological change and the original share of cropland in South-East Asia (14 %) indicating relative higher scarcity of land in Europe (30 %) (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 datasets 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 datasets 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, 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 that outputs at national or regional scale lack spatial explicitness and thus miss 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, Darwin et al. 1995). 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. A major drawback of land cover/land use datasets employed in other approaches might be the conceptual inconstancy of merging land cover and land use information (Erb et al. 2007). 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. Secondarily, our endeavour to share a common historical cropland database in an integrated land use optimization and global dynamic vegetation modelling framework[3] requires substituting the current cropland distribution to ensure smoothness in time series.

Our objectives constitute (1) to develop and make use of data integration rules for determining the spatially-explicit available land for cropland expansion, (2) to implement the available land base and plausible exogenous land conversion rates into MAgPIE, and (3) to analyse model behaviour in projections until 2055. Corresponding research questions and indicators pertain to the (1) hierarchy and categories of integrated land use, land suitability, intact & frontier forest and protected area datasets, (2) scenario elaboration along the thematic and quantitative gradient of available land and

[3] We strive for the soft-coupling of MAgPIE with the global dynamic vegetation model *Lund-Potsdam-Jena with managed Land* (LPJmL) (Sitch et al. 2003).

historically-observed cropland expansion, and (3) the variability of total costs, land use patterns, and rates of required technological change.

This paper presents the part of the study that deals with the variability of particular model outputs to the change in land conversion parameters demonstrated for a scenario on available land.

The next section introduces the model and gives evidence on the available land elaborations in methodological context, underlying assumptions and the determination of the land conversion rate. Results and the discussion of land use patterns and the sensitivity of selected model outputs to changes in conversion rates are provided in section 3. Section 4 offers the conclusions and an outlook.

Methodological framework

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 the total output of food production to the projected total food consumption (ibid.). Land that is available for expansion in addition to current cropland is defined as the total land per cell minus crop and pasture area as pasture land is conceptually fully used for grazing and browsing (ibid.). The initial setup of a static cropland mask relies on the data set of Ramankutty, Foley (1998) to start from with the optimization of costs of production in decadal time steps. MAgPIE employs the rule to use land that is initially allocated to agricultural crop production and, if necessary, to allow for cropland expansion at additional costs. The extent of maximal convertible land per time step is tightened by an exogenous scaling parameter which makes up a constant share of the available non-agricultural land stock. Conversion costs mimic regional-specific relative higher costs for developed regions[4] than developing regions[5] (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 use types following a static approach. As immediate solution the introduction of proxies of land required in other sectors through available land scenarios

[4] 3 developed economic regions: Europe, North America, Pacific OECD countries

[5] 7 developing economic regions: Subsaharan Africa, Centrally-planned Asia, Latin America, Pacific Asia, South Asia, Former Soviet Union, Middle East and North Africa

and historically-based land conversion rates is supposed to be the adequate approach. Therefore, the global land budget calculation is based on consistent land use datasets (Erb et al. 2007) as main pillars with one exception and includes bio-physical and normative constraints. 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).

Non-economic and economic assumptions help to narrow down the stock of land that appears physically available for cropland expansion.

(1) The urban land use comprises housing, business and administrative uses and is assumed to represent the most developed type of land use with the highest value of land. Thus conversion to lower valued agricultural land is unlikely. Urban land is excluded from conversion assuming the global land share of 1.1 % (own calculations from Erb et al. 2007) and potential urban growth rates to be negligible.

(2) The ratio of irrigated to total cropland is kept static at level of the year 2000 (Fader et al., submitted). It is derived from relating the sum of irrigated areas to the sum of irrigated and rainfed areas over all crop types.

(3) The share of pasture land, managed grassland and rangelands is assumed to stay in pasture use.

(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 takes place from the most to the least suitable land parcel, associated with declining productivity and rising average costs of production. Land that does not pass the suitability threshold is excluded simply because crop production is assumed economically unviable due to the low productivity.

(5) The pool of available land may be 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 (WRI 1997, Greenpeace 2005) and reflect the appropriately valued social benefits.. The union of the datasets represents a conservative assumption in data integration.

(6) Alternatively, IUCN protected areas (UNEP-WCMC 2006) may be non-convertible by political consensus. The obstacle concerning IUCN categories lays in the various redundant and spurious ways they could be integrated. 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.

A hierarchical nested structure is assumed in data integration. Land use classes (Erb et al. 2007) make up the first order and integrate subsets of suitable land at the second order (Fischer et al. 2002, v. Velthuizen et al. 2007). The third order incorporates intact and frontier forest (Bryant 1997, Greenpeace 2005) complemented by a fourth-order union of suitable intact and frontier forest and IUCN protected areas (UNEP-WCMC 2006).

The backbone of data integration is established by datasets 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.

- Elaboration of land conversion rates

Land conversion rates have been estimated from the summed historical arable and permanent cropland area change taken from statistical time-series datasets for 1961 to 2001 (FAO 2004). Linear trends in regionally aggregated cropland shares over time are assumed which fits well with the statistical data[6]. Declining cropland shares are observable in Europe and the Former Soviet Union. Historical data for North America requires the use of a quadratic function as cropland expansion took place from 1961 to

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

the turning point in 1990. In order to simplify calculations we linearly approximate the quadratic function and calculate the average slope per decade. The extrapolated fitted cropland area and the corresponding change of the scenario-dependent non-cropland area from 2005 to 2055 are employed to calculate the % change of non-cropland per decade which is simply the coefficient of the summed annual slope of the cropland expansion to its base year. The % rate of non-cropland change per decade until 2055 enters the model as input. In MAgPIE, the scenario-dependent % rate of change and available land stock prescribe the upper and lower regional constraint of land conversion activity per time step relative to the available land stock.

For the sensitivity analysis, we simply keep the intercept value at constant and scale the slope of the best fit line of historical cropland shares including its standard deviation by a scalar factor to cover variability in parameter space. Parameter shifts of accelerated and decreased conversion aim at reflecting at what would happen if uncertainty about future rates is taken into account. Due to linearity in maximal cropland expansion, land is actually used up if the increase in conversion rate does not warrant an additional unit of the prescribed expansion in absolute terms.

The costs of land conversion are still exogenously provided and are not subject to further refinement at this stage.

- 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 define the baseline scenario from scenario group 1 to be forestry and unused land in natural vegetation bearing 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). Additional scenarios may cover the change in land suitability, the exclusion of global or tropical intact and frontier forests or IUCN areas for land suitability options at varying rates albeit several combinations of data set modules may serve for scenario definition. Hereafter, we run a scenario on marginally suitable land to be available for cropland conversion. We vary the historical rate by an intuitively set gradient of ± 10% and 20% to demonstrate the sensitivity to the slope parameter which corresponds to the regression coefficient from fitted observed data.

The model is initialized with cropland which is at least marginally suitable and includes irrigated areas. The conversion activity excludes pasture land. In order to contrast the depiction of output sensitivity over regions we opted to include deliberately selected regions based on 1) the relative share of available land and 2) the historical cropland conversion rate.

- 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 patterns and area, C at t_0, and the optimized remaining land 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. The magnitude of land expansion in the allocation procedure is restricted by upper and lower constraints (2)(3). They define 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.

$$y\_land_{i,m_{crop}} \geq land\_const_{i,m_{non\_crop}} * (lcr_i - 2 * \sigma) \qquad (2)$$

$$y\_land_{i,m_{crop}} \leq land\_const_{i,m_{non\_crop}} * (lcr_i + 2 * \sigma) \qquad (3)$$

The subscript *non_crop* comprises the initially or optimized available land respectively. Thus the cellular conversion constraint applies (4).

$$\sum_k x_{i,k} * y\_land_{i,m_{crop}} \leq land\_const_{i,m_{non-crop}} \qquad (4)$$

In each subsequent time step $t_1 \ldots t_m$[7], 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

[7] In this paper, 7 time steps for model runs until 2055 are considered.

to imitate desirable forest conservation scenarios or IUCN protection scenarios. MAgPIE runs in GAMS 22.5 using the non-linear solver CONOPT (Drud 1996).

Projections of land use patterns in an available land scenario until 2055

Results pertain to the available land stock and the change of land use patterns in the selected scenario. In addition, we present results on the sensitivity of global outputs, i.e. the total costs of agricultural production, and regional outputs, i.e. the required rate of technological change in selected regions, to the change in land conversion rates.

We found the magnitude of historical linear cropland conversion to impose an optimization constraint which is too strict. Given the scenario-based available stock, land does not get used up. However, the impact of a second resource constraint, the spatially-explicit availability of water may prevent cropland expansion at the historical rate. Due to this result, we decided to keep historical patterns of conversion and applied them to the reference scenario. Even though the magnitude of conversion is different, the trend in land use patterns as well as the sensitivity of model outputs to historical patterns of conversion can be studied. The available land for cropland expansion, historical cropland conversion rates 1961-2003, and actually converted areas until 2055 are compiled in Table 2.

The projected distribution of land use depends on the region-specific average per-hectare production costs[8] that accrue to the social planer for crop and livestock-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 unit food energy which leads to distinct patterns of land use. Figure 3 shows the change in optimized cropland shares between 2005 and 2055 applying the historical patterns of land conversion.

<<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, highly productive cells are used as cropland up to 100% particularly in the Amazon and the Congo basin. This result bases on the scenario definition to allow for the conversion of suitable intact and frontier forest.

The large regional variation of 44 % in Latin America, 2.4 % in the Middle East and North Africa, and a loss of -6.1 % in Europe and -16.3 % in North America, respectively,

[8] The regional cost structure comprises variable factor inputs like labour, chemicals and other capital in unlimited supply and land in limited supply.

demonstrates the imitation of historical patterns of change. 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). In total, global cropland is expanded by 9.4 % between 2005 and 2055.

Sensitivity analysis with regard to land conversion rates

We contrast the sensitivity of total costs and the rate of required technological change to a 10 % and 20 % increase and decrease of the slope parameter of fitted linear functions on historical land conversion.

- Total costs of agricultural production

The relative total costs of agricultural production represent the variation of the globally minimized total costs of agricultural production to the change in land conversion rates (Figure 4).

<<*Figure 4*>>

The result pinpoints the relatively insensitive behaviour, i.e. the % change of total costs to shifts in the land conversion rate. Nevertheless, the trend of lower relative costs from

2015 to 2055 can be ascribed to the % change in conversion rate that decreases the steepness of positive and negative rates (parameter value: slope*0.8). This trend appears contra-intuitive at first glance due to the assumed cost reduction by expanding cropland rather than purchasing relatively more expensive technological change, if needed. The perspective changes when taking the net cost effect of slowed down land abandonment in Europe, Former Soviet Union and North America versus the reduced expansion in other regions into account. The relative total costs are lower if the benefits from reducing abandonment, i.e. cost reduction due to less required yield increase needed, outweigh the foregone benefits, i.e. the cost reduction, in the latter.

- Required rates of technological change

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). We use the effective required yield increase which excludes productivity changes due to rotational effects (ibid.). Two regions, Europe and Latin America are contrasted (Figure 5). Criteria for contrasting pertain to the availability of land for cropland conversion, the algebraic sign of historical conversion and higher costs of technological change in Europe than in Latin America.

<<Figure 5>>

Latin America shows a decrease of required technological change in 2055 down to 28 % for a 20 % increase of conversion rate and the same magnitude for an increase if the expansion rate is shifted down by 20 %. The algebraic sign of the deviation from the historical rate is not surprising. However, the magnitude of change indicates that the required technological change rate is sensitive to the change in parameter value. The output increase from 2005 to 2055 may be indicated by two opposing trends. On the one hand, the increase of projected food demand in line with the growth of the GDP per capita requires the increase in productivity, i.e. yield increase, on a constant area of land. On the other hand, we force the model to reduce the compensating area expansion below the reference rate. In the opposite case relatively more cropland is prescribed to expand than needed to balance food supply with demand. The rate of required yield increase drops.

For Europe, the interpretation of results is not straightforward. The trend observed in decreasing the rate of cropland abandonment by 20 % coincides with a relative decrease of the required technological change in a similar way to the relative increase of land expansion in Latin America by 20 %. If less crop area is taken out of production compared to the reference than the yield increase required to compensate that effect has to be less. Increased land abandonment requires higher yield increase but results also show volatile changes in the technological change rate. However, the analysis of sensitivity to additional parameters is not pursued in this paper.

Conclusions and outlook

We presented a work-in-progress version of the implementation of an available land scenario in the agricultural land use optimization model MAgPIE. The modelling exercise implemented the patterns of historical cropland conversion rates to imitate historical trends in global cropland expansion and abandonment..

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.

In reference to the effect of implemented historical cropland conversion rates we conclude that the impact of additional optimization constraints in the model, like the water availability, needs further exploration. Though, the basic mechanism of land conversion for an exogenously defined available land stock linked to patterns of historical conversion rates has been demonstrated. Additionally, the analysis of different scenarios on the available land stock is required to study the impact of the magnitude of land to be converted in total.

The impact of varying conversion parameter estimates on particular model outputs constituted a first test. Due to partly volatile changes in outputs additional research is necessary to test the sensitivity of required technological change rates to changes in trade and costs of technological change parameters in addition to changes in the available land stock.

Thus, in a next step, additional scenarios on restricted land are implemented and help to contrast, *inter alia*, total costs and required rates of technological changes. Further analysis of model sensitivity 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.

References

Bouwman, A.F.; Kraum, T.; Klein Goldewijk, K. (2006): Integrated modelling of global environmental change – An overview of IMAGE 2.4. Netherlands Environmental Assessment Agency (MNP). Bilthoven, The Netherlands.

Darwin, R.; Tsigas, M.; Lewandrowski, J.; Raneses, A. (1995): World Agriculture and Climate Change: Economic Adaptations. Agricultural Economic Report No. 703. U.S. Department of Agriculture. Economic Research Service, U.S. Government Printing Office, Washington, D.C. http://www.ers.usda.gov/Publications/AER703/. 20th Nov. 2008.

Darwin, R.; Tsigas, M.; Lewandrowski, J.; Raneses, A. (1996): Land use and cover in ecological economics. Ecological Economics 17:157-181.

Drud, A.S. (1996): CONOPT: A System for Large Scale Nonlinear Optimization. Reference manual for CONOPT Subroutine Library. ARKI Consulting and Development A/S. Bagsvaerd, Denmark.

Erb, K.-H.; Gaube, V.; Krausmann, F.; Plutzar, C.; Bondeau, A.; Haberl, H. (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.

Fader, M.; Rost, S.; Müller, C.; Gerten, D.: Virtual water content of temperate cereals and maize: Present and potential future patterns. Journal of Hydrology (submitted).

FAO (Food and Agriculture Organization of the United Nations) (2002): World agriculture: towards 2015/2030. Summary report. FAO, Rome, Italy. http://www.fao.org/docrep/004/Y3557E/Y3557E00.HTM. 20th Nov. 2008.

FAO (2004): FAOSTAT Database. http://faostat.fao.org/. 21th Nov. 2008.

Fischer, G.; Shah, M.; v. Velthuizen, H.; Nachtergaele, F.O. (2002): Global Agro-ecological Assessment for Agriculture in the 21st Century. International Institute for Applied Systems Analysis (IIASA), FAO. http://www.iiasa.ac.at/Research/LUC/Papers/gaea.pdf. 14th June 2008

Heistermann, M.; Mueller, C.; Ronneberger, K. (2006): land in sight? Achievements, deficits and potentials of continental to global scale land-use modeling. Agriculture, Ecosystems and Environment 114:141-158.

IMAGE team (2001): The IMAGE 2.2 implementation of the SRES scenarios. CD-ROM. National Institute for Public Health and the Environment. Bilthoven, The Netherlands.

Klein Goldewijk, K. (2001): Estimating global land use change over the past 300 years: The HYDE Database. Global Biological Cycles 15(2):417-433.

Klein Goldewijk, K.; v. Drecht, G.; Bouwman, A.F. (2007): Mapping contemporary global cropland and grassland distributions on a 5x5 minute resolution. Journal of Land Use Science 2(3):167-190.

Lotze-Campen, H.; Müller, C.; Bondeau, A.; Rost, S.; Popp, A.; Lucht, W. (2008): Global food demand, productivity growth and the scarcity of land and water resources: a spatially explicit mathematical programming approach. Agricultural Economics 39(3):325-338.

Müller, C.; Bondeau, A.; Lotze-Campen, H.; Lucht, W.; Cramer, W. (2006): Comparative impact of climatic and non-climatic factors on the carbon and water cycles of the terrestrial biosphere. Global Biogeochemical Cycles 20(4):GB4015.

European Commision Joint Research Centre (2003): The Global Land Cover Map for the Year 2000. GLC2000 database, European Commision. Joint Research Centre. http://www-gem.jrc.it/glc2000.

Portmann, F., Siebert, S., Bauer, C., Döll, P., 2008. Global data set of monthly growing areas of 26 irrigated crops. Frankfurt Hydrology Paper 06, Institute of Physical Geography, University of Frankfurt, Frankfurt am Main, Germany.

Portmann, F., Siebert, S., Döll, P.: MIRCA 2000 – Global Monthly Irrigated and Rainfed Crop Areas around the year 2000: A new high-resolution data set for agricultural and hydrological modelling. Global Biogeochem. Cycl. (submitted).

Ramankutty, N.; Foley, J.A. (1998): Characterizing patterns of global land use: an analysis of global croplands data. Global Biogeochemical Cycles 12:667-685.

Ramankutty, N., Evan, A.T., Monfreda, C. Foley, J.A., 2008. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. Global Biogeochem. Cycles 22, GB1003.

Rosegrant, M.W.; Meijer, S.; Cline, S.A. (2002): International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description. International Food Policy Research Institute (IFPRI). Washington, DC. http://www.ifpri.org/themes/impact/impactmodel.pdf. 20th Nov. 2008.

Rosegrant, M.W.; Ringler, C.; Msangi, S.; Sulser, T.B.; Zhu, T. Cline, S.A. (2008): International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description. International Food Policy Research Institute (IFPRI). Washington, DC. http://www.ifpri.org/themes/impact/impactwater.pdf. 20th Nov. 2008.

Sands, R.; Leimbach, M. (2003): Modelling agriculture and land use in an integrated assessment framework. Climate Change 56:185-210.

UNEP-WCMC (United Nations Environment Programme – World Conservation Monitoring Centre) (2006): World Database on Protected Areas (WDPA). CD-ROM. Cambridge, U.K. http://sea.unep-wcmc.org/wdbpa/. 14th June 2008.

v. Velthuizen, H.; Huddleston, B.; Fischer, G.; Salvatore, M.; Ataman, E.; Nachtergaele, F.O.; Zanetti, M.; Bloise, M.; Antonicelli, A.; Bel, J.; De Liddo, A.; De Salvo, P.; Franceschini, G. (2007): Mapping biophysical factors that influence agricultural production and rural vulnerability. Environment and natural resources series 11. FAO, Rome. http://www.fao.org/docrep/010/a1075e/a1075e00.htm. 14th June 2008.

WRI (World Resources Institute) (1992): World Resources 1992-1993. Oxford University Press, New York. USA. http://archive.wri.org/publication_detail.cfm?pubid=2865. 14th June 2008.

Appendix

Figure 1: Available land modules and scenario groups

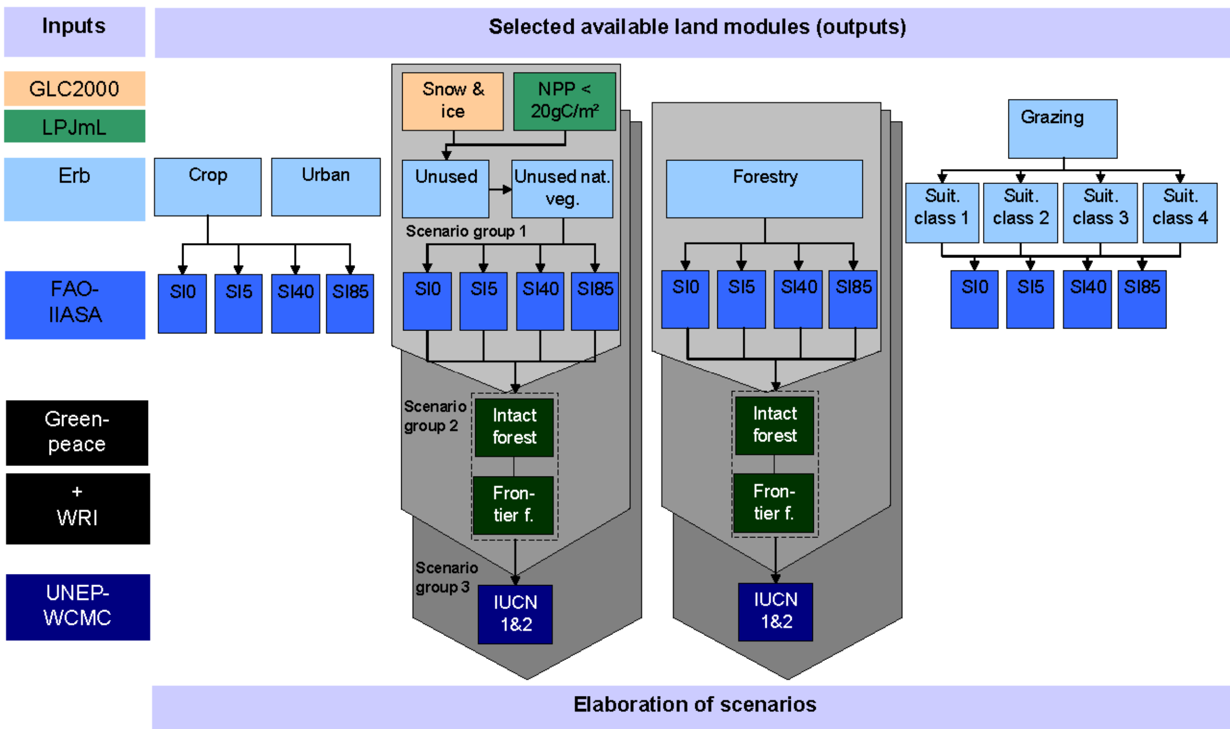

Figure 2: Concept of feedback mechanisms in space and time of allocating existing cropland and available non-cropland to agricultural production

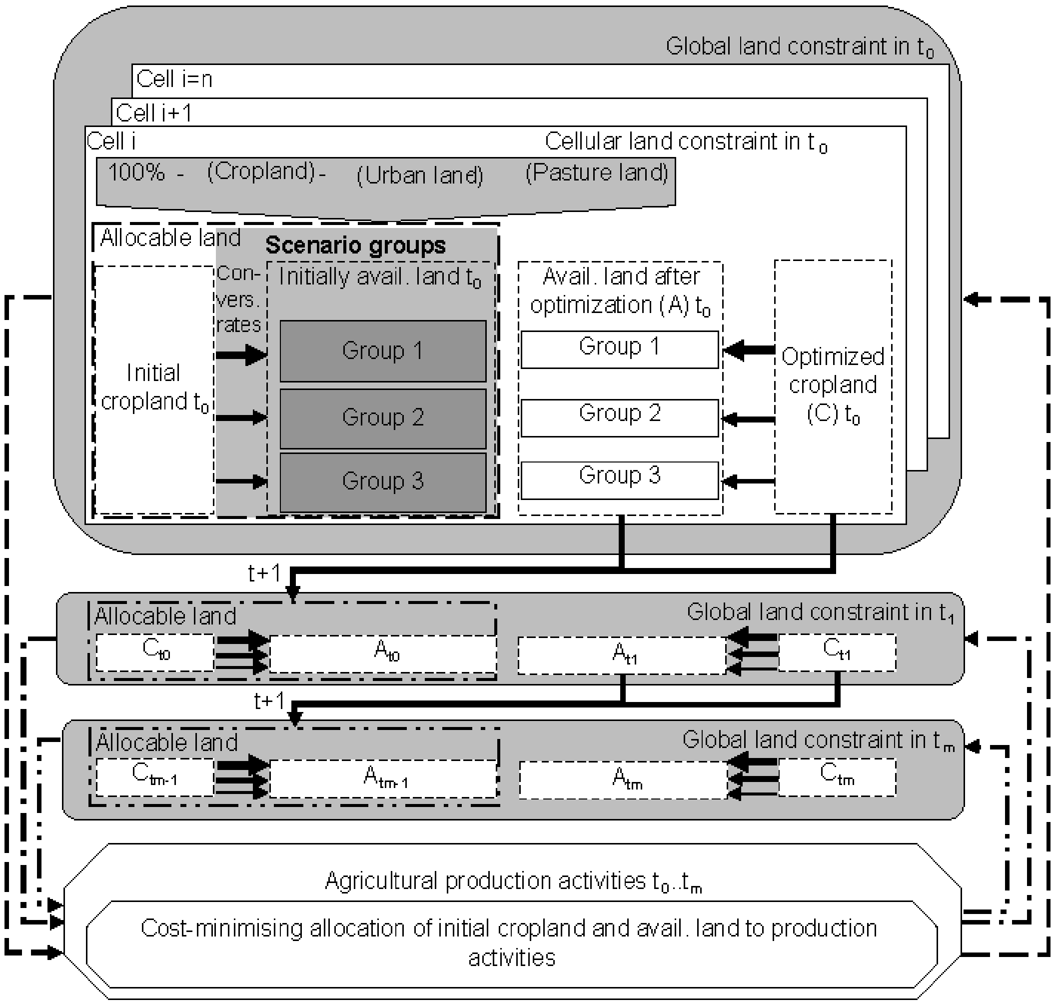

Figure 3: Change in optimized cropland share imitating the historical cropland conversion rate 2005 to 2055

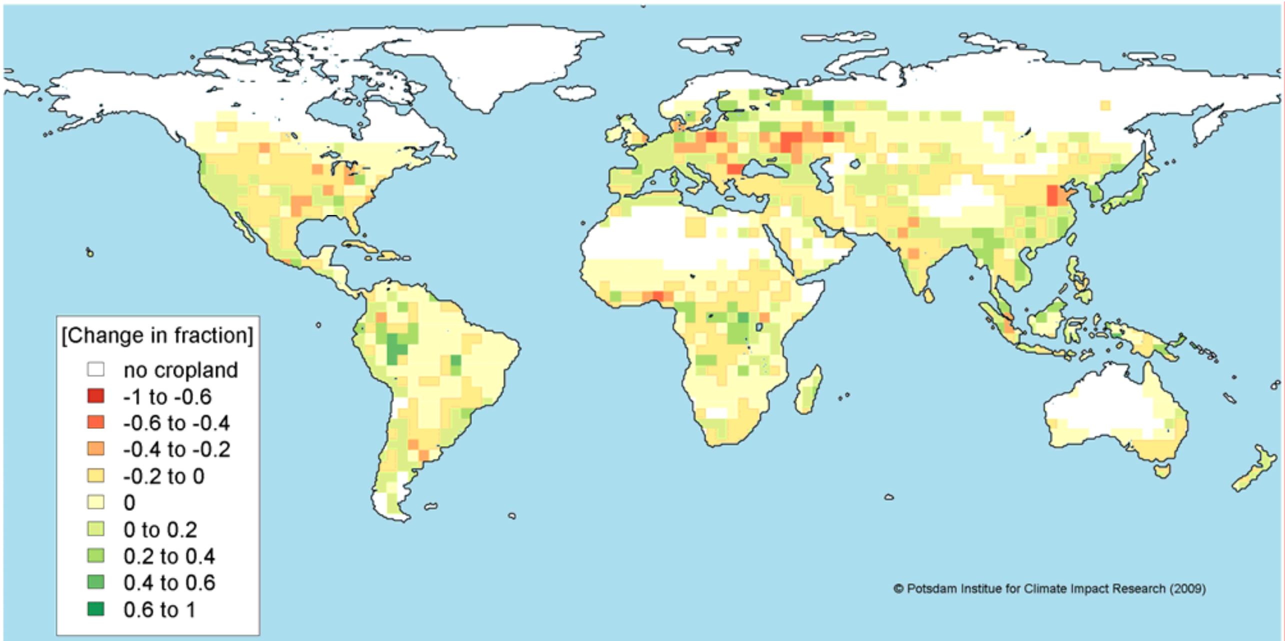

Figure 4: Relative total costs of global agricultural production [Baseline = 100]

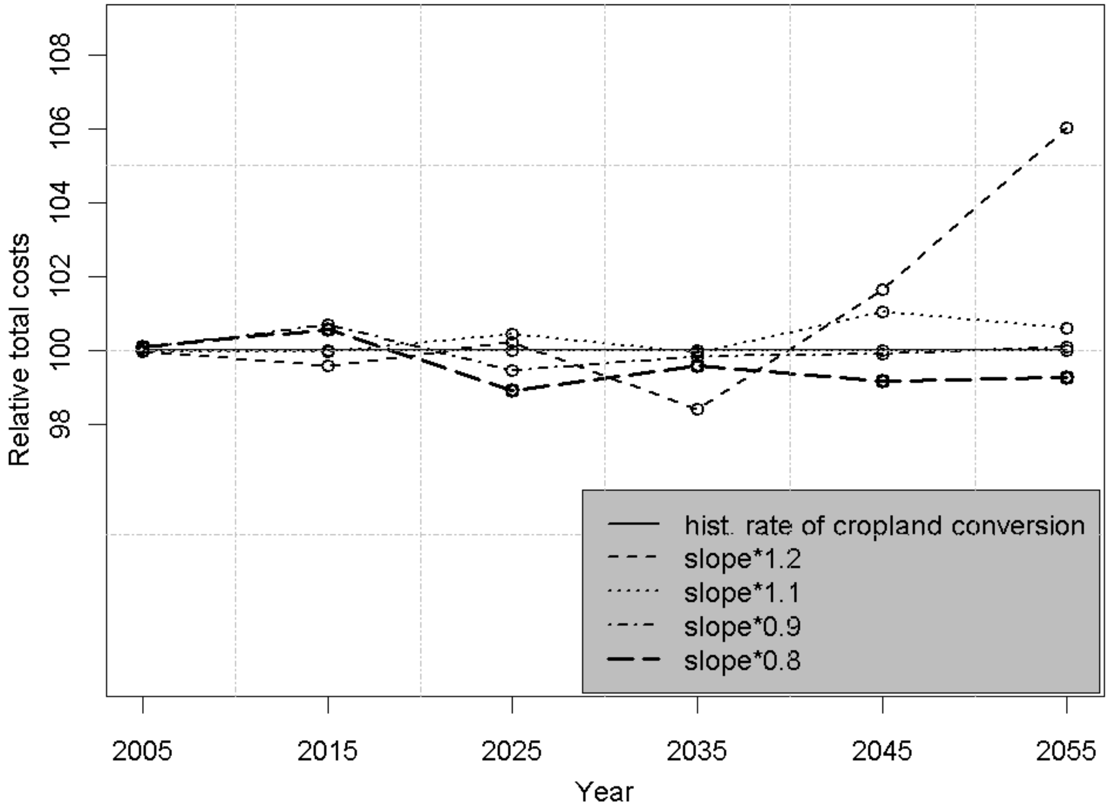

Figure 5: Sensitivity of the required technological change to variations of the slope of historical land conversion

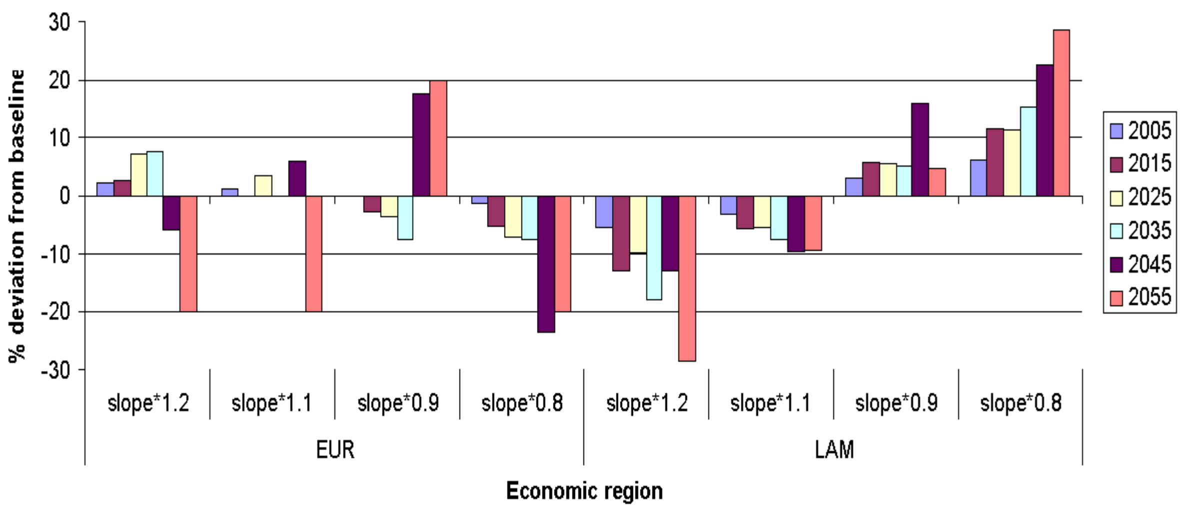

Table 1: Employed geographic datasets

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 (2006)
Intact forest	World intact forest landscapes map	2005	Polygons, geographic projection, 69°/ -55° lat, -172°/ 178° lon	all	Greenpeace	Greenpeace International, 2006)
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	http://www-gem.jrc.it/glc2000

Table 2: Available land for cropland expansion, historical cropland conversion rates 1961-2003, and actually converted areas 2005-2055

Economic region	Initialized cropland (1000ha)	Stock of convertible land (at least marginally suitable)		Historical cropland conversion (annual mean %) (FAO 2004)	Total area of converted land 2005-2055 (1000ha)
		(1000ha)	% of total land		
World	1288473.2	**3047408**	23.3	0.36	120,653
AFR	166492.3	**615947**	26.1	0.96	32,123
CPA	139915.8	**183029**	16	1.1	20,471
EUR	150236.2	**161560**	25.8	-0.21	-9,216
FSU	173372.1	**258817**	11.6	-0.28	-5,810
LAM	149157.7	**1001160**	49.2	1.19	65,438
MEA	22753.2	**24603**	2.2	0.58	597
NAM	187458.7	**314398**	16.9	0.19, ~-0.01	-30,616
PAO	27812.1	**163940**	19.4	0.63	6,098
PAS	79262.9	**190694**	50.4	0.98	31,776
SAS	192012.2	**133260**	24.7	0.15	9,792