KLUM@GTAP: Spatially-Explicit, Biophysical Land Use in a Computable General Equilibrium Model*

by

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KLUM@GTAP: SPATIALLY-EXPLICIT, BIOPHYSICAL LAND USE IN A COMPUTABLE GENERAL EQUILIBRIUM MODEL

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Abstract

In this paper the global agricultural land use model KLUM is coupled to an extended version of the computable general equilibrium model (CGE) GTAP in order to consistently assess the integrated impacts of climate change on global cropland allocation and its implications for economic development. The methodology is innovative as it introduces dynamic economic land-use decisions based also on the biophysical aspects of land into a state-of-the-art CGE; it further allows the projection of resulting changes in cropland patterns at a spatially explicit level. A convergence test and illustrative future simulations underpin the robustness analysis and serve to highlight the potential of the coupled system. Reference simulations with the uncoupled models emphasize the impact and relevance of the coupling; the results of coupled and uncoupled simulations can differ by several hundred percent.

Keywords

Land-use change, computable general equilibrium modeling, integrated assessment, climate change

JEL Classification

C68, R14, Q17, Q24

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1. Introduction

Land use is one of the most important links of economy and biosphere, representing a direct projection of human action onto the natural environment. Large parts of the terrestrial land surface are used for agriculture, forestry, settlements and infrastructure. Among these, agricultural production is still the dominant land use accounting for 34% of today's land surface (Leff *et al.*, 2004), compared to forestry covering 29% (FAO, 2003) and urban area which is taking less than 1% of the land surface (Gruebler, 1994). On the one hand, agricultural management practices and cropping patterns have a vast effect on biogeochemical cycles, freshwater availability and soil quality; on the other hand, the same factors govern the suitability and productivity of land for agricultural production. Changes in agricultural production directly determine the development of the world food situation. Thus, to consistently investigate the future pathway of the economic and natural environments, a realistic representation of agricultural land-use dynamics on a global scale is essential.

Traditionally, land-use decisions are modeled either from an economic or geographical perspective. Geographical models focus on the development of spatial patterns of land-use types by analyzing land suitability and spatial interaction. Allocation of land use is based either on empirical-statistical evidence or formulated as decision rules, based on case studies and "common sense". They add information about fundamental constraints on the supply side, but they lack the potential to treat the interplay between supply, demand and trade endogenously. Economic models focus on drivers of land-use change on the side of food production and consumption. Starting out from certain preferences, motivations, market and population structures, they aim to explain changes in land-intensive sectors. The biophysical aspects of land as well as the spatial explicitness of land-use decisions are commonly not captured in such models. A new branch of integrated models seeks to combine the strengths of both approaches in order to make up for their intrinsic deficits. This is commonly done by coupling existing models, which describe the economy to a biosphere model, or by improving the representation of land in economic trade models. For a more detailed discussion of different approaches to large scale land-use modeling, see Heistermann *et al.* (2006).

We present here the coupled system KLUM@GTAP of the global agricultural land-use model KLUM (*Kleine*s Land Use Model, (Ronneberger *et al.* , 2005)) with GTAP-EFL model, which is an extended version of the Global Trade Analysis Project model GTAP (Hertel, 1997). The main aim of the coupled framework is to improve the representation of the biophysical aspects of land-use decisions in the computable general equilibrium model (CGE). This is the first step towards an integrated assessment of climate change impacts on economic development and future crop patterns.

A similar approach was realized in the EURURALIS project (Klijn *et al.*, 2005), where the Integrated Model to Assess the Global Environment IMAGE (Alcamo *et al.*, 1994; Zuidema *et al.*, 1994; RIVM, 2001) has been coupled to a version of GTAP with extended land use sector (van Meijl *et al.*, 2006). In this coupling, the change in crop and feed production, determined by GTAP, is used to update the regional demand for crops and pasture land in IMAGE. Then IMAGE allocates the land such as to satisfy the given demand, using land productivities, which are updated by management induced yield changes as determined by GTAP. The deviation of the different changes in crop production determined by the two models is interpreted as yield changes resulting from climatic change and from changes in the extent of used land.[1] These yield changes together with an endogenous feed conversion factor are fed back to GTAP. The land allocation is modeled on grid level by means of specific allocation rules based on factors such as distance to other agricultural land and water bodies.

Our approach differs in several ways. In our coupling, the land allocation is exogenous in GTAP-EFL and replaced by KLUM. The land-use decisions are limited to crops, excluding livestock. Instead of crop production changes, we directly use the crop price changes determined in GTAP-EFL. Our allocation decisions are not based on allocation rules aiming to satisfy a defined demand, but are modeled by a dynamic allocation algorithm, which is driven by profit maximization under the assumption of risk aversion and decreasing return to scales. This ensures a strong economic background of the land allocation in KLUM.

Another approach to introduce biophysical aspects of land into economic model is the so called Agro-Ecological Zones (AEZ) methodology (Darwin *et al.*, 1995; Fischer *et al.*, 2002).

According to the dominant climatic and biophysical characteristics, land is subdivided into different classes, reflecting the suitability for and productivity of different uses. GTAP is currently extending its databases and models to include such an improved representation of land, known as GTAP-AEZ (Lee *et al.*, 2005; see also Chapter 10[2] of this volume). From this our approach differs in three crucial ways. The standard version of GTAP has one type of land, whereas the land use version has 18 types of land. The 18 land types are characterized by different productivities. Each GTAP region has a certain amount of land per land type, and uses part of that. The first difference is that we have a more geographically explicit representation of land. Like GTAP-AEZ, KLUM@GTAP keeps track of aggregate land use; but unlike GTAP-AEZ, KLUM@GTAP has spatially disaggregated land use as well. The allocation algorithm of KLUM is scale-independent. In the present coupling, KLUM is calibrated to country-level data, but Ronneberger *et al.* (2006) use KLUM on a 0.5x0.5 degree grid (for Europe only). The second difference is that KLUM@GTAP does not have land classified by different productivity; instead productivities vary continuously over space, again allowing the direct coupling to large scale crop growth models (Ronneberger *et al.*, 2006) to simulate implications of environmental changes. In GTAP-AEZ, a change in e.g. climate or soil quality requires

[1] A change in the extent implies a change in the yield structure of the used land.

[2] GTAP Working Paper No. 48

an elaborate reconstruction of the land database. KLUM@GTAP can be coupled directly and dynamically to a biophysical model, while in GTAP-AEZ such coupling is indirect and by route of a static database. A third difference is that KLUM@GTAP has consistent land transitions. In GTAP and GTAP-AEZ, a shift of land from crop A to crop B implies a (physically impossible) change in area; this drawback is the result from calibrating GTAP to value data (KLUM@GTAP uses area) and from normalizing prices to unity and using arbitrary units for quantities. That is, GTAP-AEZ does not keep track of actual areas, but uses productivity-adjusted areas instead (see Chapter 4[3] for further discussion).

In the next section we outline the basics of GTAP-EFL and KLUM and describe the coupling procedure. The greatest challenge of the coupling is to guarantee the convergence of the two models to a common equilibrium. In section 3 we discuss the convergence conditions and present the results of a convergence testing with the coupled system. The system is used to simulate the impact of climate change; the influence of a baseline scenario, and the coupling on the results, are highlighted by reference situations. Section 4 outlines the different simulation setups. The results of these simulations are presented in section 5. Section 6 summarizes and concludes.

2. The Models

2.1. GTAP-EFL

In order to assess the general equilibrium effects of climate change on agriculture and land use, we use a multi-region world CGE model called GTAP-EFL. GTAP-EFL is a variant of the GTAP-EF model (Bosello *et al.*, 2006, 2007),[4] which itself is a variant of GTAP-E (Burniaux and Truong, 2002),[5] which is in turn based on the GTAP model[6] (Hertel, 1997). In the GTAP-EFL model, a different land allocation structure has been modeled for the coupled procedure. Finer industrial and regional aggregation levels are considered (17 sectors and 16 regions, reported in Table A1 and A2).

As in all CGE frameworks, the standard GTAP model makes use of the Walrasian perfect competition paradigm to simulate adjustment processes. Industries are modeled through a representative firm, which maximizes profits in perfectly competitive markets. The production functions are specified via a series of nested Constant Elasticity of Substitution (CES) functions (Figure A1). Domestic and foreign inputs are not perfect substitutes, according to the so-called *Armington assumption*, which accounts for product heterogeneity. A representative consumer in each region receives income, defined as the service value of national primary factors (natural resources, land, labor and capital). Capital and labor are perfectly mobile domestically, but immobile internationally. Land

[3] GTAP Working Paper No. 42

[4] GTAP-EF is specifically developed for analyzing the general equilibrium effects of climate change.

[5] GTAP-E is best suited for the analysis of energy markets and environmental policies. There are two main changes in the basic structure. First, energy factors are separated from the set of intermediate inputs and inserted in a nested level of substitution with capital. This allows for more substitution possibilities. Second, database and model are extended to account for CO_2 emissions related to energy consumption.

[6] The GTAP model is a standard CGE static model distributed with the GTAP database of the world economy (www.gtap.org). For detailed information see Hertel (1997) and the technical references and papers available on the GTAP website.

(imperfectly mobile) and natural resources are industry-specific. The national income is allocated between aggregate household consumption, public consumption and savings (Figure A2). At this level, the expenditure shares are generally fixed, which amounts to saying that the top level utility function has a Cobb-Douglas specification. Private consumption is split in a series of alternative composite Armington aggregates. The functional specification used at this level is the Constant Difference in Elasticities (CDE) form: a non-homothetic function, which is used to account for possible differences in income elasticities for the various consumption goods. A money metric measure of economic welfare, the equivalent variation, can be computed from the model output.

In the standard GTAP model, the land input is exogenously fixed at the regional level; it is imperfectly substitutable among different crops or land uses. Indeed a transformation function (CET) distributes land among 5 sectors (rice, wheat, other cereals, other corps, and animal husbandry) in response to changes in relative rental rates. Substitutability is equal among all land-use types. When coupled to KLUM@GTAP, sectoral land allocation is made exogenous (as given by KLUM) in GTAP-EFL. Consequently, the total land value change is freed up. The latter is defined as the sum of the land allocation change per sector weighted by the share of the value of purchases of land by firms in sector *j* in the value of land in region *r*, all evaluated at market prices.

2.2. KLUM

The global agricultural land-use model KLUM is designed to link economy and vegetation by reproducing the key features of large-scale crop allocation. For this, the maximization of achievable profit under risk aversion is assumed to be the driving motivation underlying the simulated land-use decisions. In each spatial unit, the expected profit per hectare, corrected for risk, is calculated and maximized separately to determine the most profitable allocation of different crops on a given amount of total agricultural area. Additionally, decreasing returns to scale is assumed. Mathematically the sum of these local optima is equivalent to the global optimum, assuring an overall optimal allocation.

Profitability of a crop is determined by its price and yield, which are the driving input parameters to the model. Furthermore, a cost parameter per crop and a risk aversion factor for each spatial unit are calibrated according to observed data. Risk is quantified by the variance of profits.

Specifically, the total achievable profit π per hectare of one spatial unit is assumed to be:

$$(1) \qquad \pi = \sum_{k=1}^{n} \left(p_k \alpha_k - c_k l_k L \right) l_k - \gamma \mathrm{Var}\left[\sum_{k=1}^{n} \left(p_k \alpha_k - c_k l_k L \right) l_k \right]$$

The first part of the equation describes the expected profit, where p_k is the price per product unit, α_k is the productivity per area and l_k denotes the share of total land L allocated to crop k of n crops; c_k is the cost parameter for crop k. Total costs C are assumed to increase in land according to

(2) $$C = \sum_{k=1}^{n} c_k \left(l_k L \right)^2$$

where $l_k L$ denotes the total area allocated to crop *k*. With unit costs increasing in land allocated, we have in fact decreasing returns to scale *at crop level*.

The second term of the equation represents the risk aversion of the representative landowner. Risk perception is quantified by the variance of the expected profit, weighted by a risk aversion factor $\gamma > 0$.

Maximizing π under the constraint that the land shares add up unity, an explicit expression for each land-share l_k allocated to crop *k* can be derived:

(3) $$l_k = \frac{0.5 \sum_{j=1}^{n} \frac{\beta_k - \beta_j}{c_j L + \gamma \sigma_j^2} + 1}{\sum_{j=1}^{n} \frac{c_k L + \gamma \sigma_k^2}{c_j L + \gamma \sigma_j^2}}; \beta_i := \left(p_i \alpha_i - c_i l_i L \right) l_i; \sigma_i^2 := \mathrm{Var}\left[\left(p_k \alpha_k - c_k l_k L \right) l_k \right]$$

The temporal variability of total costs is assumed to be negligible compared to the variability of prices and productivities. Ronneberger *et al.* (2005) show that l_k is increasing in the profitability of crop *k*, decreasing in the profitability of crop *j*, decreasing in the variability of crop *k*, and increasing the profitability of crop *j*.

For the coupling, we calibrate KLUM to 4 crop aggregates: wheat, rice, other cereal crops and other crops (e.g., vegetables & fruits) so as to match the crop aggregation of GTAP-EFL (cf. Table A2). . For the calibration we use data of the FAOSTAT (2004) and World Bank (2003). Yields are specified for each country, prices instead are defined for the 16 different regions equivalent to the regional resolution of GTAP-EFL. Missing data points are adopted from adjacent and/or similar countries of the same region, where similar is defined according to the yield structure of the respective countries. For all countries for which there are observations, the cost parameters as well as the risk aversion factor are determined in the calibration and held constant during all simulations.

The assumption of decreasing returns to scale underlying the cost structure of KLUM has consequences for the interpretation and extrapolation of the calibrated cost parameters. We interpret the increasing cost with increasing area share such that the most suitable land is used first and with further use more and more unsuitable land is applied. This implies that the calibrated cost parameters depend on the total amount of agricultural area assumed in the calibration and on its relative distribution of quality concerning crop productivity. Thus, the cost parameters calibrated for one country cannot simply be adopted in other countries. Instead these values need to be adjusted according to the differences in total agricultural area. Assuming that the relative quality distribution does not change, a doubling of the total area would imply a bisection of the cost, since the double amount of suitable area would be available. So, the cost parameter c_a of country *a* is adjusted for country *b* by scaling it according to:

(4) $$c_a = c_b \frac{L_b}{L_a}$$

where L_b and L_a denote the total agricultural area of countries *b* and *a*, respectively. This procedure assures that under identical conditions, the size of a country (or rather the amount of agricultural area) does not impact the result. Ideally, one would want to use factor prices to extrapolate farming costs from county *b* to country *a*. However, we only use the above procedure for countries for which we do not have much information anyway.

2.3. Validation

We use the available data of FAOSTAT (FAO, 2004) for the time-period 1966-1997 on yield, prices and harvested area. We aggregate the data of 134 available crops to 8 aggregates.[7] Prices are standardized to constant 1995 US dollars. Excluding countries with data for less than 6 years or 1 crop-aggregate leaves us with 163 countries for the validation exercise. Prices are aggregated to 16 regions and averaged over 5 years in order to mimic GTAP output. We keep the total available land L constant.

For each country, we use the first half of the available data for calibrating risk-aversion and cost parameters. For this, we minimize the sum of mean squared errors. We use the second half of the data to calculate the evolving crop-pattern and compare the results to the observed data on harvested area. It should be noted that the first and the second period are not independent observations. For most countries the crop allocation (especially of the maincrops) does not change that much over time. Still, this validation is the best numerical evaluation of the system we can get, given the available data.

Figure 1 compares the observed and modeled pattern of prevailing crops. The prevailing crop is defined as the crop with the highest area-share, averaged over the validation time-period. Note that this does neither necessarily imply that the majority of the available land is allocated to the prevailing crop, nor that the crop has a predominant economic relevance in that country.

Figure 2 depicts the percentage deviation of simulated from observed means. Figure 3 shows the correlation of model results and observed data. We do this for *wheat*, *ric*e and *other cereal grains*. The accordance of means reflect the spatial exactness of the simulated pattern, whereas the correlation quantifies the degree of temporal accuracy. As a measure of correlation, we chose the Fisher-Z transformed correlation coefficient, since in its value it accounts for the amount of data points and, moreover, allows a direct comparison of different values. In order to emphasize units where the depicted crop exceeds a certain relevance with respect to the cultivated area share, we highlight countries with a respective land share $l_k \geq 0.1$.

All figures show a good accordance of model results and observed data. Only for 33 of the 163 countries the prevailing crops are falsely predicted. The number and percentage of countries with false predicted prevailing crop in each region and observed and simulated prevailing crop on the regional aggregation can be found in Table 1. Falsely

[7] Note that these aggregates do not coincide with the GTAP crop aggregates. The 8 crop aggregates are used for validation only. Below, we further aggregate to 4 crop aggregates to match the sectoral aggregation of the GTAP-EF model. While the aggregation of the GTAP is flexible, this is not the case for GTAP-EF as the model is calibrated to the future years of 2010, 2030 and 2050.

predicted prevailing crops are often a result of similar price and/or yield structure for two crops (such as wheat and other cereal grains for price and yield in Canada, or the price of cereal grains and other crops in Sub-Saharan Africa). Similar profitabilities can lead to two dominant crops. The dominance of one over the other is a matter of habit or politics, which cannot be reproduced by the chosen mechanism. Even though the highest percentage of failure occurs in Canada, Western Europe and South America, only for Canada and Mediterranean Africa, the prevailing crop is predicted incorrectly on a regional aggregation of area and area shares.

The deviations of simulated and observed mean are in general rather low. For area shares of more than 10% of total cropland, the deviations of simulated and observed mean seldom exceed 20% and are even lower for most of these countries. The same goes for the correlation, which also tends to be better for crops with *relevant* area shares. Of the depicted crops, the results for *wheat* show the best correlation and the results for *other cereal grain*s are in greatest accordance with the observed mean. *Paddy rice* projections are weakest in correlation and mean, which can be interpreted as just another aspect of the fact that crops with high area shares are reproduced better. Note that, because of the investment in irrigation, paddy rice areas do not expand or contract rapidly, and are therefore in fact easier to predict than other crop areas. The overall picture shows that the model is weakest in Africa and strongest in Asia, except for *paddy rice*, which is weakest in China. The relatively bad performance of *paddy rice* in China results from a strong decrease in China's *paddy rice* production in favour of *oil seeds* and *other crops,* which is not represented by the model in the validation period. This trend is not explainable by the profitability of the crops as it is not visible in price and yield data. Thus, this change cannot be reproduced by the model. This was a period of substantial change in China, and government interventions may have distorted the market. The data may be less reliable too.

2.4 The coupling procedure

The coupling of the two models is established by exchanging crop prices and management-induced yield changes, as determined by GTAP-EFL, with land allocation changes, as calculated by KLUM. In the coupled framework the crop allocation in KLUM is determined on country level. Aggregated to the regional resolution the percentage change of allocated area shares is fed into GTAP-EFL. Based on this the resulting price and management induced yield changes are calculated by GTAP-EFL and used to update prices and yields in KLUM.

In GTAP-EFL management changes are modeled as the substitution among primary and among intermediate inputs. By using, for instance, more labor than capital or more machines than fertilizer, the per-hectare productivity of the land is changed. We determine the management induced changes in yield $\mathrm{d}\alpha_i$ by adjusting the change qo_i of the total production of crop i by the change in its harvested area $qoes_i$, according to:

$$\mathrm{d}\alpha_i = \frac{qo_i - qoes_i}{1 + qoes_i} \qquad (5)$$

Note that this is measured in percentage changes in the code.[8]

The coupling can be divided into 3 methodologically different procedures: a convergence test, a baseline simulation transferring both models to the future and the simulation of the impact of climate change (see Figure 4).

Convergence test The convergence test aims to investigate the convergence of the coupled system and, in case a divergence is detected, to adjust accordingly the key parameters in order to reach convergence. The productivity of land for all crops in all regions in GTAPEFL is shocked with an uniform increase of 2% .[9] Resulting price and yield changes including the original land productivity changes are applied to KLUM. The land allocation changes as calculated by KLUM are appended to the original productivity changes and reimposed on GTAP-EFL. This loop is repeated for ten iterations. This procedure is run with different elasticities of substitution for primary factors in GTAP-EFL. The determined elasticity for which the coupled model converges is then used in the succeeding simulations (see Section 3 for further details).

Baseline simulation The baseline simulation transfers both models to a consistent benchmark of the future. The values of key economic variables shaping the 1997 equilibrium in GTAP are updated according to likely future changes. This step is done with the GTAP model with *endogenous* land allocation. The resulting changes thus also imply land allocation changes with respect to 1997. Crop price and land productivity changes are imposed onto KLUM, which also determines land allocation changes relative to 1997. It should be noted that only the *deviations* from the mean change in land productivity are applied to KLUM; the general mean change implies an increase in costs and riskiness common to all crops and therefore does not affect the results. The differences of land allocation changes in KLUM relative to GTAP-EFL are applied to GTAP-EFL with exogenous land allocation on top of the new benchmark, that is, the GTAP-EFL land allocation in the benchmark is set to that in KLUM. The results of this simulation mark the final benchmark of the future situation. Similarly, price and yield changes from GTAP-EFL are used to adjust prices and yields in KLUM. To test for consistency, we do a convergence test similar to the one described above.

Climate change simulation To simulate the relative impact of climate change we impose a climate change scenario on top of the previously established benchmark. We start by applying to KLUM climate-induced yield changes on country level. Resulting allocation changes and the regionally aggregated yield changes are applied to GTAP-EFL and exchanged with crop price and management changes for ten iterations. It should be noted that we correct the management changes of GTAP-EFL (equation 5) for the before imposed climate-induced yield changes. The mean value of the last four iterations is fed back to both models to reach the final results. The convergence path is audited in order to guarantee the consistency of the modeling framework.

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[8] Note that

$$qo_i = \frac{Q_{i-1} - Q_i}{Q_{i-1}} = \frac{L_{i-1}M_{i-1} - L_iM_i}{L_{i-1}M_{i-1}} = \frac{L_{i-1}M_{i-1} - L_{i-1}(1+qoes_i) - M_{i-1}(1+d\alpha_i)}{L_{i-1}M_{i-1}} = qoes_i + d\alpha_i(1+qoes_i)$$

[9] The chosen quantity of change is arbitrary. Indeed any perturbation to the initial GTAP equilibrium would have originated a set of changes in crops prices that could have been used as the first input in KLUM to start the convergence test.

3. Convergence

To ensure the consistency of the coupled system, the convergence of the exchanged values to stable and defined quantities needs to be guaranteed. Running the coupled models with their original parameterization shows that the two systems diverge. Not only land quantities and prices diverge, but also, after the 4th iteration, the GTAP-EFL model is unable to find a meaningful economic equilibrium: some variables decrease by more than 100%. This is the consequence of two main problems. The first results from the different initial land allocations assumed in the two models; the second is due to the general constraint imposed by the structure of the CGE model itself.

The problem of the different initial situations seems like a minor challenge from the conceptual side; however, it poses a great practical problem. The difficulty originates from the fact that all equilibrium equations in GTAP are formulated in terms of value, instead of quantities (Hertel, 1997). During the solution procedure, the changes are distinguished into changes in quantity and changes in price, so that the imposition of quantity changes, as calculated in KLUM, is conceptually consistent. But since prices are set to unity in the benchmark, implicitly the quantity of land is equaled to the value of land. In the absence of data on the price of land, this makes land quantity data incomparable between GTAP and FAOSTAT (2004), to which KLUM is calibrated.

The different initial situations in GTAP-EFL and KLUM are presented in Table 2; for KLUM, we give shares of area; for GTAP-EFL, we give shares of land value. Region- and crop-specific values as well as the global totals of regions and crops differ tremendously. The global share of land used for wheat production in GTAP-EFL is only half of the share used in KLUM. Other crops use twice as much global cropland in GTAP-EFL as in KLUM. As KLUM measures area and GTAP-EFL measures value, this deviation is understandable. But for the coupled framework, this means that small absolute changes in the area of "other crops" in KLUM translate into large absolute changes in GTAP-EFL. Also the shares of total area used in the different regions differ notably. In GTAP-EFL, large shares of total global cropland value are situated in Western Europe, South Asia and the USA. In KLUM, the largest areas of cropland are in South Asia, China, Subsaharan Africa and the Former Soviet Union. These differences are of less importance in the KLUM model where each spatial unit is optimized independently. In GTAP-EFL, however, the trade structure is impacted by the regional distribution of resources. Thus, relatively small changes of aggregated absolute allocation in Western Europe can cause large shocks in GTAP-EFL.

In principle the optimal solution would be to recalibrate the GTAP-EFL model according to the observed land allocation consistent with KLUM. However, this would entail a complete recalibration of to the CGE. This would be a major task, and it would be arbitrary without data on land prices or crop areas that is consistent with the original GTAP calibration.[10] See Chapter 4[11] for a discussion of how to change allocation of

[10] Land price data are not available. Dividing GTAP land values with FAOSTAT crop areas leads to absurd land prices. FAOSTAT's explicit crop areas are not consistent with GTAP's implicit crop areas.
[11] GTAP Working Paper No. 42

value-added in agriculture under the assumption that total value-added by crop is unchanged.

The "structural rigidity" of CGE models follows from their theoretical structure. Economic development is simulated by equating all markets over space and time, assuming that a general economic equilibrium is the best guess possible to describe economic patterns and to project their development for different scenarios. All markets are assumed to clear, and the equilibrium is assumed to be unique and globally stable. Guaranteeing these assumptions while assuring applicability to a wide range of economies and policy simulation implies that a number of regularity conditions and functional specifications need to be imposed. Accordingly, such models generally may find difficulties in producing sound economic results in the presence of huge perturbations in the calibration parameters or even in the values of exogenous variables characterizing their initial equilibrium. We replace GTAP endogenous land allocation mechanism with exogenous information provided by the land use model. This new allocation is not driven by optimal behavior consistent with the GTAP framework and can thus distort the system in such a way that convergence can no longer be guaranteed. This is also the reason why we use GTAP with endogenous land allocation to establish the first instance of the baseline benchmark. Combining the large shocks of the baseline scenario with the exogenous land allocation mechanism determined by KLUM would overstrain the solving algorithm of GTAP-EFL.

To assure convergence, the land-use model would need to be formulated as a consistent part of the CGE -assuring all markets to be in equilibrium. This, however, would be difficult to combine with the intention of replacing the purely economic allocation decisions by a more flexible model, which takes into account the biophysical aspects of land-use decisions on a finer spatial resolution. Thus, for the moment – to lower the influence of the initial situation on the one hand, and to promote convergence on the other hand – we simply decrease the responsiveness of GTAP-EFL to changes in land allocation. The key parameter governing this is the sectoral elasticity of substitution among primary factors *ESBV*.[12] This parameter describes the *ease* with which the primary factors (land, labor and capital) can be replaced by one another for the production of the *value-adde*d (see e.g. (Hertel, 1997) for more details). We conduct convergence loops with ten iterations each for the original and appropriately increased elasticities *ESBV*.

3.1. Results of the convergence test

A first set of simulations (not presented here) revealed that price, yield and area-share-changes for the region *Res*t *o*f *th*e *worl*d diverged quickly and distorted the performance of the complete system, preventing the existence of a common equilibrium. This region encompasses the residual countries not included in any of the other regions. The composition slightly differs between the two models on the one hand and this region is of minor importance on the other hand. Thus we completely exclude this region from the

[12] The land allocation elasticity *ETREA* is obsolete, as the land allocation part of the GTAP-EL is replaced by KLUM@GTAP.

coupling experiment. No data is exchanged between KLUM and GTAP-EFL for this region in any of the presented simulations.

Figure 5 depicts the iteration process for doubled and tripled elasticity for North Africa and South Asia. We chose these regions as representatives, because they best show all the dominant behavior observed also in the other regions. The plots depict the abstract space spanned by the percentage changes in price, yield and area-share. Each point in this space characterizes a defined state of the system. In this space we mark the state of the system after each iteration. In case of convergence, the system reaches a stable state, which would imply that after iteration *n* each further iteration should end in the same state i.e. we should observe a clustering of the markers over time. For divergence instead the markers will spread further and further representing the ever changing state of the system. Thus the total spread of the marked states (visualized by the axes) as well as their temporal evolution (visualized by the shading) relative to some defined point (in our case the mean value of the last 4 iterations, marked red) characterized the convergence behavior of the system.

For doubled elasticity, a strong divergence of the iterating values can be observed in both regions for all crop areas. Only the results for wheat area in North Africa reveals converging behavior, as can be seen from the markers tightly clustered around the mean value. This corresponds to the initial differences in land allocation: in both regions for nearly all crops the initial area shares for the different crops differ considerably between the two models (Table 2); only wheat area in North Africa shows similar shares in both models. Generally, the divergence is much stronger in South Asia than in North Africa. This indicates that the influence of trade emphasizes the observed changes: according to GTAP-EFL South Asia holds about a sixth of total global cropland land rental value, making it one of the potentially largest crop producers. North Africa instead is one of the smallest producers in term of harvested area (compare Table 2). Of course the described trends cannot be mapped linearly to all regions and crops. But the general tendency is visible throughout the results.

Convergence is clearly improved with tripled elasticity. Whereas the spread of exchanged values for the double-elasticity simulations is increasing with increasing iteration number, the data points of the tripled-elasticity simulations are tightly clustered, approaching the marked mean (the empty red marker) with proceeding iteration step. Yet, it should be noted, that the absolute values of exchanged quantities are generally smaller for tripled elasticity due to the lowered responsiveness of GTAP-EFL. Thus, identical relative changes of the exchanged values appear larger in Figure 5 for the doubled-elasticity case than for the tripled-elasticity one. Still, an investigation of the relative changes (not shown here) underpins the impression given in the presented graphs. With tripled elasticity the standard deviation of the last four iterations is less than 5% of the respective mean value for 85% of all exchanged quantities, confirming the observed convergence. Thus, for all following simulations the tripled elasticity $ESB\mathrm{V} = 0.711$ is used (see Appendix).

4. Experimental Design

KLUM@GTAP was developed to assess the impact of climate change on agricultural production and the implications for economic development. We first apply an economic baseline scenario, which describes a possible projection of the world in 2050 without climate change; this simulation is referred to as *baselin*e in the following. On top of that we impose estimates of climate change impacts so as to portray the situation in 2050, with climate change; the respective simulation is called *cc2050*. Climate change is introduced as a change in yields in KLUM@GTAP, and as a change in agricultural productivity in GTAP-EFL (see Appendix B).

The convergence of the system is highly influenced by the "starting point". Thus to clarify the impacts of the baseline on our climate change assessment and to confirm the stability of the coupled system we perform also a reference simulation: the climate change scenario is directly applied onto the 1997 benchmark; this simulation is referred to as *cc1997*.

The effect of the coupling on the results is highlighted by estimating the climate change impacts also with the uncoupled models (referred to as the *uncouple*d simulations). In both models we use the benchmark equilibrium 2050 of the *baselin*e simulation as the starting point and apply the climate change scenario. The GTAP-EFL model is used with endogenous land allocation. Country-level allocation shares of the KLUM benchmark 2050 are used to aggregate the yield changes of the climate change scenario to the regional level. KLUM standalone is driven by the climate change scenario and exogenous price and management changes according to the *uncouple*d GTAP-EFL. Like this the KLUM model describes a partial equilibrium situation.

The different scenarios are summarized in Table 3. More detail on the explicit assumptions and used data are given in Appendix B.

5. Results

The simulation results can be divided into general changes of the economy and those directly affecting the coupled crop sector. As general economic changes we study changes in GDP, welfare, CO2 emissions and trade. Changes in the crop sector are described by changes in crop prices and production and in the allocation of cropland.

5.1. Baseline scenario

The changes according to the baseline scenario in CO2 emissions and GDP (Table 4) and crop production (Table 5) are positive in the order of several hundred percent for all regions. This reflects rapid population and economic growth. See Chapter 10[13] for a discussion of the demand for food.

For emissions, GDP and crop production the growth is up to 1.5-4.0 times stronger in currently developing regions, such as Sub-Saharan Africa and China, than in developed

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regions, such as the USA and Western Europe. These results directly reflect the scenario assumptions of a long-term convergence of developing to developed regions. Between 1997 and 2050 the trade balance changes only slightly (Table 4). Negative changes appear in Africa, the Middle East, South America, the Former Soviet Union and Europe. They are largest for Western Europe. In Western Europe, the land productivity increases much less than in the other countries. Crop prices generally decrease by around 20-60% for all regions and crops (Table 6). This is a result of the assumed increase of the productivity of land and labor, leading to lower production costs, which more than offset the increased demand due to population growth (see Table B1).

Impacts on the cropland allocation are pictured in Figure 6. The plots suggest that other crops are largely replaced by wheat and other cereals, as the demand for feed increases with meat consumption and affluence. Only in South Asia and some countries of Central America and North Africa the area share for other crops is increased, as the demand for fruit & vegetables also increases with per capita income. Also rice cropland is strongly reduced in most countries. Only in the Former Soviet Union, South East Asia and a number of Sub-Saharan countries an increase in area for rice is visible. Wheat and other cereals show an increase in harvested area for nearly all the countries. Only in the Eastern part of the Asian continent wheat is planted less, the area for cereals is decreased in North America; Argentina decreases its area share for both crops.

5.2. Climate change in 2050 (cc 2050)

The climate impacts are several orders of magnitude smaller than the baseline changes. This is the result of the comparably small climate-induced yield changes (see Appendix B, Figure B1). We thus concentrate on the trends and intercomparison of changes, rather than on the absolute extent.

The impact of a changing climate on land allocation and the crop sector, according to KLUM@GTAP are shown in Figure 7 and Table 5 and 6. We observe increases in the area share and price for rice production in nearly all countries and regions; production instead is decreasing. Obviously the losses in yield are counteracted by an increase of the area share, increasing the prices. Also for several other regions and crops, such as other cereals in China and USA or wheat in South America, yield losses are compensated by area gains and prices rise. Only for vegetables & fruits this pattern is not observable; as the yields are unaffected in our climate change scenario, this is not surprising. In general, for the majority of regions the production of rice and vegetables & fruits is decreasing, whereas for wheat and other cereals more regions increase the production (Table 4); price changes show an opposite pattern. The cropland changes of wheat and other cereals reveal an interesting scheme: they are of opposed signs in nearly all countries. As we do not observe the same pattern in the imposed yield changes, this can be interpreted as direct competition of these crops. The similar price, allocation and yield structure of wheat and other cereals makes their relative allocation changes sensitive to small perturbations: according to minor price and yield changes either one or the other is preferred in production.

The crop production changes by and large explain the pattern of losses and gains observed for GDP and welfare (Figure 8, red bars). Losses in GDP and welfare are present in most, but not all the regions. We observe strong gains in Central America and South Asia and smaller gains in Sub-Saharan Africa, Canada and Western Europe: all regions where also for crop production the increases prevail. Generally CO2 emissions (from fossil fuel use) change in accordance with GDP. Only the USA, the Former Soviet Union, and Eastern Europe are notable exceptions. In these regions, the ”composition” effect (particularly, fertilizer use) dominates the ”size” effect (total demand for food). Also the trade balance reveals a clear connection to GDP and welfare changes: for nearly all regions gains in GDP and welfare are accompanied by losses in the trade balance and vice versa. In terms of trade, WEU shows the highest losses.

5.3. The effect of the baseline on the climate change simulation (cc 1997)

We assess the effect of the baseline scenario on the estimations of climate impacts by comparing results of scenario *c*c *199*7 (where the climate scenarios is imposed on the current situation) to those of scenario *c*c *205*0 (where the climate change scenario is applied to the baseline benchmark of 2050). Figure 9 shows that excluding the baseline generally leads to an increase in allocation changes. Contrary, crop prices and production changes exceed the climate impacts with the baseline in the order of some ten percent (Table 4 and 5). This reflects the way land is treated in the CGE. In the baseline scenario the productivity of land increases, causing an increase of land value. In the climate simulations starting from the baseline thus due to the unity prices in the benchmark the land quantities increase as well. An introduced percentage change in land hence translates to a much larger absolute change in the 2050 benchmark situation than in the 1997 benchmark situation. Principally, however, the pattern of changes in crop prices, productions and land allocation is conserved, indicating the stability of the coupled system.

The same is true for the economic changes of the *cc199*7 simulation (green bars in Figure 8). For almost all regions and indicators the sign as well as the relative extent of the changes are similar to those projected relative to the baseline (red bars). The trade balance in Eastern Europe and the USA are the only exceptions; in Eastern Europe, the impact on the trade balance is very small in each case; in the baseline scenario, the USA loses its competitive advantage in agriculture to other regions, which explains the reversal in sign. Evidently, the changes in welfare are much smaller, if no baseline is applied. This, however, only reflects the initial welfare difference of the 1997 and the 2050 benchmark as welfare changes are expressed in US dollar equivalents rather the percentages. Qualitatively, the welfare impacts are very similar. In this particular case, imposing climate change on “today’s” economy is actually a good approximation of the actual impact of climate change, which will of course befall a future economy.

5.4. The effect of the coupling on the climate change simulation (uncoupled)

Also for the coupling we assess the effect on the results by studying differences of uncoupled to coupled simulation. GTAP-EFL standalone is driven only by the regionally aggregated climate-induced yield changes; land allocation is endogenous. KLUM standalone is driven by the climate change scenario and crop prices and management-induced yield changes of GTAPEFL standalone; feedbacks, though, are excluded.

5.5. GTAP-EFL -standalone

The resulting land allocation changes of GTAP-EFL standalone (with endogenous land allocation and trippled elasticity *ESBV* = 0.711) differ from the results of the coupled system simulation by several hundred up to thousand percent (shown in Table 7); in some cases even the signs differ. We see the highest differences for other cereals and rice, indicating that greater yield changes emphasize the gap between coupled and uncoupled simulation. Also crop prices and productions differ notably between the coupled and the uncoupled simulation: differences are in the order of some ten up to several hundred percent. For rice GTAP-EFL standalone underestimates most of the changes in prices and productions, whereas for vegetables & fruits overestimations prevail. Some few estimates even change sign due to the coupling. Whereas for the coupled simulation e.g. prices of cereal crops increase in Western Europe and fall in the Former Soviet Union, they show the opposite behavior in the uncoupled scenario. The largest differences between the simulations can be seen for vegetables & fruits. Note that vegetables and fruits are assumed not be affected by climate change directly; these changes result from the indirect impacts on allocation. Even though the region *Res*t *o*f *th*e *worl*d was excluded from the coupling, we reveal large differences between the coupled and the uncoupled simulation for the price changes in this regions. These are purely indirect effects.

The economic changes in GTAP-EFL standalone (Figure 8, yellow bars) differ from those in KLUM@GTAP in extent but not in sign. The differences are generally low, only for China they reach up to several hundred percent; again the effect is strongest on the trade balance. The low differences reflect the general low responsiveness of these indicators in GTAP-EFL to land allocation changes, which is even damped in our simulations by the increased elasticity.

5.6. KLUM -standalone

The percentage differences of land allocation changes in KLUM standalone to KLUM@GTAP are in the range of ±10 - 100%, reaching up to several hundred percent (Figure 10). We see even a change of sign in some countries, especially for the case of vegetables & fruits; generally the differences for vegetables & fruits are largest and mainly positive. Again, these changes are solely triggered by price and management changes or indirect allocation effects. Obviously, these factors are strongly impacted by the coupling procedure: in the general equilibrium setting of the coupled simulation these factors are dampened by inter sectoral effects and trade. We see that KLUM standalone tends to overestimate decreases and underestimate increases of area changes in rice production; the total area share of rice is thus underestimated. The pattern of deviations for wheat and other cereals are rather similar but with generally stronger deviations for other cereals. This underpins the observation that the coupling effect grows stronger with larger scenario changes.

6. Summary and Conclusion

We present in this paper the coupling of a global computable general equilibrium model with a global agricultural land-use model in order to consistently assess the integrated impacts of climate change on global cropland allocation and the implication for economic development. The linking of the models is established, by exogenizing the land allocation mechanism of GTAP-EFL and by replacing it with the dynamic allocation module KLUM. Price and management changes, according to GTAP-EFL and country specific yield values drive KLUM; regionally aggregated area changes determined by KLUM are used to update the cropland shares in GTAP-EFL. This intimate link allows a direct and spatially more explicit projection of biophysical aspects of land-use decisions onto economic crop production; the effects of economic trade and production decisions are projected back onto country specific crop patterns. By this the framework provides a consistent picture of the economy and of agricultural land cover.

In the first part of the paper we investigated the convergence behavior of the coupled system. We identified as key problem of an ensured convergence the initial situation of land allocation in GTAP-EFL combined with the ”rigid structure” of the model. The initial cropland shares in GTAP-EFL are given in ”value added of production”. But due to the assumptions of unity prices in the benchmark, the same numbers are treated as quantity values during the simulations and are updated by the changes determined by KLUM. KLUM on the other hand calculates allocation changes based on observed area shares of FAOSTAT (2004), which differ substantially from the values used in GTAP. This difference causes a distortion of the introduced changes and can lead to divergence.

As a workaround we lowered the responsiveness of the CGE to the introduced cropland share changes by increasing the sectoral elasticity of substitution for primary factors. By means of a convergence test with the coupled framework we were able to show a clear improvement of the convergence behavior due to this tactic. Moreover the test confirmed the connection of the discriminative initial situations and the convergence behavior. With a tripled elasticity convergence was reached in all regions for all crops. The change in results caused by the new elasticity are acceptable considering the general uncertainties underlying the values of elasticities (Hertel, 1997). Moreover the initial elasticity was rather low (Hertel, 2006, personal communication). The tripled elasticity ($ESBV = 0.711$) was used in the succeeding simulations and convergence was audited for the performed experiments.

However, a general guarantee of convergence for the coupled system cannot be established by means of the convergence test. The complex system of the CGE is distorted by the inclusion of the land-use model that is not formulated consistently with the general equilibrium framework. Above this, the offset caused by setting land values to quantities in the benchmark is even enhanced when land becomes scarce and thus more valuable, as in our baseline scenario. One way to solve the convergence problem is to use constant elasticity of substitution (CES) production functions in KLUM, and to take intermediate inputs to agriculture from GTAP-EFL as well. This would tighten the interaction between GTAP-EFL and KLUM. Yet, it would also imply that KLUM can no longer be run as a standalone model, hampering model validation and the coupling to biophysical models at a finer geographical resolution.

In the second part of the paper we illustrate that plausible estimations of climate change impacts are still feasible under the aforementioned uncertainties. Crop production changes according to the pattern of induced yield changes. Yield losses are often compensated by area increases, causing prices to rise. A negative impact of climate change for nearly all regions in terms of GDP and welfare was revealed. Only Central America and South Asia show strong gains and some smaller gains are revealed in Sub-Saharan Africa, Canada and Western Europe. This also reflects the pattern of induced yield changes. The remaining economic indicators follow the pattern of GDP and welfare. Emission and crop production changes are in line with GDP and welfare changes; trade balance and crop price changes are of opposite sign.

The convergence of the system is highly influenced by the starting point. The effect of the baseline scenario on the results as well as the stability of the coupled system was thus studied by a reference scenario in which the climate impacts were directly introduced to the current situation. The baseline assumptions influence the extent but not the general pattern of the results, reflecting the robustness of the model. Crop prices and production changes are enhanced by the baseline scenario; crop allocation changes instead are dampened in nearly all countries. This demonstrates the above said: the increased value of land in the baseline scenario (due to productivity improvements) rises the responsiveness of GTAP to the land allocation changes.

The effect of the coupling on the results of the climate change simulation was studied by reference simulations with the uncoupled models. With both models the climate impacts relative to the afore established benchmark of 2050 were estimated. A clear impact of the coupling can be revealed for both models. The results of standalone simulations generally differ from those of the coupled simulation by some ten up to several hundred percent and show opposite signs for some cases. The differences are lower for the general economic indicators, reflecting the damped responsiveness to land-use changes of the GTAP-EFL due to the tripled elasticity. Land allocation changes in GTAP-EFL standalone and KLUM@GTAP differ by several hundred up to thousand percent. This clearly demonstrates the relevance of the improved allocation mechanism. Moreover the differences are larger for greater yield changes -indicating that the effect of the coupling will be even more pronounced for extreme scenarios.

All this strongly supports the hypothesis that a purely economic, partial equilibrium analysis of land use is biased; general equilibrium analysis is needed, taking into account spatial explicit details of biophysical aspects.

Concluding, the presented approach is a step in the right direction to reach an integrated modeling framework for the estimation of the mutual impacts of economic and environmental changes such as climate change. It establishes an interactive and close link between the two models, bearing the potential of consistently integrating the biophysical aspects of land-use decisions into the economic model. The flexible spatial resolution of

KLUM additionally facilitates the use of a spatial resolution needed for a meaningful biophysical analysis of the environmental aspects. Yet, to really establish a satisfactory modeling framework that allows reliable projections of the integrated changes of the natural and economic system a long way is still ahead. Most pressingly, the presented convergence problems and inconsistency in the interpretation of land quantity need to be resolved. This requires an elaborative revision of some mechanisms in the general equilibrium model and -in all likelihood -a recalibration of the model. A dynamic formulation of GTAP-EFL would help to simulate future pathways with the coupled framework without relying on a baseline scenario with heavy shocks. This would further improve the conditions for convergence. Apart from that, the allocation algorithm of KLUM needs to be extended to include other agricultural sectors such as animal production and finally also forestry and industrial land. The coupling of the land use model to a dynamic vegetation model is already performed for the European level (Ronneberger *et al.*, 2006). To reach full integration both couplings need to be consolidated on the global level. Besides competition for land, the model should be extended to include competition for water resources.

All in all the presented work should be seen as a feasibility study pointing out the direction of further work to be done.

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Tables and Figures

Table 1. Number and percentage of falsely predicted prevailing crops per region.

Region	False/total	%	Observed	Simulated
ANZ	0/2	0	Wheat	Wheat
CAM	0/8	0	Cereal grains nec	Cereal grains nec
CAN	1/1	100	Wheat	Cereal grains nec
CEE	2/6	40	Cereal grains nec	Cereal grains nec
CHI	0/3	0	Paddy rice	Paddy rice
JPK	0/2	0	Paddy rice	Paddy rice
MAF	1/5	20	Wheat	Cereal grains nec
MDE	3/14	21	Wheat	Wheat
SAA	0/7	0	Paddy rice	Paddy rice
SAM	6/13	46	Cereal grains nec	Cereal grains nec
SEA	1/11	9	Paddy rice	Paddy rice
SIS	5/29	17	Sugar cane/beet	Sugar cane/beet
SSA	7/43	16	Cereal grains nec	Cereal grains nec
USA	0/1	0	Cereal grains nec	Cereal grains nec
WEU	7/19	37	Cereal grains nec	Cereal grains nec

Table 2. Initial shares in GTAP (value) and KLUM (area). The emphasized totals are relative to total global cropland (as quoted in the lower right corner). The region-specific shares relate to the regional totals.

Crop	Rice		Wheat		Cereal crops		Veg & Fruit		Total	
Region	GTAP	KLUM	GTAP	KLUM	GTAP	KLUM	GTAP	KLUM	GTAP	KLUM
USA	0.011	0.017	0.172	0.336	0.546	0.495	0.271	0.153	0.147	0.078
CAN	0.000	0.000	0.336	0.447	0.244	0.305	0.419	0.249	0.007	0.026
WEU	0.003	0.007	0.323	0.302	0.345	0.374	0.329	0.317	0.196	0.060
JPK	0.369	0.573	0.005	0.030	0.146	0.057	0.480	0.340	0.066	0.005
ANZ	0.016	0.008	0.210	0.533	0.293	0.353	0.480	0.106	0.006	0.020
EEU	0.004	0.001	0.121	0.273	0.295	0.480	0.580	0.246	0.016	0.030
FSU	0.182	0.005	0.068	0.420	0.106	0.370	0.644	0.206	0.011	0.113
MDE	0.030	0.018	0.116	0.477	0.134	0.269	0.720	0.236	0.012	0.042
CAM	0.025	0.023	0.038	0.047	0.466	0.703	0.470	0.227	0.040	0.017
SAM	0.042	0.086	0.074	0.145	0.230	0.392	0.654	0.377	0.075	0.060
SAS	0.243	0.324	0.085	0.208	0.166	0.213	0.506	0.255	0.156	0.187
SEA	0.350	0.564	0.000	0.000	0.148	0.227	0.502	0.209	0.108	0.075
CHI	0.166	0.225	0.058	0.209	0.121	0.239	0.655	0.326	0.086	0.151
NAF	0.001	0.047	0.357	0.379	0.184	0.306	0.458	0.268	0.008	0.015
SSA	0.171	0.064	0.023	0.019	0.427	0.587	0.379	0.330	0.016	0.115
RoW	0.127	0.083	0.082	0.000	0.246	0.163	0.545	0.754	0.039	0.004
Total	0.133	0.157	0.129	0.231	0.276	0.346	0.462	0.266	965573	268948

Table 3. Overview over the different simulations: *year* denotes the initial, benchmark situation of the model; *start* is the model on which the initial change, described in column *imposed changes* is imposed.

	model	year	imposed changes	start
baseline	KLUM@GTAP	1997	Baseline scenario (Table C1)	GTAP-EFL
cc 2050	KLUM@GTAP	2050	Climate change scenario (Figure C1)	KLUM
cc 1997	KLUM@GTAP	1997	Climate change scenario (Figure C1)	KLUM
uncoupled	GTAP-EFL	2050	Climate change scenario (Figure C1), aggregated to the regional level	GTAP-EFL
	KLUM	2050	Climate change scenario (Figure C1), price and management induced yield changes of uncoupled GTAP-EFL simulation	KLUM

Table 4. Changes in the economy until 2050: Percentage changes in CO_2 emission and GDP, and absolute change in the trade balance (mln $) in the *baseline* scenario according to KLUM@GTAP.

Region	CO2 emissions	GDP	Trade balance
NAF	448.1	659.2	-55079
EEU	429.2	621.6	-177502
ANZ	269.1	444.3	10644
ROW	576.3	865.9	-40101
CAN	304.1	489.6	30906
CAM	511.2	689.9	9703
SSA	618.4	950.2	-95355
SAS	641.1	733.2	96738
FSU	381.9	706.5	-112725
MDE	495.5	698.0	-176199
SEA	468.7	740.8	338141
CHI	656.4	783.7	347770
SAM	539.5	732.9	-17941
JPK	283.0	436.1	263582
USA	304.6	444.2	22448
WEU	273.9	466.9	-445029

Table 5. Impacts on crop production. For the *baselin*e and the *c*c *205*0 scenario the percentage changes according to KLUM@GTAP are given. Rows *cc 199*7 and *uncoupled* state the effect on the climate impacts of the baseline assumption and the coupling, respectively. In both cases, the differences are given in percent of *cc 2050*.

Crop	scenario	USA	CAN	WEU	JPK	ANZ	EEU	FSU	MDE	CAM	SAM	SAS	SEA	CHI	NAF	SSA	RoW
Rice	baseline	269.8	199.5	180.2	346.6	343.4	370.8	472.1	481.4	448.1	504.9	294.5	604.2	674.5	230.0	729.0	486.8
	cc 1997	4.95	41.72	-65.80	-51.43	-33.93	-69.51	-15.15	-64.29	26.17	0.00	-21.05	-27.59	0.00	-31.58	60.00	-66.67
	cc 2050	-0.202	0.163	-0.193	-0.035	-0.056	-0.082	-0.033	0.014	0.149	-0.011	0.038	-0.058	-0.002	0.133	-0.005	0.003
	uncoupled	0.50	-0.61	-15.54	-5.71	-3.57	21.95	-21.21	-7.14	-18.79	-9.09	-13.16	-18.97	50.00	-12.03	-20.00	0.00
Wheat	baseline	307.9	363.9	347.1	364.6	433.6	423.1	426.3	502.5	610.2	595.6	260.9	733.5	568.5	343.0	835.4	567.3
	cc 1997	-15.22	-18.35	-22.22	-8.81	-14.33	45.45	7.69	63.64	-32.53	-11.48	-29.89	-42.99	-71.43	-53.13	-43.24	-18.18
	cc 2050	-0.184	0.632	0.045	-0.159	-0.656	-0.022	0.013	-0.022	-0.083	-0.061	0.087	0.107	0.014	0.032	0.074	0.011
	uncoupled	2.72	0.16	-11.11	4.40	-4.73	-27.27	-69.23	-45.45	1.20	-9.84	-6.90	14.95	-7.14	6.25	0.00	0.00
Cereals	baseline	271.9	289.3	233.9	232.1	306.8	406.7	329.6	530.6	539.1	552.7	510.3	542.8	728.7	-337.3	587.3	567.1
	cc 1997	-26.15	6.44	0.96	-5.45	-6.29	-393.33	208.33	-1.42	-22.98	10.10	-46.24	-43.18	-20.25	-70.00	-12.83	-8.93
	cc 2050	-0.325	0.807	0.104	-0.110	-0.289	0.015	0.012	0.212	1.075	-0.307	0.372	-0.044	-0.242	0.010	0.187	0.056
	uncoupled	-2.46	-10.90	-19.23	13.64	-15.57	53.33	-358.33	-14.15	-2.33	-13.03	-10.48	15.91	-21.49	-40.00	-25.13	-8.93
Veg &	W2q	233.0	298.3	193.4	165.4	278.9	322.7	384.8	454.9	410.1	457.4	444.9	475.2	619.0	467.0	605.2	486.6
Fruit	cc 1997	-100.00	-29.17	-42.86	-33.33	33.33	87.50	100.00	-60.00	-44.44	0.00	100.00	-12.50	28.57	300.00	300.00	-50.00
	cc 2050	-0.002	0.024	0.007	-0.027	-0.006	-0.008	0.002	0.005	0.009	-0.001	0.010	-0.040	-0.007	-0.001	-0.001	0.002
	uncoupled	1900.0	212.5	128.6	114.8	33.3	0.0	-1000.0	180.0	144.4	0.0	20.0	50.0	-71.4	-300.0	-1600.0	150.0

Table 6. Impacts on crop prices. For the *baselin*e and the *cc 2050* scenario the percentage changes according to KLUM@GTAP are given. Row *cc 1997* and *uncouple*d state the effect on the climate impacts of the baseline assumption and the coupling, respectively. In both cases the differences are given in percent of *cc 2050.n.a*. marks cases where the prices only change in the reference simulations.

Crop	scenario	USA	CAN	WEU	JPK	ANZ	EEU	FSU	MDE	CAM	SAM	SAS	SEA	CHI	NAF	SSA	RoW
Rice	baseline	-24.46	-33.82	-36.24	-27.33	-32.89	-27.77	-32.28	-41.97	-51.88	-43.24	-61.60	-43.48	-40.78	-42.47	-52.63	-47.81
	cc 1997	-33.47	31.75	-21.36	-25.04	-27.79	-18.78	-24.01	-22.67	22.44	-12.45	80.17	-21.23	-26.47	7.10	-2.56	-33.33
	cc 2050	0.475	0.063	0.220	0.699	0.511	0.362	1.266	-0.075	-0.205	0.257	-0.116	0.796	0.136	0.183	0.039	0.009
	uncoupled	-0.84	-3.17	-15.00	-10.30	-10.76	0.00	-30.57	-13.33	-37.07	-17.12	-18.97	-27.39	-21.32	-20.77	-10.26	111.11
Wheat	baseline	-27.73	-33.14	-31.80	-34.11	-36.28	-33.32	-31.67	-45.59	-45.65	-45.36	-58.32	-43.57	-50.84	-40.76	-48.80	-45.76
	cc 1997	-26.39	-8.99	-7.69	-16.36	-16.52	-11.43	-23.81	-10.20	-25.71	-21.85	22.99	-12.50	-50.75	3.70	-200.00	-18.75
	cc 2050	0.216	-0.089	-0.013	0.220	0.339	0.105	0.021	0.098	0.140	0.151	-0.087	0.088	-0.067	0.027	-0.013	0.016
	uncoupled	-1.39	4.49	-100.00	-0.91	-4.42	-6.67	104.76	-15.31	0.71	-8.61	-12.64	-11.36	22.39	-22.22	7.69	25.00
Cereals	baseline	-27.78	-33.60	-35.03	-35.19	-39.89	-42.21	-34.75	-45.35	-54.12	-48.83	-59.25	-48.35	-48.89	-41.11	-51.41	-46.43
	cc 1997	-30.32	-19.06	150.00	-15.61	-11.80	120.31	-31.82	-5.26	30.22	-4.71	34.53	-23.05	-26.48	6.58	-314.29	-22.58
	cc 2050	0.663	-0.278	0.004	0.506	0.695	0.064	-0.022	0.019	-0.321	0.446	-0.278	0.308	0.759	0.152	0.007	0.062
	uncoupled	-11.31	-6.12	-150.00	-11.46	-19.86	-51.56	-127.27	-57.89	9.03	-16.82	-4.32	-17.21	-22.27	-15.79	14.29	-50.00
Veg &	W2q	-25.49	-33.24	-32.90	-35.75	-33.43	-35.18	-34.57	-43.03	-42.44	-40.23	-30.31	-40.57	-38.64	-36.75	-45.86	-46.90
Fruit	cc 1997	-33.33	-16.67	0.00	-34.04	-5.26	30.00	n.a.	0.00	-16.67	-200.00	-25.00	5.13	-12.50	0.00	9.09	-25.00
	cc 2050	0.015	0.012	0.004	0.047	0.019	0.020	0.000	0.003	0.024	0.002	0.012	0.039	0.016	0.003	0.011	0.008
	uncoupled	406.7	91.7	250.0	163.8	189.5	70.00	n.a	166.7	91.7	1050.0	33.3	184.6	-12.5	133.3	63.6	150.0

Table 7. Effect of the coupling on climate change impacts on cropland allocation. The results of the GTAP-EFL standalone (*uncoupled*) and the KLUM@GTAP simulation (*cc 2050*) are compared; differences are expressed in percent of the latter. *n.a.* marks cases where the allocation changes only in GTAP-EFL standalone.

Region	Rice	Wheat	Cereals nec	Veg & Fruit
USA	-7.52	6.30	137.23	457.89
CAN	7.69	172.73	1500.00	-1500.00
WEU	301.10	-123.53	-105.26	-97.22
JPK	138.82	17.05	-860.00	177.39
ANZ	40.79	-105.56	768.00	4233.33
EEU	10.55	107.69	-140.00	-10.00
FSU	n.a.	n.a.	16800.00	n.a.
MDE	125.00	2316.67	-728.57	-1700.00
CAM	-3100.00	-27.66	-327.73	-218.75
SAM	422.22	-376.47	1826.67	220.00
SAS	-559.09	194.44	205.71	-4.55
SEA	283.05	-81.05	-74.07	40.63
CHI	260.00	-15.49	245.10	-14.71
NAF	405.08	-146.43	1040.91	640.00
SSA	127.27	1.37	-500.00	-260.00
RoW	n.a.	n.a	n.a.	n.a.

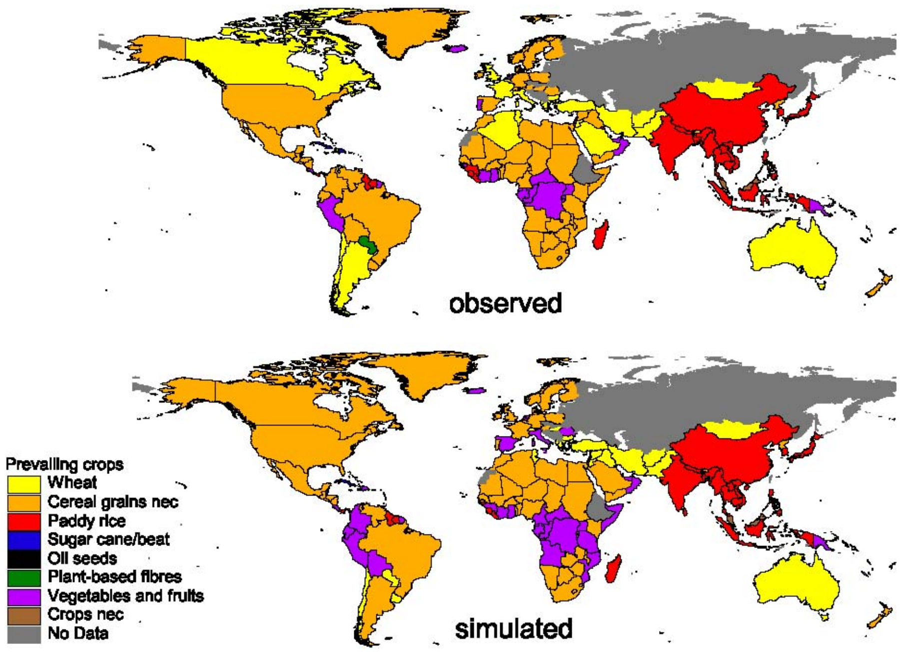

Figure 1. The pattern of prevailing crops for the validation period.

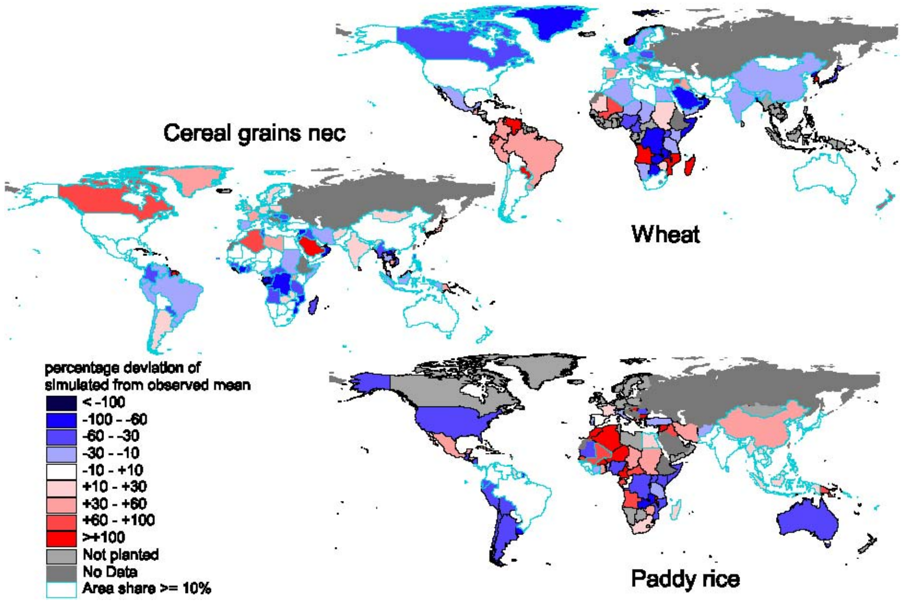

Figure 2. The percentage deviation of mean area share over the validation period for model results to observed data. For blue countries the model underestimates the changes, for red countries the changes are overestimated by the model.

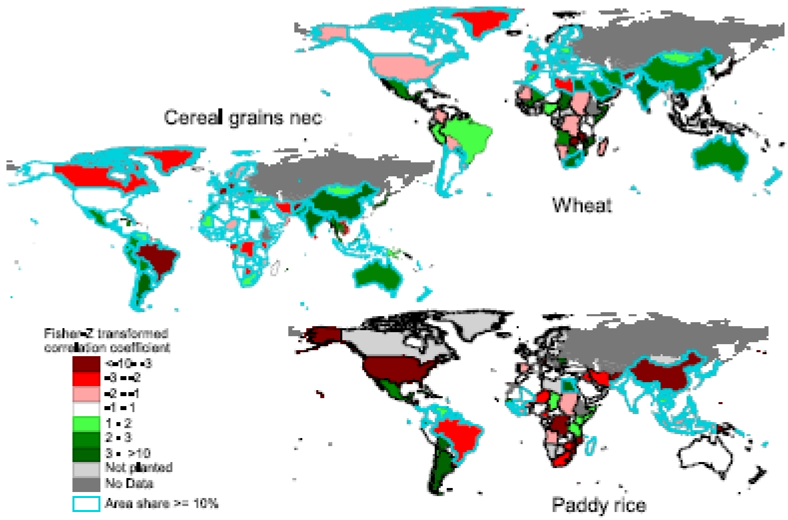

Figure 3. The Fisher-Z-transformed correlation coefficients over the validation period of model results and observed data. Green symbolizes good correlation, whereas red depicts negative correlation.

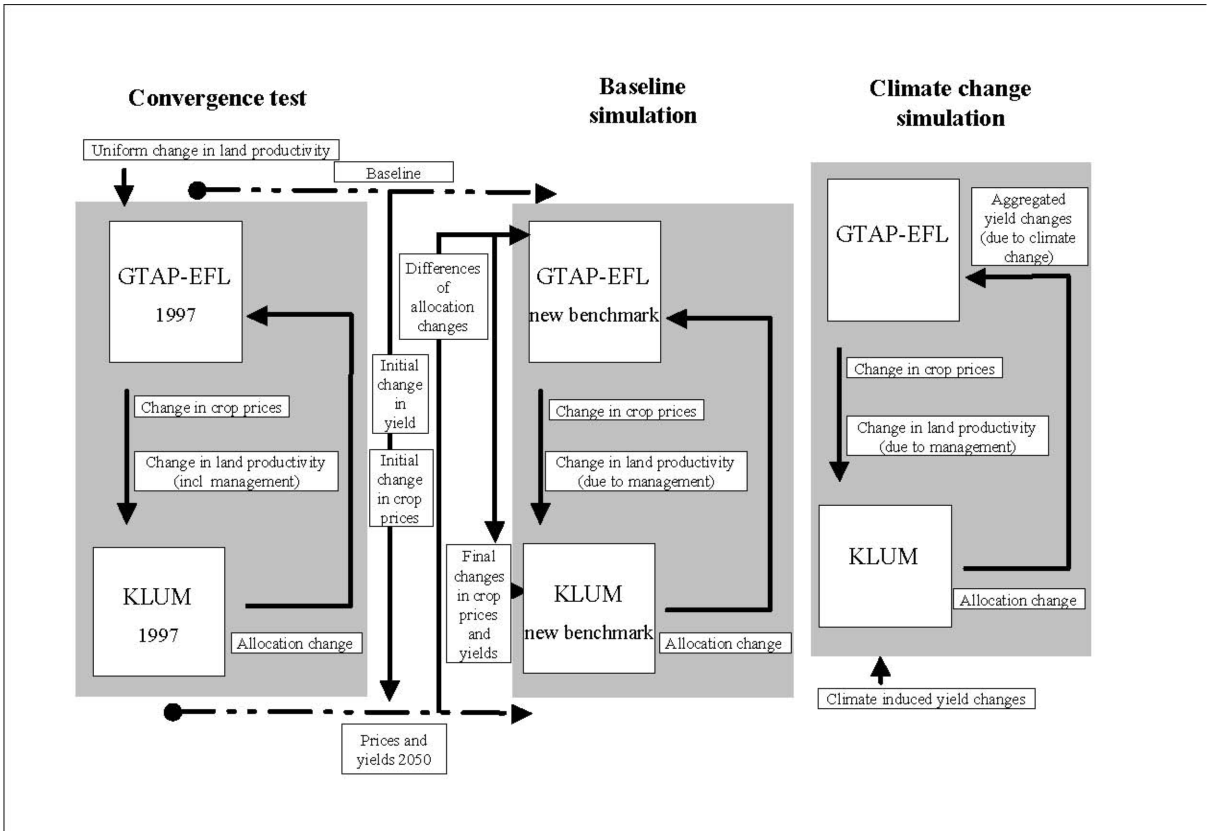

Figure 4. The coupling scheme of KLUM@GTAP.

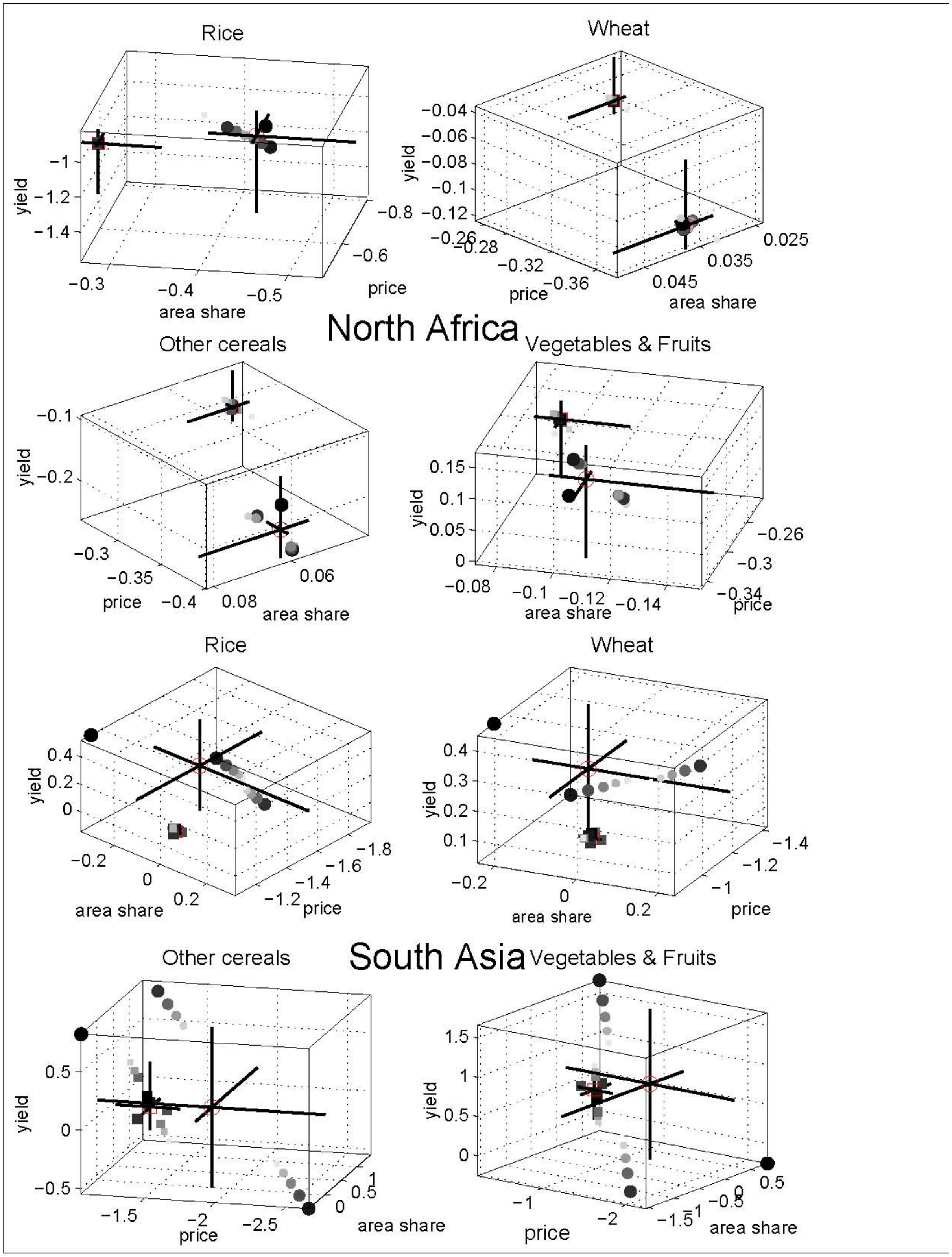

Figure 5. Results of the convergence test for North Africa and South Asia: The plots depict the space spanned by the percentage changes in price, yield and area-share. Round markers: results under doubled elasticity; Square markers: results under tripled elasticity.

With proceeding iteration size and darkness of the markers gradually increase. The empty red marker marks the mean value of the last four iterations; the length of the axes crossing at this point mark the total spread of all iteration states. The perspective of the coordinate system differs among plots to allow an optimal view on the respective data.

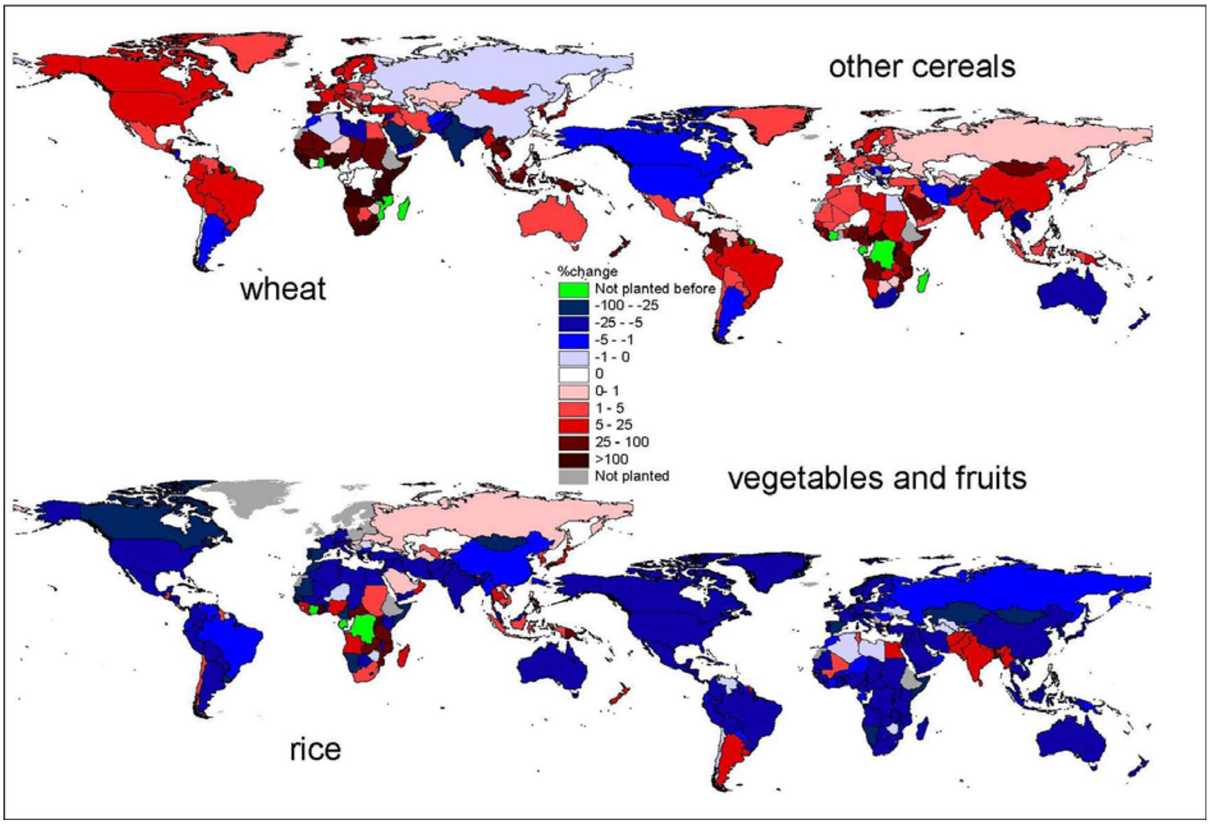

Figure 6. Cropland allocation changes until 2050: Percentage changes in cropland allocation in the *baselin*e simulation according to KLUM@GTAP. In gray countries the crop is either not planted or no data is present.

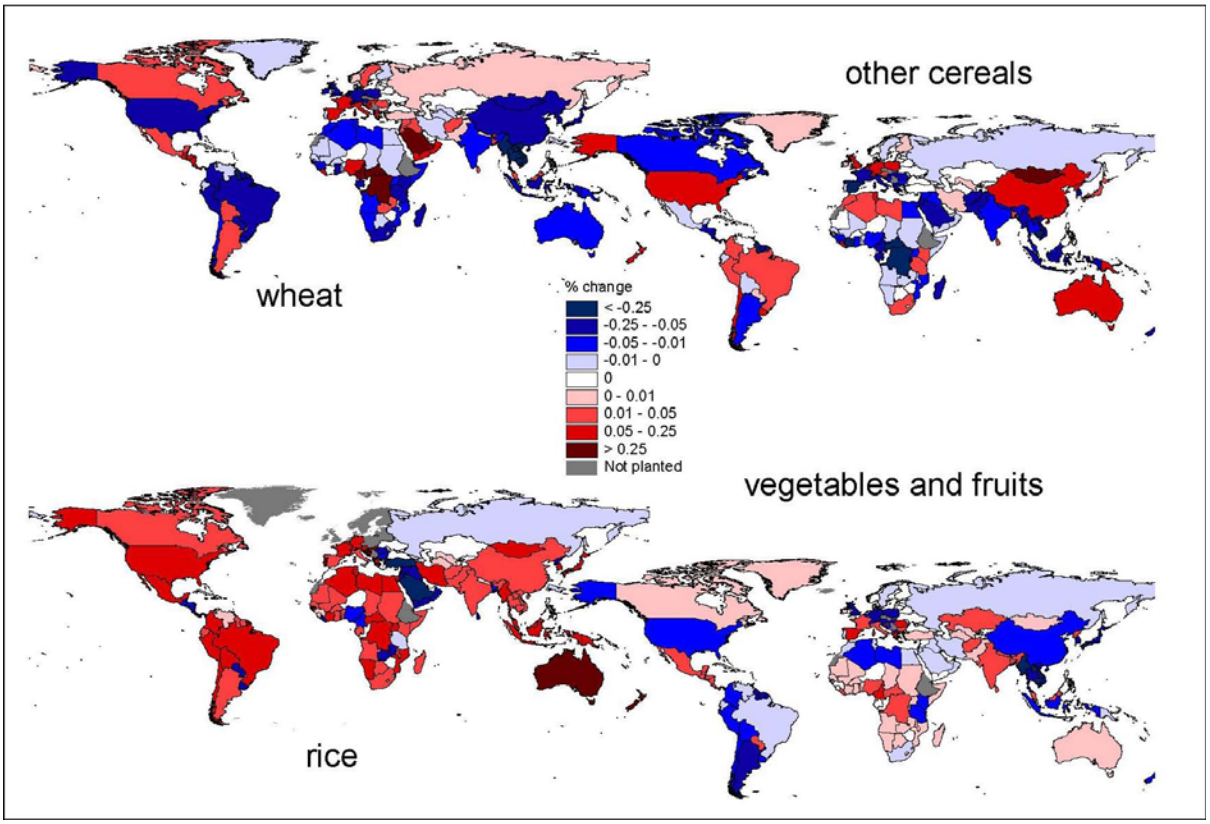

Figure 7. Climate change impacts on cropland allocation: Percentage changes in cropland allocation in the climate change scenario relative to 2050 (*c*c *2050*) according to KLUM@GTAP. In gray countries the crop is either not planted or no data is present.

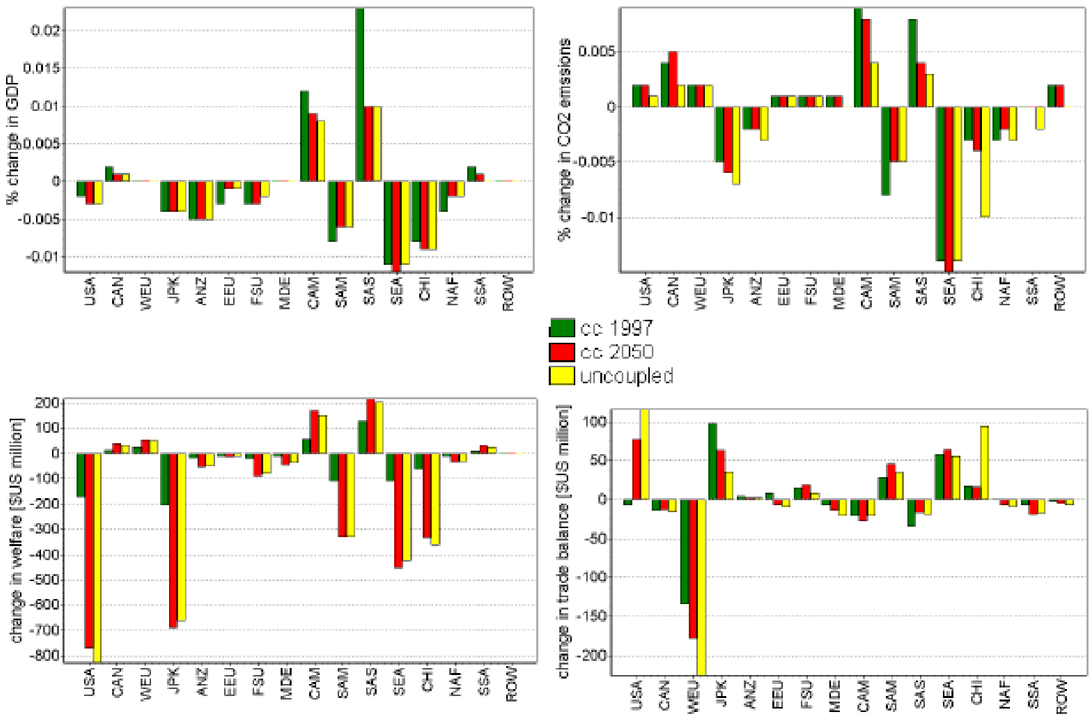

Figure 8. Climate change impacts on the economy: Changes in economic indicators according to the different climate change simulations. The cc *205*0 and cc *199*7 simulations are performed with the coupled system. The *uncouple*d simulation is performed with GTAP-EFL standalone.

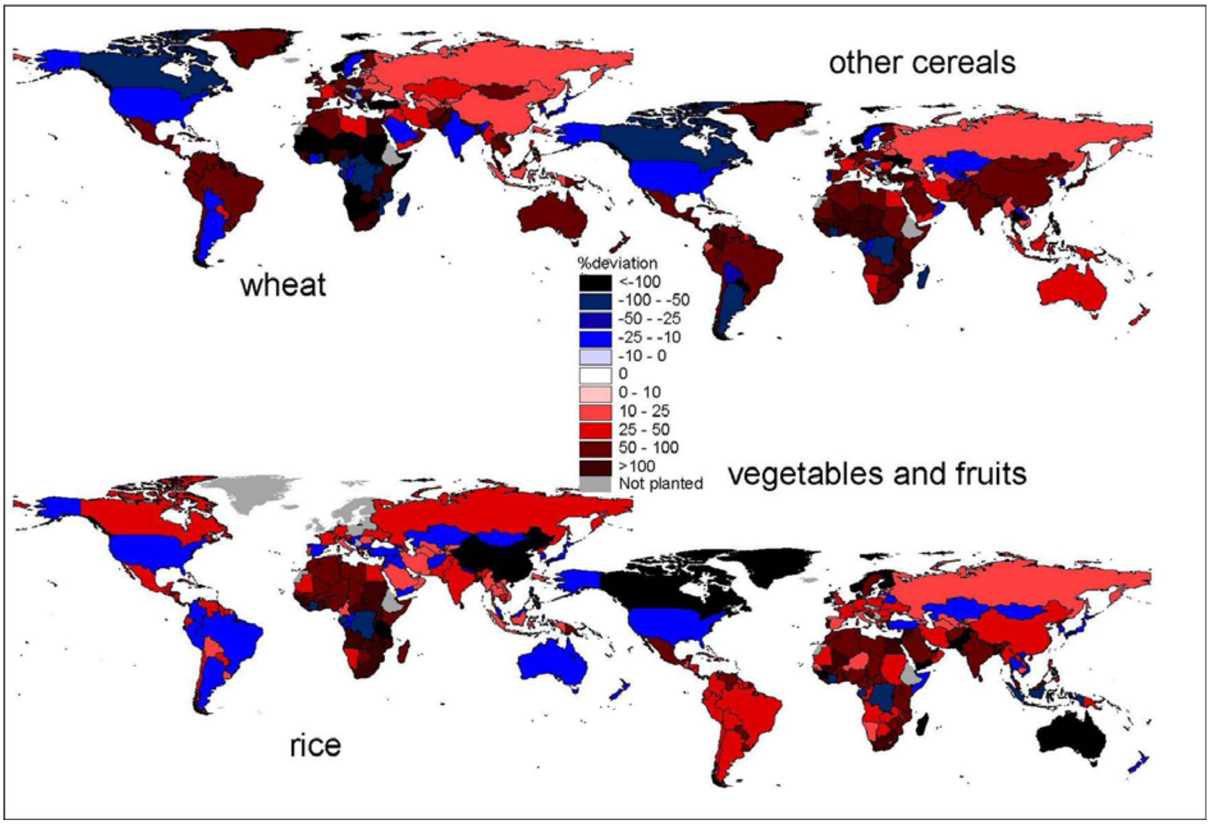

Figure 9. Effect of the baseline scenario on simulated climate impacts: Climate impacts relative to the current situation (*c*c *1997*) are compared to those estimated relative to the baseline (*c*c *2050*). The differences are expressed in percentage of the latter. In gray countries the crop is either not planted or no data is present.

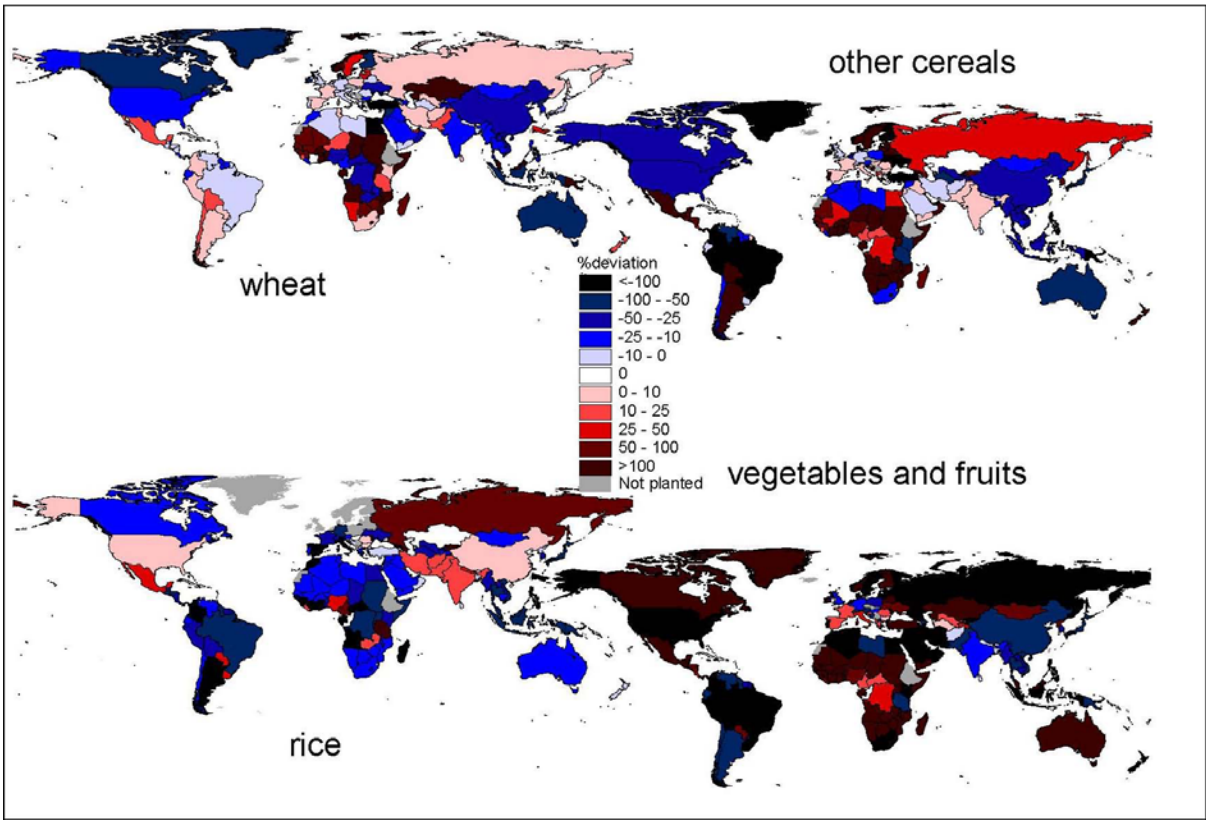

Figure 10. Effect of the coupling on simulated climate impacts: Climate impacts according to KLUM standalone (*uncoupled*) are compared to those of KLUM@GTAP (*c*c *2050*). The differences are expressed in percentage of the latter. In gray countries the crop is either not planted or no data is present.

Appendix A Specification of GTAP-EFL

A Aggregations

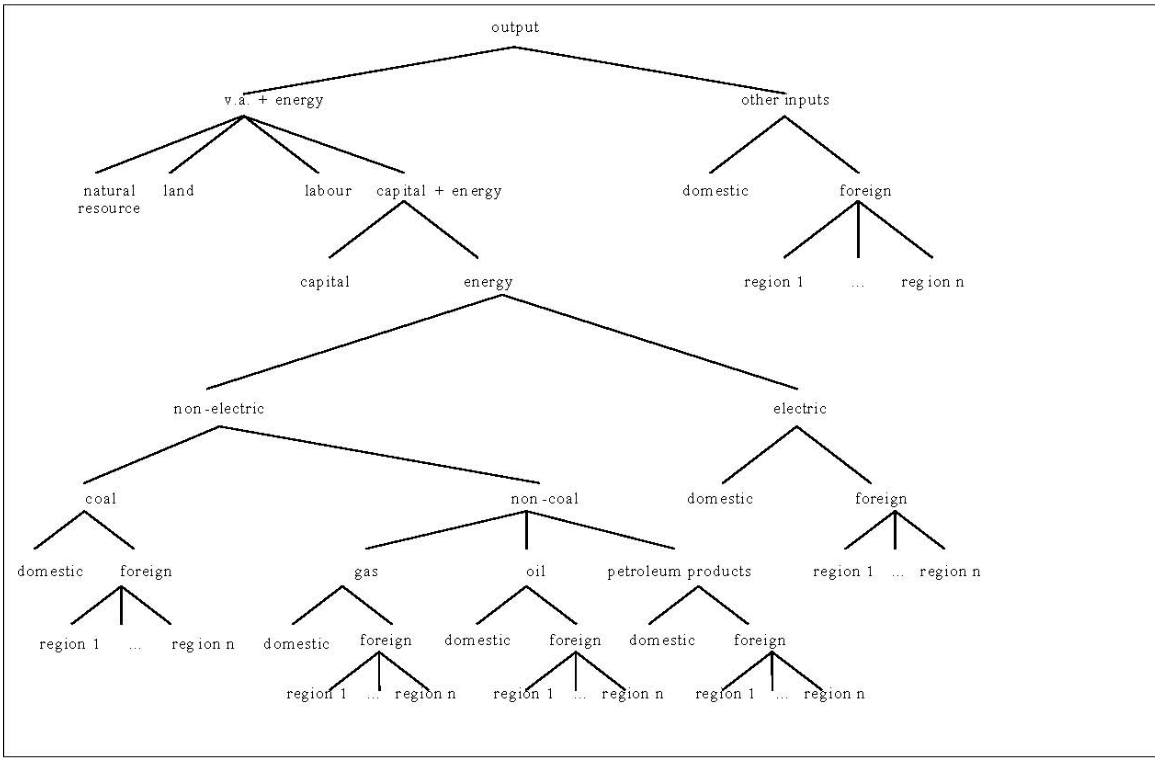

Figure A1. ***Industrial Production:*** *Nested tree structure for industrial production processes in GTAP-EFL*

Table A1. ***Regional aggregation of the coupled model***

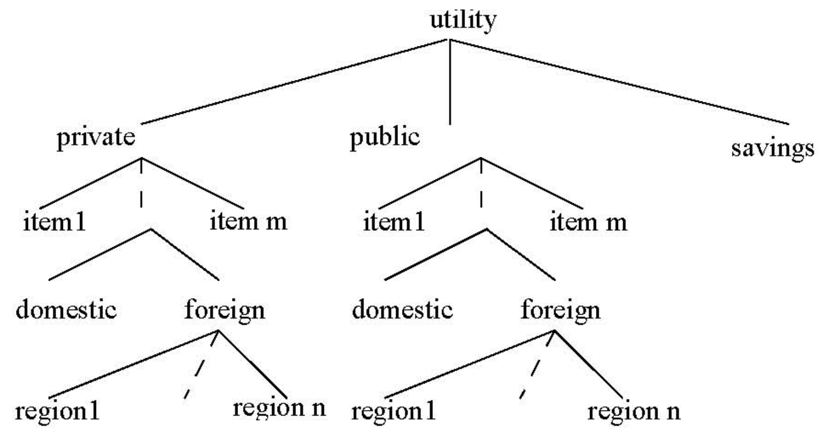

Figure A2. ***Final demand:*** *Nested tree structure for final demand in GTAP-EFL*

Table A1. Regional aggregation of the coupled model

USA	USA
CAN	Canada
WEU	Western Europe
JPK	Japan and South Korea
ANZ	Australia and New Zealand
EEU	Central and Eastern Europe
FSU	Former Soviet Union
MDE	Middle East
CAM	Central America
SAM	South America
SAS	South Asia
SEA	Southeast Asia
CHI	China, North Korea & Mongolia
NAF	North Africa
SSA	Sub-Saharan Africa
ROW	Rest of the World

Table A2. Sectoral aggregation of GTAP-EFL

Rice	Rice
Wheat	Wheat
CerCrops	Other cereals and crops
VegFruits	Vegetable, Fruits
Animals	Animals
Forestry	Forestry
Fishing	Fishing
Coal	Coal Mining
Oil	Oil
Gas	Natural Gas Extraction
Oil Pcts	Refined Oil Products
Electricity	Electricity
Water	Water collection, purification and distribution services
En Int ind	Energy Intensive Industries
Oth ind	Other industry and services
MServ	Market Services
NMServ	Non-Market Services

Appendix B Scenarios assumptions

The economic baseline scenario describes the essential changes of key economic variables for 2050 without climate change (see Table B1). Instead of relying on current calibration data, we base our exercise on a benchmark forecast of the world economy structure. To this end, we derive hypothetical data-sets for 2050 using the methodology described in Dixon and Rimmer (2002). This entails imposing forecasted values for some economic variables on the model calibration data to identify a hypothetical general equilibrium state in the future.

Since we are working on the medium to long term, we focus primarily on the supply side: forecasted changes in the national endowments of labor, capital and population as well as variations in factor-specific and multi-factor productivities. Most of these variables are *naturall*y *exogenou*s in CGE models. For example, the national labor force is usually taken as given. In the baseline scenario, we shock the exogenous variable *labo*r *stock*, changing its level from that of the initial calibration year (1997) to 2050. In the model, simulated changes in primary resources and productivity induce variations in relative prices and a structural adjustment for the entire world economic system. The model output describes the hypothetical structure of the world economy, which is implied by the selected assumptions of growth in primary factors.

We obtain estimates of the regional labor and capital stocks by running the G-Cubed model (McKibbin & Wilcoxen, 1998). This is a rather sophisticated dynamic CGE model of the world economy, which could have been used -in principle -to directly conduct our simulation experiments. However, we prefer to use this model as a data generator for GTAP, because the latter turned out to be much easier to adapt for our purposes, in terms of disaggregation scale and changes in the model equations.

We get estimates of agricultural land productivity from the IMAGE model version 2.2 (IMAGE, 2001). IMAGE is an integrated assessment model, with a particular focus on land use, reporting information about seven crop yields in 13 world regions, from 1970 to 2100. We run this model by adopting the most conservative scenario about climate change (IPCC B1), implying minimal temperature variations.

In our climate change scenario we reduce the effect of a changing climate to its impact on crop yields. The scenario is based on yields presented in Tan & Shibasaki (2003), who provide estimates of changes in yield due to climate change of the major crops for several countries around the world. They utilize climate change data from the first version of the Canadian Global Coupled Model (CGCM1) to quantify monthly minimum and maximum temperature and precipitation. Adaptation is taken into account by means of changing planting dates. The assumed yield changes are relatively small in extent, but similar in sign when compared to estimates of as e.g. Rosenzweig *et al*. (1993) and FAO (2002). We chose the presented source as it offers estimates for a larger amount of countries than the other sources.

Based on these estimates for 2050 we determine potential yields under climate change of wheat, rice and other cereals (see Figure B1). We use the predictions of yield changes in maize to adjust potential production of other cereals, even though this is an aggregate of many different cereal crops weighted differently in different countries. However, in around half of the simulated countries maize production makes more than half of the total production of cereal crops and only for around 20% of all countries this share is below 30%. Thus, we conclude that the applied simplification is acceptable. Potential productions of the vegetables & fruits aggregates are assumed to stay on the level of 1997.

In all simulations the variances σ^2, reflecting the riskiness of a crop, are set to the temporal average of past variances and held constant. Throughout all simulations we exclude the region *Rest of the World* from the coupling and assume the elasticity of substitution for primary factors *ESB*V = 0.711, which is the triple of the original value.

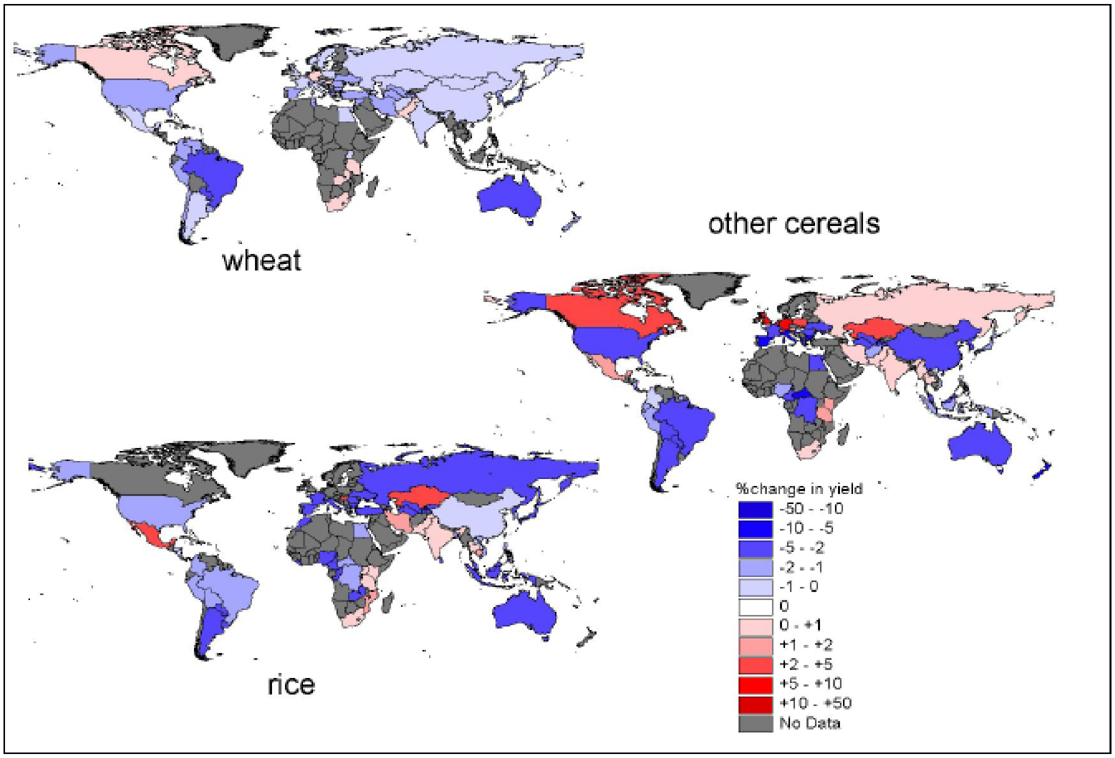

Figure B1. Yield changes assumed in the climate change scenarios. After Tan and Shibasaki (2003).

Table B1. Baseline scenario: Exogenous changes in key macroeconomic variables applied in the 2050 baseline. Values are expressed as percentage changes relative to 1997 quantities. *LUS* refers to the land-using sectors Rice, Wheat, CerCrops, VegFruits and Animals; *Energy* comprise the energy sectors Coal, Oil, Gas and Oil Pcts. *Labor* refers to "effective labor", that is: number of workers times the average productivity per worker.

	% change in stocks			% change labor productivity				% change
	population	capital	labor	LUS, Forestry, Fishing, En_Int_ind	Energy	Electricity	Water, Oth_ind, MServ, NMServ	land productivity LUS
USA	30.4	253.7	249.6	120.1	0.0	69.5	100.0	114.0
CAN	15.6	186.3	263.7	134.1	6.1	80.1	157.6	225.5
WEU	-3.7	164.0	266.6	140.8	9.4	85.3	177.2	52.8
JPK	-11.6	177.5	214.5	133.6	0.0	79.8	163.1	162.5
ANZ	18.7	184.8	263.7	133.0	6.1	79.4	156.3	225.5
EEU	-2.7	260.1	257.0	221.9	47.5	148.3	267.1	267.3
FSU	-2.7	275.5	257.0	235.0	50.3	157.1	282.9	267.3
MDE	107.7	373.7	324.2	227.3	48.7	151.9	276.2	379.9
CAM	54.9	375.4	352.4	287.8	72.8	197.1	353.2	379.9
SAM	51.0	411.4	352.4	315.4	79.7	216.0	207.0	379.9
SAS	72.6	500.8	254.4	346.3	75.0	237.1	330.0	339.5
SEA	68.9	336.7	352.4	258.2	65.3	176.8	316.8	379.9
CHI	29.4	463.4	254.4	251.2	63.5	172.0	306.7	339.5
NAF	127.0	235.1	352.4	180.2	45.6	123.4	221.2	379.9
SSA	135.8	375.9	352.4	288.2	72.9	197.4	353.7	379.9
ROW	49.1	419.9	352.4	321.9	81.4	220.4	332.6	379.9