KLUM@LPJ: Integrating dynamic land-use decisions into a dynamic global vegetation and crop growth model to assess the impacts of a changing climate.
A feasibility study for Europe

***Kerstin Ronneberger*[a,b,c]**, Luca Criscuolo*[d,c]*, Wolfgang Knorr*[e] *and Richard S.J. Tol*[a,f,g]
[a]*Deutsches Klimarechenzentrum GmbH, Bundesstr. 55, 20146 Hamburg, Germany*
[b]*Research Unit Sustainability and Global Change, Hamburg University and Centre for Marine and Atmospheric Science, Bundesstr. 55, 20146 Hamburg, Germany*
[c]*International Max Planck Research School for Earth System Modelling, Bundesstr. 53, 20146 Hamburg, Germany*
[d]*Max-Planck Institute for Biogeochemistry, Hans-Knöll-Str. 10, 07745 Jena, Germany*
[e]*QUEST, University of Bristol, Department of Earth Sciences, Wills Memorial Building Queen's Road, BS8 1RJ, UK*
[f]*Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands*
[g]*Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA*

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Abstract

We test the hypothesis that models should be coupled to accurately project the impacts of climate change on the agro-economic and agro-environmental system. We couple the LPJ-C global dynamic vegetation model for crops to the global agricultural land-use model KLUM. Potential crop yields, from LPJ-C, and crop prices drive the land-use decisions; cropland allocation from KLUM scale the carbon entering the soil litter pool in LPJ-C. Through the crop prices, economic

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* Corresponding author: E-mail: ronneberger@dkrz.de; Phone: +49 40 41173 322; Fax: +49 40 41173 270

effects are projected directly on the carbon cycle. Global change impacts are projected on the agricultural sector and can be economically assessed.

The coupled model performs reasonably well for the observed climate and prices for 6 crops in Europe on a 0.5x0.5 longitude-latitude grid.

We estimate the impact of climate change on agriculture in Europe for A1 and B2 scenarios of the IPCC. The coupled model reproduces the essential processes and interactions of the modeled system. Simulations with the uncoupled models are used to estimate the accuracy added by the model coupling. Sign and size of the biases from ignoring the feedbacks are substantial for some parameters, and particularly their spatial pattern, while for other parameters (e.g., the European total of soil organic carbon) biases are negligible. The answer to the question “Should models be coupled?” is “It depends on what you’re interested in”.

1 Introduction

Agricultural land use strongly influences carbon, nutrient and water fluxes between soil and atmosphere. It shapes the natural environment and provides the basis for the nutrition of human society. Changes in agricultural land use are one of the essential links at the interface between biosphere and anthroposphere. Crop patterns are determined by both the biophysical and the agroeconomic conditions. To understand the combined effect of these factors on land-use decisions, an integrated modeling framework is required to represent essential biophysical and economic processes and the feedbacks between the two systems. This is true in principle. In this paper, we present such a model – and use it to estimate the biases that would occur using uncoupled models. We thus test the hypothesis that models should be coupled – in practice.

Current approaches to simulate large scale land-use changes tend to over-emphasize either the geographic or the economic aspect, neglecting their interactions. Geographic models are commonly based on detailed biophysical characteristics of land. They focus on the dynamics of spatial patterns of land-use types by analyzing land suitability and spatial interaction. Projections of human actions are based on observed behavior rather than on underlying economic motivations. This limits their capability to represent the impact of market interactions, such as competition among land intensive sectors. In economic models, land is usually implemented as an input in the production of land-intensive commodities and the focus is more on market impacts than on its allocation. The limitation of these models mainly manifests itself in the representation of land, which is treated as homogeneous and space-less, ignoring biophysical characteristics and spatial interactions. A number of integrated approaches try to overcome these weaknesses by combining economic rationale and biophysical assessment in an integrated framework (Heistermann et al., 2006). In the ACCELERATES project, for example, the farming model SFARMOD is coupled to the crop model ROIMPEL (Rounsevell et al., 2003; ACCELERATES, 2004). SFARMOD determines the most profitable combination of crops based on yields, given management options and crop prices, while ROIMPEL provides the respective crop yields and management parameters. ROIMPEL is a process-based model, using climate data from GCMs and GIS-based soil data. The main disadvantage of this framework is the large amount of input data. Furthermore the impacts of crop growth and land use decisions on the carbon balance are not considered, limiting its suitability for studies concerned with the carbon cycle.

In this work, we include the global agricultural land-use model KLUM (*Kleines* Land Use Model) (Ronneberger et al., 2005) in the dynamic global vegetation model (DGVM) LPJ-C (Lund-Potsdam-Jena model for crops) (Criscuolo et al., 2005), so as to simulate impacts of climate change. LPJ-C is the standard LPJ model (Sitch et al., 2003) with an added crop growth compartment. The model provides an integrated representation of both natural vegetation and crops, taking into account carbon and water cycles within a single grid-based modeling framework. So far, the model has been applied only with a fixed crop mask. By including KLUM, we enable a dynamic representation of the changing crop patterns according to the simulated yields (and crop prices). KLUM is a coupling tool for global economic and vegetation models. It reflects the essential biophysical and economic aspects of large-scale agricultural land-use changes by determining the most profitable crop allocation, based on crop prices and yields. Similar to the SFARMOD-ROIMPEL approach, this framework provides a link between dynamically modeled yield projections and economic motivated agricultural land-use decisions. However, our system requires less detailed input data facilitating large-scale applications and long-term predictions. Furthermore, the dynamic representation of the terrestrial carbon and water balance in LPJ-C enables an integrated assessment of the carbon cycle. KLUM provides an interface to dynamically couple the framework to a global trade model, in order to further enhance the integration of economics (Ronneberger et al., 2006).

We use the coupled system to study the impact of two representative climate change scenarios on economic production, crop distribution and soil carbon accumulation for the EU25 countries. The European continent faced important changes in agricultural production and land use over the last 50 years. The fast increase of productivity and the changing market led to a contraction of cultivated areas (Rabbinge & van Diepen, 2000; Rounsevell et al., 2003). Still, food supply currently exceeds demand (Ewert et al., 2005). A further decline of the current agricultural areas can be expected (Rounsevell et al., 2005). Croplands make up nearly half of the terrestrial land surface of Europe.

The climatic conditions of Europe have changed during the last one hundred years. The average annual mean surface temperature has increased by 0.8°C over the last century (Beniston & Tol, 1998); precipitation has increased in the Northern parts of Europe, and decreased in the Southern parts (Hurrell & van Loon, 1997). According to the Intergovernmental Panel of Climate Change (IPCC), the increasing concentration of greenhouse gases will reinforce this trend during the current century (McCarthy et al., 2001). Current predictions show an average temperature increase of 4-6°C within the next 100 years (IPCC, 2001), and a reduction in precipitation by up to 20% in the Mediterranean areas (Ragab & Prudhomme, 2002; Chartzoulakis & Psarras, 2005). All this makes Europe a suitable region for a feasibility study with the coupled model.

We use observations of current crop patterns to evaluate the performance of the coupled model. Climate change scenarios are used to demonstrate the integrity and capability of the coupled system to provide plausible projections of future pathways. For the moment, we exclude hard-to-predict drivers such as management, but also the development of total available cropland, with the intention to focus on the coupling effects. Crop production is simulated under ideal conditions of potential production, assuming perfect irrigation and crop management. Natural vegetation is excluded.

Besides the base case simulations with the coupled model, we run the same simulations with the uncoupled models. We use the results to estimate the sign and size of the biases that come from ignoring the feedbacks between the ecological and human systems. Alternatively, we estimate the accuracy added by the model coupling. We find that the coupled model behaves substantially differently for some parameters than do the uncoupled models, while for other parameters differences are negligible. That is, the answer to the question “Should models be coupled?” is “It depends on what you’re interested in”.

In the following section, we outline the characteristics of the two models and describe the coupling procedure. Section 3 introduces the experimental design. Section 4 presents a comparison of model results and observations. In Section 5 we present and discuss the results of future and reference simulations. Section 6 summarizes and concludes.

2 Modelling Framework

The KLUM@LPJ framework runs on a 0.5 × 0.5 longitude-latitude grid, with a time-step size ranging from one day to one year, depending on the process. The framework is designed for global coverage and a possible time horizon of several centuries. In this study, however, we restrict our analysis to the European Union. The two original models are dynamically coupled, exchanging data on a yearly basis.

2.1 The LPJ-C model

The LPJ-DGVM is a representation of the terrestrial ecosystem with large-scale and process-based dynamics. The modeled dynamics take account of the carbon and water cycling in the vegetation and the soil, of vegetation structure and composition, and of fire disturbance. The LPJ-C model incorporates crops and natural vegetation within a single framework, in which the two vegetation types use a common photosynthesis-assimilation scheme, while carbon dynamics and development are differently described. A comprehensive description of the general model is given by Sitch et al. (2003), and for the crop growth compartment by Criscuolo et al. (2005). The natural vegetation in each grid cell is represented by a combination of plant functional types. Crops are represented as crop functional types (CFTs) with specific carbon dynamics and canopy attributes. CFTs are modeled as annual plants with no competition for resources. Crop growth can be simulated under potential and water-limited conditions. No stress affects the plant in the first case, so that the growth is driven only by temperature and light; in water-limited simulations, water availability limits the productivity.

In this work, six CFTs (rice, wheat, maize, barley, potato, sugar beet) are simulated in potential production conditions. The crop parameterization sets are derived from Boons-Prins et al. (1993) and adapted for the modeling requirements of LPJ. No specific calibration was performed on the crop parameters.

The soil is divided into two layers and contains three soil organic carbon (SOC) pools with different decomposition rates: a slow (0.001yr−1 at 10_C) a medium (0.03yr−1 at 10_C) and a fast one (0.35yr−1 at 10_C). Decomposition depends explicitly on temperature (adopted from Lloyd and Taylor, 1994) and soil moisture (adopted from Foley, 1995). For details of SOC equations see Sitch et al. (2003). Generally, a warm environment allows a larger flux of CO2 to the atmosphere, leaving less SOC in the soil. Crop residues first enter the fast pool; part of the carbon is directly released to the atmosphere, while the rest of SOC and the remaining litter are left in the soil.

2.2 The KLUM model

The global agricultural land-use model KLUM is designed to link economy and vegetation by reproducing the key dynamics of global crop allocation (see Ronneberger et al. (2005) for a detailed description of model development and evaluation). 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 to determine the allocation of different crops on a given amount of land (see the Appendix for mathematical formulation). In this, decreasing returns to scale is assumed; that is, marginal costs rise with increasing production.

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 to observations. Risk is quantified by the variance of achievable profit, calculated for the preceding five years.

For the current study, we recalibrate the original KLUM version to match the resolution of LPJ-C: the allocation of six crops (rice, wheat, maize/corn, barley, potato and sugar beet) is simulated with a resolution of 0.5°×0.5° for the area of the EU25 countries. For the calibration procedure, we use data of the years 1991-2001 on yields and planted area on NUTS2 level[1] of the EUROSTAT database Eurostat New Cronos (2005), and country level data on prices of FAOSTAT (2005). We adjust prices for inflation and convert them to 1995 US$ by means of data of the Word Bank (2003). Prices are averaged to 5-year means and aggregated to three multi-national-regions (Western Europe, Eastern Europe and Former Soviet Union) as described in Ronneberger et al. (2005), matching the typical resolution of a global trade model (to enable later coupling). We assign each grid cell of the 0.5° × 0.5° grid to a NUTS2 region according to

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[1] The Nomenclature of Territorial Units for Statistics (NUTS) is a geocode standard for referencing the administrative division of countries for statistical purposes, developed by the European Union. NUTS1 depicts the coarsest resolution, NUTS2 and NUTS3 are respectively finer resolved (see also http://europa.eu.int/comm/eurostat/ramon/nuts).

the minimal distance of centers. The agricultural area is supposed to be equally distributed over all grid cells. Cost parameters are adjusted accordingly as described in the appendix. To represent crops with insufficient data or absent crops (e.g. maize or rice in Northern Europe), we adopt the cost parameters (again adjusted) and initial profit variability of close by units in the same world region[2] with similar biophysical characteristics as indicated by the yield structure of the remaining crops. For NUTS2 regions without data, we either use data on NUTS1 or even country-level for the calibration (for large parts of Germany, the UK, Portugal and Finland) or adopt the complete calibration of adjacent, biophysically similar regions (e.g. for Smaaland and Västsverige, the calibration of Östra Mellansverige is adopted). For most of Finland, yield data is only available on country level, whereas the planted area could be taken on NUTS2 level. Some crop prices for the region of the Former Soviet Union are missing, so we adopt slightly adjusted prices from Eastern Europe. We omit urban areas such as London, Hamburg or Stockholm.

2.3 KLUM@LPJ

The two models are coupled via an exchange of potential yields and the crop allocation pattern. KLUM calculates the share of the agricultural area to be allocated to each crop according to given crop prices and the potential yields, determined by LPJ-C. In order to provide KLUM with a choice, LPJ-C initially simulates each crop, as if it would occupy the entire grid cell.

Since in LPJ-C, crops are not assumed to compete for resources, the crop allocation pattern only affects the accumulation of the crop waste that is transferred to the soil litter pool. We assume that only the storage organs (grains for cereals, roots for tuber crops) are taken away from the field for harvest. The harvested share of the crop's total biomass is determined by the dynamically modeled carbon distribution among the plant's structural components. The rest of the plant goes into the soil litter and follows the decomposition process. Thus, the area shares, as calculated by KLUM, are used in LPJ-C to determine the contribution of the different crops to the total soil litter; that is, the crop waste is scaled by the land allocation coefficients before it is transferred to the soil litter (**Figure 1**).

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[2] For the Former Soviet Union we adopt some prices and the complete calibration for rice from countries of Eastern Europe. For Finland we adopted the calibration for maize and rice from Latvia and Eszak-Alfold (Hungary) as they give a better fit than all western European regions.

We technically realize the coupled system of LPJ-C and KLUM by directly implementing a C++ version of KLUM into the C++ LPJ-C framework. In each yearly time step, the potential production and the allocation shares are exchanged between KLUM and LPJ-C, according to the scheme above.

3 Experimental Design

Our simulations cover the period 1991-2100 and the area of the EU25. To reach equilibrium in the SOC for the initial year, we spin up the model for 100 years. Grid cells where no crop reaches maturity during the spin-up period are excluded from our simulations, as the initial level of soil organic carbon cannot be determined. This mainly concerns the area at the Norwegian border of Sweden. The scenario setup and assumptions are described in more detail in Appendix B.

The study is divided into three different steps. In the first step, the capability of the coupled system to reproduce current crop patterns is evaluated by comparing model results to observations. We have to accept a certain error in our coupling by using the potential instead of actual yields to determine the crop pattern in KLUM. We do this as management is currently not represented in the system and the only alternative would be the inclusion of an estimated correction factor. We prefer to accept the known error with known source instead of including an estimation with unknown uncertainty, especially when transferred over time. Additionally, the allocation decisions in KLUM mainly depend on relative yields, determining the competition among different crops. Thus, the deviations of potential and actual yields may turn out to be neglible for the simulation results. The evaluation helps to asses the accepted error.

In the second step, we use the coupled system to investigate the impact of climate change on biomass as well as economic production, on changes in crop allocation, and on soil carbon accumulation for Europe. We choose the two extreme IPCC scenarios A1 and B2 to highlight the different potential effects of temperature and atmospheric CO2 on crop growth and allocation dynamics. The LPJ-C model so far has been used only with a fixed crop map (Criscuolo et al.,2005; Criscuolo & Knorr, 2005). The KLUM model has been applied as a stand-alone-model (Ronneberger et al., 2005) and coupled to an economy model (Ronneberger et al., 2006). The climate change simulations are important to assess the integrity of the coupled system. Plausible results signify that the coupling does not distort the process representations in the original models.

In the last step we assess the impact of the coupling on the climate change analysis. In order to isolate the effects of the coupling on the resulting estimates, we repeat the future simulations with the uncoupled models. For this purpose we apply the climate forcing on LPJ-C, but keep the crop allocation in the initially observed state of 1991 (see section 2.2). In KLUM, only the prices change according to the applied scenario; yields are assumed to stay as in 1990 (as determined by the uncoupled LPJ-C after the spin-up).

4 Evaluation of the coupled framework

The period 1991-2000 is used to evaluate the capability of the coupled system to reproduce observed crop patterns. We compare the simulated area shares to observed data for the year 2000. We use the first years as a spin-up period for KLUM, which is needed because of the effect on the risk perception of initial differences in observed and simulated yields.

The simulated area shares are aggregated to the NUTS2 regional level in order to compare them to the observed values. The ratio of simulated to observed values is shown in **Figure 2**. The shares of sugar, maize and rice are largely underestimated, in favor of wheat and barley, which are mainly overestimated; only in the very South and North, we find some underestimation of the allocation share for wheat. For potatoes, the area shares are overestimated in the South- Eastern part of Europe and underestimated in the North-West. Generally, the ratio of simulated to observed values is in the range of 0.5-1.5 for the three major crops wheat, barley and potatoes. Only in Sweden, we observe a large underestimation for potatoes and wheat. According to the simulations, these crops do not reach maturity far up in the North. The ratio of simulated to observed area shares for maize, sugar and rice are lower than 0.5 for most regions. The underestimation of these three crops can partly be explained by the shifted yield structure in the coupled system, due to potential instead of actual yields. But KLUM also has difficulties with minor crops (Ronneberger et al., 2005). All in all, the usage of potential instead of actual yields seems to shift the crop pattern for the benefit of the major crops. The general pattern, however, is not dramatically distorted.

5 Simulation results

We use the coupled system to assess the impact of a changing climate for the period 2001-2100 in Europe. The two extreme IPCC scenarios A1 and B2 are used to isolate the effects of temperature, CO2 concentration and economic development. We first outline the results obtained with the coupled system; the emphasis is placed on their plausibility according to the represented processes. We then present the differences of these results to those obtained with the uncoupled models. The impact and relevance of the coupling is the focus of that section.

5.1 Climate change analysis with the coupled system

The results of the climate change simulations with the coupled system can be divided into results describing the natural system (retrieved mainly from LPJ) and those describing the agroeconomic system (mainly produced by KLUM).

Climate change and the natural system

In order to sketch the impact of climate change on crop growth and carbon storage, we show in **Figure 3**-A the temporal development of mean carbon biomass per cropland area at harvest time. **Figure 3**-B shows the mean ratio of storage organs over total biomass weighted by area share, reflecting the changes in carbon allocation within the plant[3]. The ratio of grid cells where maturity is reached to total grid cells (**Figure 3**-C) describes the spread of the potential growing area. The mean soil organic carbon (SOC) per area of cropland is shown in **Figure 3**-D. The spatial pattern of the soil organic carbon changes is depicted in **Figure 4**.

The results reflect the typical effect of the increase in temperature and CO2 concentration on crop growth: CO2 fertilization increases biomass production, while a higher surface temperature can lead to a decrease in biomass production due to a shortened growing season (Criscuolo et al., 2005). For the cold C3 cereals wheat and barley, this leads to a decrease of total biomass after around 2040 for the warmer scenario (**Figure 3**-A). For the colder scenario B2, the factors cancel each other, leading to an almost constant mean total biomass. In both scenarios, however, the relative carbon allocation to the storage organs for wheat and barley increases (**Figure 3**-B), indicating that for this part of the plant CO2 fertilization prevails (compare Criscuolo et al., 2005). In contrast, for the warm C3 cereal rice, the negative temperature effect on total biomass is less pronounced, but the relative carbon allocation to the grains is decreasing. For maize, the mean total biomass as well as the relative carbon allocation to the grains is decreasing in both scenarios. As a C4 plant, CO2 fertilization is not simulated for maize by LPJ-C. Potatoes show a clear increase in total biomass production as well as in the share allocated to the storage organs. For potatoes we see no differences between the two scenarios.

The changes in potential growing area clearly follow the temperature signal (**Figure 3**-C). For all crops that do not already cover the entire grid we see strong increases in growing area, more pronounced in the warmer scenario A1.

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[3] Note that this also defines the harvest index in our study

The development of soil organic carbon mirrors the trend of the summed biomass production of all crops, slightly modified by the temperature effect on respiration (Lloyd & Taylor, 1994). We see a slight increase until around 2040; after that, SOC is decreasing in both scenarios, more pronounced in the warmer scenario A1. The spatial distribution of soil carbon changes (**Figure 4**) reveals that the decreasing trend in scenario B2 is the result of a decrease in the East that dominates the increase in the South-West of Europe. For scenario A1, the decrease is more uniformly distributed over the entire grid, but also distinct in the Eastern Baltic countries.

Climate change and the agroeconomic system

Changes in the agroeconomic system are characterized by changes in crop patterns (indicating the impact on the natural system) and changes in crop production and revenue (describing economic impacts). We illustrate changes in the crop pattern at the European level by the development of the area share for a certain crop (**Figure 5**-A) and by the spread of a crop over the grid, quantified by the share of all grid cells used for cultivation of this crop (**Figure 5**-C).

The spatial pattern of allocation changes are depicted in **Figure 6** for wheat and in Figure 7 for maize. To quantify the effects on the European crop sector, the development of crop production and the corresponding revenue are presented in **Figure 5**-B and **Figure 5**-C, respectively.

We reveal a general increase of the allocation share for maize and potatoes and a decrease for barley and wheat (**Figure 5**-A). For wheat, barley and potatoes, this mainly reflects the trends we observed in biomass production; for maize, this is a consequence of the increasing spread over the grid (**Figure 5**-C) and consequently more pronounced in the warmer scenario A1. Also for rice, we see a large increase in the share of cultivated grid cells from less than 20% to 60% in scenario A1 and 30% in scenario B2. Yet, little land is allocated to rice, so this increase hardly shows up in the area shares. The development of cultivated to total gridcells follows the trend of gridcells where maturtiy is reached to total gridcells (compare **Figure 3**-C). Still, only potatoes and rice are also cultivated in all the gridcells where they reach maturity. For the remaining crops, cultivation is not profitable everywhere.

Again in total crop production, we see a decrease for wheat and barley and an increase for potatoes. Maize production, however, is largely unaffected; the increase in area share is outbalanced by the decrease in yield (compare **Figure 3**-A and **Figure 3**-B). For all crops, production is larger in the colder scenario B2, clearly indicating a loss of production for large temperature increases. This is even more pronounced in the development of revenue. Until 2100, the summed revenue of all crops triples in scenario B2 but drops to one fourth in scenario A1. This clearly reflects the imposed price changes.

The spatial pattern of changes in wheat allocation (**Figure 6**) reveals that the decrease in the total area share of wheat (**Figure 5**-A) masks an increase in the very South and North which are compensated by decreases in Central Europe. This pattern is less obvious in the colder scenario B2, where losses and gains are more distributed over the entire grid. An extension of wheat production to the North can be revealed in both scenarios. For maize, we mainly see an opposite pattern (Figure 7): the area share is increasing in Central Europe, but decreasing in the South. This indicates that wheat production is replaced by maize production in Central Europe, whereas wheat production dominates over maize in the South. For Northern Europe and the British Isles, we reveal an extension of the cultivation area of maize. All these trends are more pronounced in the warmer scenario A1.

5.2 Impact and relevance of the coupling

The impact of the coupling can be evaluated by comparing the results of the uncoupled models to those of the coupled system. The differences are a consequence of neglected feedbacks in the uncoupled models.

LPJ-C standalone

In LPJ-C, the coupling impacts the accumulation of soil organic carbon. Figure 8 depicts the changes in soil organic carbon according to the uncoupled LPJ-C model for the two climate scenarios. The crop pattern is kept at the observed level of 1991 in these simulations. Excluding crop allocation generally leads to a much more uniform pattern of changes of generally lower extent. For instance, the decreases of soil carbon we observe in the coupled simulation for scenario B2 in Eastern Europe are absent in the results of the uncoupled run. Obviously they are the result of crop pattern changes. The strong increase of potato cultivation in Eastern Europe (results not shown here) might be the cause; potatoes allocate only 20% of their total biomass to waste (compare **Figure 3**-B). Also for scenario A1, the observed decreases over the entire grid are largely absent or underestimated in the uncoupled simulation with LPJ-C. A changing crop pattern obviously lowers the carbon stored in the soil.

KLUM standalone

In the uncoupled simulations with KLUM, the potential growing area as well as the crop yields are kept constant on the level of LPJ-C 1990. **Figure 9**-A shows the differences of the area shares of uncoupled to coupled simulation for all crops; **Figure 9**-B depicts the effect of the coupling on economic revenue. The differences of area share and revenue are in the order of ±30%. Only the deviations for rice are in the order of 200% in the beginning of the simulation; they are scaled in both plots by a factor 10 to fit in. In both scenarios, the area shares of wheat and potatoes are generally overestimated in KLUM standalone, while maize is clearly underestimated. Rice, barley and sugar beet show a changing behavior over time for scenario A1: in the beginning of the simulation, rice is largely overestimated in the uncoupled run, while barley and sugar beets are underestimated. Towards the end of the simulation, the area shares of these crops of coupled and uncoupled runs converge. For scenario B2, this trend is only observable for rice.

We generally see larger differences for the colder scenario B2, but of the same sign. The higher price changes in this scenario amplify the differences of standalone KLUM and the coupled simulation. The differences in revenue of KLUM standalone to KLUM@LPJ largely mirror the differences in area shares, but are generally less pronounced; prices dominate the development of revenue. The uncoupled simulation slightly overestimates total revenue for both scenarios. The bias is much smaller (in the order of 10%) than for the crop-specific revenues as positives and negatives cancel.

In order to study the coupling effect on the spatial pattern of the changes, the allocation changes of wheat and maize of the uncoupled simulation are visualized in **Figure 10** and **Figure 11**, respectively. For both crops in scenario A1, the extent rather than the general pattern of changes differ from the coupled simulation (compare **Figure 6** and Figure 7). For wheat, KLUM standalone generally underestimates the extent of changes in scenario A1, without affecting the sign. For maize, the largest differences are due to the underestimation of the growing area in KLUM standalone. For scenario B2, also the pattern of changes is affected by the coupling. For wheat the widespread decreases of area share we observe in the coupled simulation are absent in the uncoupled simulation. Only in Eastern Europe, we reveal a clear decrease. For maize, hardly any of the increases in area share projected by KLUM@LPJ are anticipated by KLUM standalone. To a large extent, this is again caused by underestimations of growing area.

6 Discussion and conclusions

This study presents the coupling of the agricultural land use model KLUM to the dynamic vegetation model with crops LPJ-C in order to consistently asses the implications of a changing climate for carbon cycle and farm revenue. The linking is realized by exchanging the crop specific potential yields, as determined by LPJ-C, with the crop allocation shares, determined by KLUM. The potential yields are used to drive the land-use decisions together with exogenous crop prices; the allocation coefficients for the different crops are used in LPJ-C to scale the carbon entering the soil litter pool. The effects of a changing economy are projected via land-use decisions on the carbon cycle, while the environmental changes are projected back on the agricultural sector and expressed in economic measures. The dynamic linkage is a first step towards an integrated assessment of the consequences of environmental and economic changes and their mutual interaction on crop growth and agricultural land use. In a companion paper, we couple KLUM to a trade model (Ronneberger et.al., 2006).

Since in the current system, management and irrigation are not represented, a certain inconsistency of observed (actual) and simulated (potential) yields has to be accepted. The evaluation of the coupled system shows that this mainly results in a shift of the crop pattern for the benefit of the major crops (wheat, barley, potatoes). The general pattern, however, is not dramatically distorted.

We use the model to assess the impact of climate change for the period 2001-2100 for the European Union on crop growth, carbon storage and agricultural land use for the two IPCC scenarios A1 and B2. The results demonstrate that the coupled system is stable and reproduces the known behavior of the simulated processes.

For all crops, we observe an extension of potential growing area to the North, more pronounced in the warmer scenario. The effect of CO2 fertilization and temperature increase on plant biomass production and carbon allocation within the plant can clearly be seen in the results. The changes in soil organic carbon largely follows these trends, modified by the temperature signal: decreases are wide-spread over the grid for the warmer scenario, and concentrated in Eastern Europe in the colder scenario.

The changes in crop pattern and crop production clearly reflect the changes in yields, potential growing areas, and the imposed price scenarios. Potatoes, rice and maize increase their allocation shares at the cost of wheat and barley. Underestimation of the area shares of maize and rice allocation and overestimation of barley and wheat allocation in the initial evaluation of the coupled model suggests that these trends might even be underestimated in our simulations. A spatially explicit analysis of changes in wheat and maize allocation indicate that maize replaces wheat in Central Europe, while it is replaced itself by wheat in the South. The initial evaluation also found for wheat area allocation an underestimation in the South and an overestimation in Central Europe. This underpins the suggestion that the observed trends might be underestimated in our simulations. The spread of the crops over the grid mainly follows the extension of potential growing area. However, most crops are not generally cultivated once they reach maturity. This reflects the relevance of profitability for land-use decisions.

Total crop production and revenue follow the trends of yields, growing area and prices. On European level, wheat and barley production falls, while potato production increases. For maize the increases in area share are outbalanced by decreasing yields. Again this result might be affected by the initial underestimation of maize allocation. For all crops total production is generally higher in the colder scenario. Crop price increments in the colder scenario and decrements in the warmer scenario strongly amplify these trends for economic revenues. Until 2100, the summed revenue of all crops triples in the colder scenario and drops to one fourth in the warmer scenario.

We demonstrate the impact and relevance of the coupling for the results by means of reference simulations with the uncoupled models. For LPJ-C, the initially observed crop pattern is assumed to remain constant. KLUM is only driven by the price scenarios while yields are set constant to the potential yields of LPJ-C in 1990. For both models, the spatial pattern as well as the extent of projected changes are affected by the coupling. Spatial variations of SOC are strongly determined by the assumed crop pattern and are thus largely underestimated by the uncoupled simulation. The extent of soil carbon changes is generally lower in LPJ-C standalone; decreases observed in the coupled simulation are absent in the uncoupled, indicating that a changing crop pattern reduces the carbon stored in the soil. Aggregated to the European level, however, the effect is negligible.

The results of KLUM standalone simulations suffer from an underestimated growing area and the absence of yield changes. The underestimation of the potential growing area of a crop leads to an underestimation of area share and revenue. The temporal development of the yield has an ambiguous effect: an increase in potential production results naturally in an increase of area share and revenue; this also implies an increase in riskiness and thus leads to a decrease in area share and revenue. The competition between crops determines which factor is stronger. For rice, this leads to a large overestimation of revenue and area share especially in the beginning of the simulation. A general underestimation of area share is revealed for maize while wheat and potatoes are overestimated; this reflects the underestimated potential growing area of maize. The differences in revenue are less pronounced due to the dominance of the price signal.

For all crops larger differences between KLUM standalone and KLUM@LPJ simulations are evident for the scenario with higher price changes. This is also reflected in the spatial analysis of differences between coupled and uncoupled runs for wheat and maize allocation: the pattern as well as the extent of the projected changes are affected in scenario B2 with large price changes while only the extent of the allocation changes differs in scenario A1. This indicates that the importance of dynamic feedbacks is stronger for more extreme scenarios. These results demonstrate clearly the importance of a dynamic representation of feedbacks between carbon cycle, crop growth and land-use decisions on the one hand; on the other hand it emphasizes the relevance of spatial analysis of the results.

Concluding, the established framework carries the potential to simulate the dynamics of carbon and water cycle and crop growth as well as economically motivated land-use decisions within one consistent framework on a global level. This is to our knowledge the first time this has been shown.

In this study, we applied the model only on a European level and only for cropland in order to assess the specific performance of the coupling. However, the feasibility of a simultaneous simulation of natural vegetation and crops within LPJ-C has been shown by Criscuolo et.al. (2005) and Criscuolo & Knorr (2005); the coupling of KLUM to a global economic trade model has been demonstrated in Ronneberger et.al. (2006); the application on the global level is mainly a problem of adequate calibration data. Thus, the framework is extendable to also include the complete dynamics of natural vegetation and a dynamic feedback loop with the economy, providing a tool to consistently asses the reactions and feedbacks of natural and economic environment on future changes.

However, to eventually establish a satisfactory modeling framework that allows reliable projections of the integrated changes of the natural and economic system the current system needs further improvements. As a first step the coupled system needs to be re-calibrated and spun up as one single model. Additionally, a proper ”translation” of potential into actual yields should be found in order to make the output of LPJ-C more comparable to the observed yields. This would also dissolve the distortions in the model results of KLUM in the first years after spin up.

Also the crop harvesting of the current framework should be revised to include specific harvesting and agronomic techniques that can be relevant for the soil carbon balance.

Apart, the economic results strongly depend on the chosen price scenarios, which are static and depend on speculative assumptions. The dynamic reactions of prices to natural and economic changes need to be included: the coupling of KLUM and an economic trade model (Ronneberger et.al. 2006) has to be combined with KLUM@LPJ to represent more comprehensively the dynamic system of economy and vegetation. For realistic estimations of future agricultural land-use changes and their implications for the natural environment, the framework needs to consider management, particularly irrigation practices, and technological change, including new cultivars. These factors are difficult to project but will play a major role for future agricultural land use. The simulation of water-limited yields with LPJ-C (Criscuolo & Knorr, 2005) can provide a basis for such an extension. On the long run, LPJ-C needs to include an implementation of nutrient cycling in order to properly asses the impacts of fertilizing and to close the feedback loop of crop growth and land-use decisions. Apart from that, to represent the variability of total cropland and the respective share of natural vegetation, the allocation algorithm of KLUM needs to be extended to include other agricultural sectors such as animal production and biofuels and finally also forestry, industrial and recreational land.

Nonetheless, all in all this work is a first step in the right direction. The results show the feasibility of the chosen approach and clearly motivate a continuation of the present work.

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APPENDIX

A KLUM’s interior

The allocation algorithm of KLUM is based on the assumption that the most profitable allocation is chosen. Total achievable profit per hectare π of one spatial unit is assumed to be:

$$\pi = \sum_{k=1}^{n} (p_k \alpha_k - \tilde{c}_k \bar{L} l_k) l_k - \gamma \mathrm{Var}\left[\sum_{k=1}^{n} (p_k \alpha_k - \tilde{c}_k \bar{L} l_k) l_k \right] \quad \textbf{(A1)}$$

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 $\bar{L}$ allocated to crop $k \in \{1 \ldots n\}$ of *n* crops. $\tilde{c}_k$ is the cost parameter for crop *k*. Total costs are assumed to increase in land according to

$$C = \sum_{k=1}^{n} \tilde{c}_k L_k^2 \quad \textbf{(A2)}$$

where $L_k = l_k \bar{L}$ denotes the total area allocated to crop *k*.

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 $0 < \gamma < 1$.
Maximizing π under the constraint that all land shares need to add up to a total not greater than one: $1 \le \sum_{k} l_k$, an explicit expression for each land-share l_i allocated to crop $i \in \{1 \ldots n\}$ can be derived:

$$l_i = \frac{\frac{1}{2} \sum_{k=1}^{n} \frac{\beta_i - \beta_k}{\gamma \sigma_k^2 + c_k} + 1}{\sum_{k=1}^{n} \frac{\gamma \sigma_i^2 + c_i}{\gamma \sigma_k^2 + c_k}} \quad \textbf{(A3)}$$

where for simplicity $\beta_k = p_k \alpha_k$ displaces the profitability of crop *k*, $\sigma^2 = \mathrm{Var}[\beta_k]$ displaces the respective variance and $c_k = \tilde{c}_k \bar{L}$. The temporal variability of total costs is assumed to be negligible compared to the variability of prices and productivities (see Ronneberger et al. (2005) for a detailed description of model development and evaluation).

Adjustment of the cost parameters in KLUM

The assumption of decreasing returns to scale (Equation A2) that underlies the cost structure of KLUM has consequences for the interpretation and transferability of the calibrated cost parameters. We interpret the increasing cost with increasing area share such that the most suitable land is used first; 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 spatial unit cannot simply be adopted in other units. Instead these values need to be adjusted to account for the different amount of 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 twice the amount of suitable area would be available. So, the cost parameter c_a of unit *a* is adjusted for unit *b* by scaling it according to:

$$c_b = c_a \frac{L_a}{L_b}$$

where L_a and L_b represent the total agricultural area of unit *a* and of unit *b*, respectively. This procedure assures that under identical conditions, the spatial resolution does not impact the result. For the downscaling of the calibrated cost parameters from NUTS2-regional to grid-cell level, the fraction of L_a and L_b equals the total number of grid cells in this region.

B Scenarios

The simulation covers the period 1991-2100. To reach equilibrium in the SOC for the initial year, we spin up the model for 100 years using the 1961-1990 climatology provided in TYN 2.0 (Mitchel et al., 2004) and observed CO2 concentrations. Grid cells where no crop reaches maturity during the spin up period are excluded from our simulations, as the initial situation of soil organic carbon cannot be determined. This concerns 168 of the 1,986 grid cells, mainly situated at the Norwegian border of Sweden.

We use observed data for climate (precipitation, temperature and radiation), CO2 concentration and crop prices for the period of 1991-2001. We take mean global CO2 concentrations from McGuire et al. (2001), to cover the period 1991-1992, while data from the integrated assessment of Schlesinger & Malyshev (2001) covers the remaining period after 1992. Soil texture data is based on the FAO soil data set on a global 0.5° × 0.5° grid, as described by Sitch et al. (2003). Observed climate data for 1991-2000 is derived from the CRU TS 2.0 global climate dataset (Mitchel et al., 2004). This dataset provides monthly fields of observed mean temperature, precipitation and cloud cover on a 0.5°× 0.5° global grid over land. Crop prices for this period are based on data of FAOSTAT (2005) and of the World Bank (2003) and given on world regional level in 5-year means.

From 2001 to 2100 we use climate and atmospheric CO2 scenarios. We use the TYN SC 2.0 data set (Mitchel et al., 2004), which consists of monthly values for the period 2001-2100 on the same 0.5° × 0.5° grid as CRU TS 2.0. This set includes 16 scenarios of projected future climate, representing all combinations of four SRES emissions scenarios and four GCMs. We select the SRES-B2 and SRES-A1 scenarios from HadCM3 (see **Figure B 1**). A1 and B2 are the extremes of the SRES group and give two very different CO2 concentration paths for the 2001-2100 period (IPCC, 2000). HadCM3's behavior over Europe is typical for a range of GCMs (IPCC, 2001). Crop prices for 2000 to 2100 are adopted from ACCELERATES (2004), who developed different scenarios based on literature and expert judgment to describe the socio-economic changes driving land-use decisions in Europe according to the four different IPPC scenarios A1F1, A2, B1 and B2. With those, they provide estimates of percentage changes for the prices of cereals, maize, sugar beet and roots & tubers for the year 2020, 2050 and 2080 for the two regions EU15 and Central & Eastern Europe. We apply their scenarios A1FI and B2 to our crop price of 2000. Changes for cereals are imposed on rice, wheat and barley, and changes for roots & tubers on potatoes. The estimated changes for EU15 are assigned to our world region Western Europe and the changes in Central & Eastern Europe to the two remaining world regions. One important assumption is that prices in EU15 and Central & Eastern Europe will converge over time due to the process of accession of the eastern countries to the European Union (EU25). Full convergence to identical prices is assumed to be reached in 2080. We extended this assumption to the Former Soviet Union, suggesting a convergence of prices to the level of price in Central & Eastern

Europe in the year 2020 (see **Figure B 2**). Total available cropland is assumed to stay on current level (see **Figure B 3**) for the entire simulation.

Figures

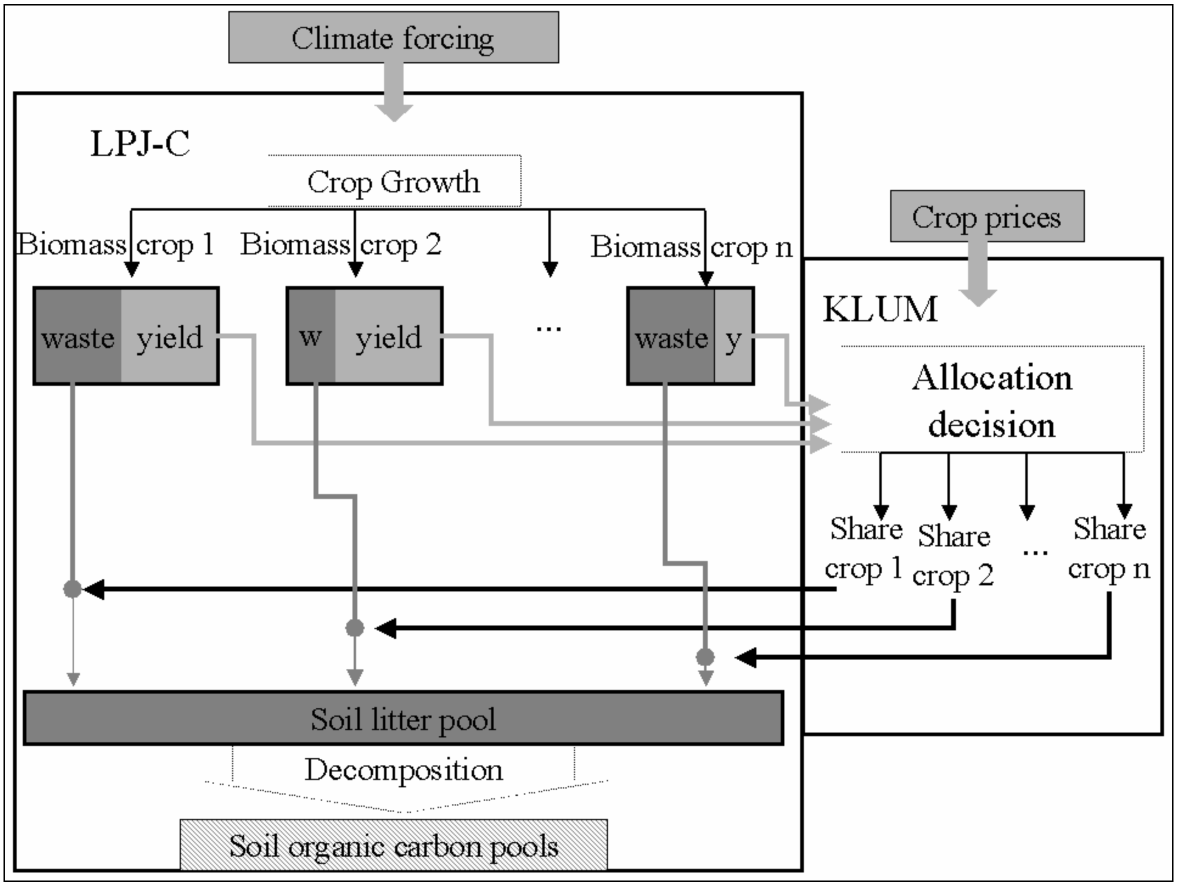

Figure 1: Coupling scheme of the KLUM@LPJ model. The share of total biomass stored in the human edible part of the crop are used in KLUM as potential yield, the rest of the plant's biomass is scaled by the calculated area share and enters the soil litter pool for further decomposition.

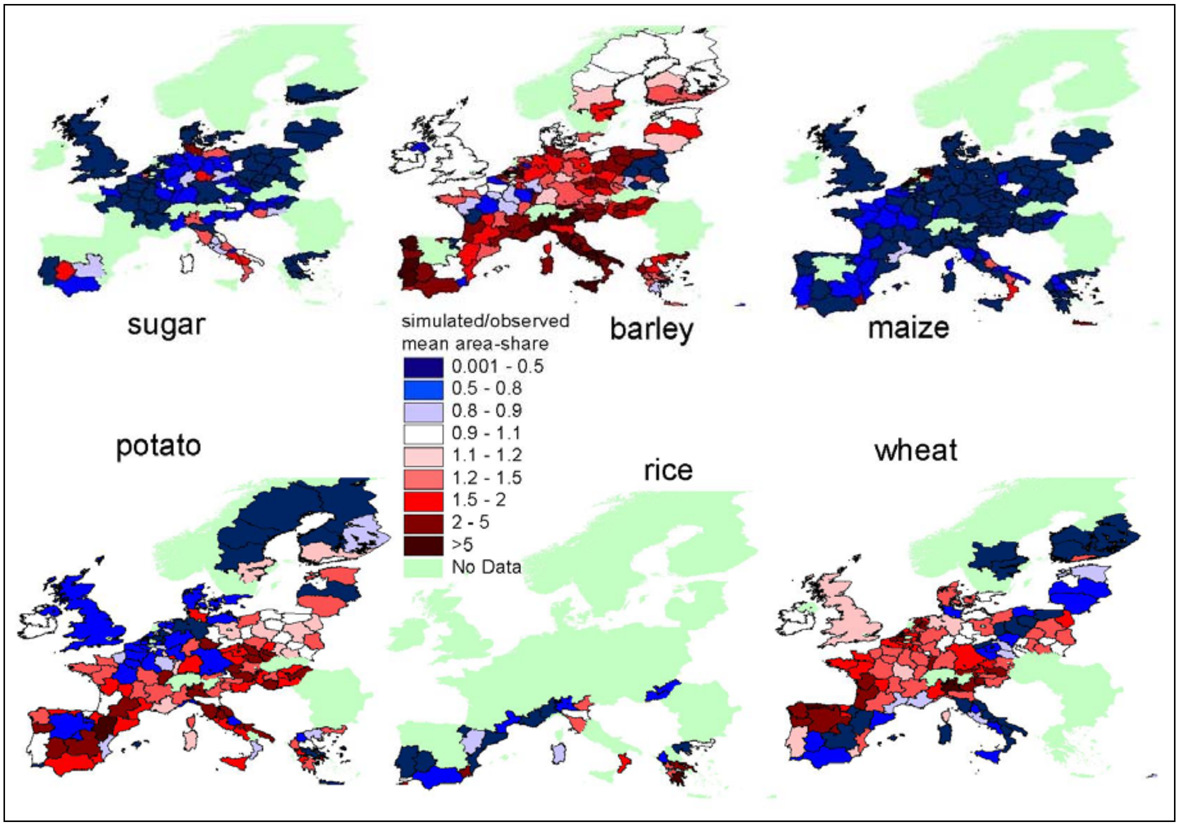

Figure 2: Ratio of simulated and observed area share for the year 2000. The values are compared on NUTS2 level; simulated values are averaged over the grid cells within one NUTS2 region.

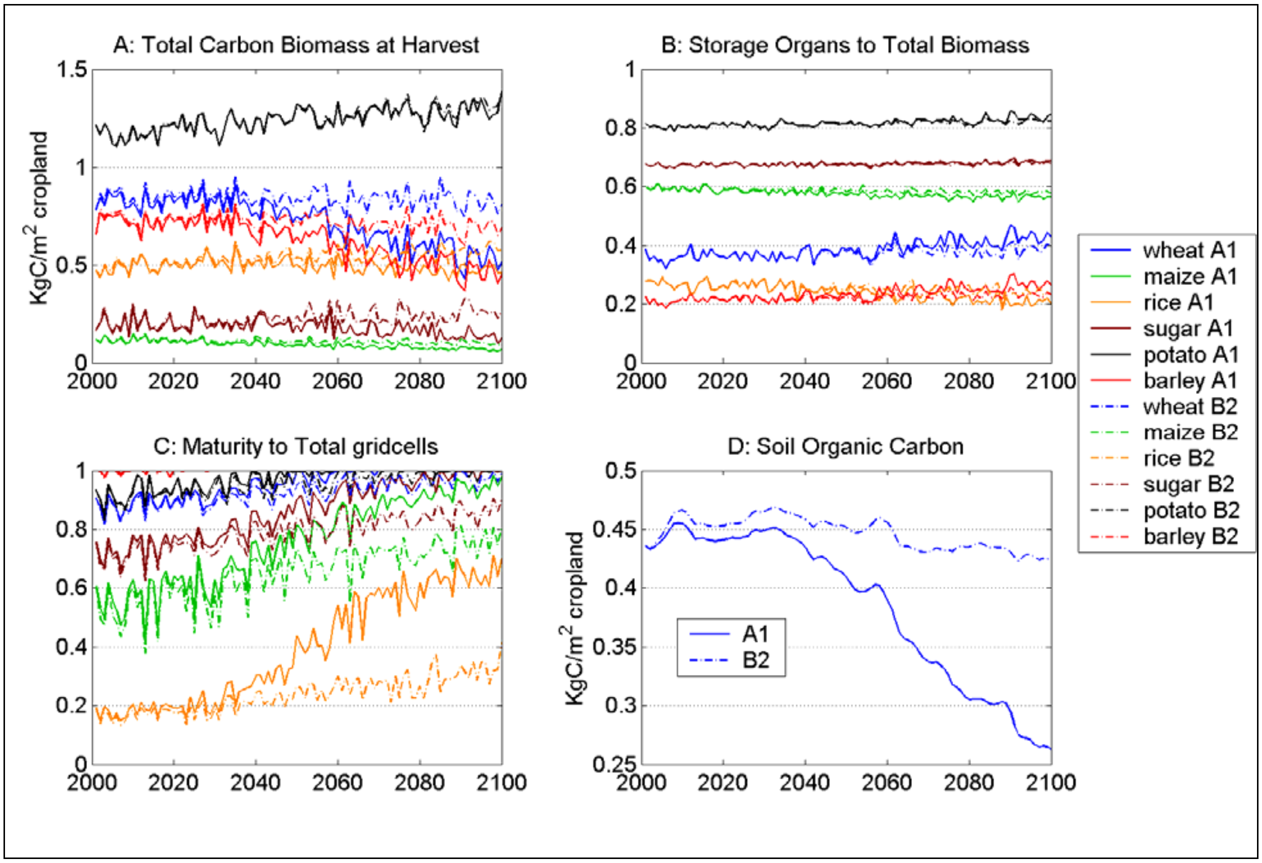

Figure 3: Temporal development of indicators describing the natural system according to KLUM@LPJ. A: Mean total biomass at harvest time; B: Mean of the ratio of a crop's storage organs to total biomass; C: Ratio of gridcells, where full maturity is reached to total grid cells; D: Mean soil organic carbon

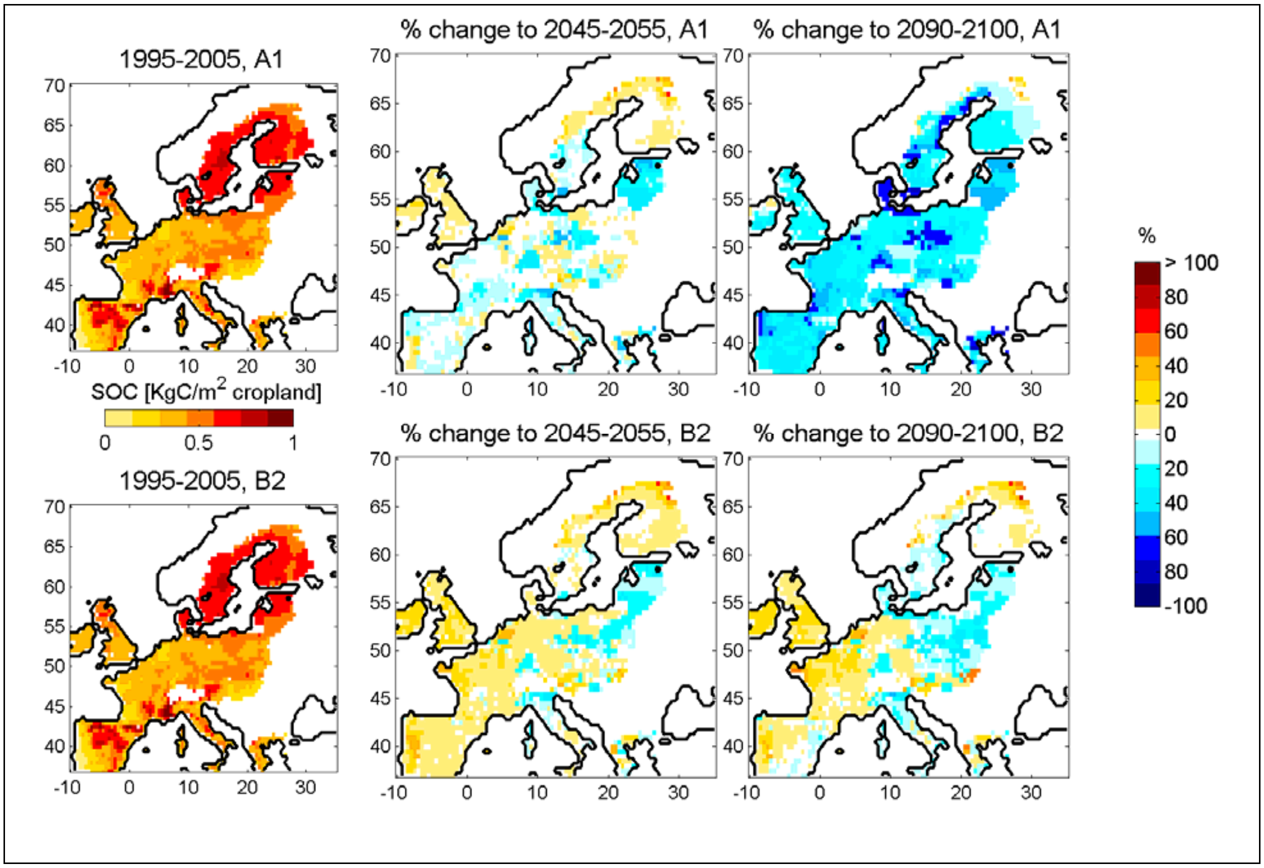

Figure 4: Soil organic carbon changes according to KLUM@LPJ. The small left-most plots illustrate the spatial distribution of SOC averaged over the reference period 1995-2005; the remaining plots depict the percentage changes relative to this situation for averages of the periods 2045-2050 and 2090-2100 for scenarios A1 and B2.

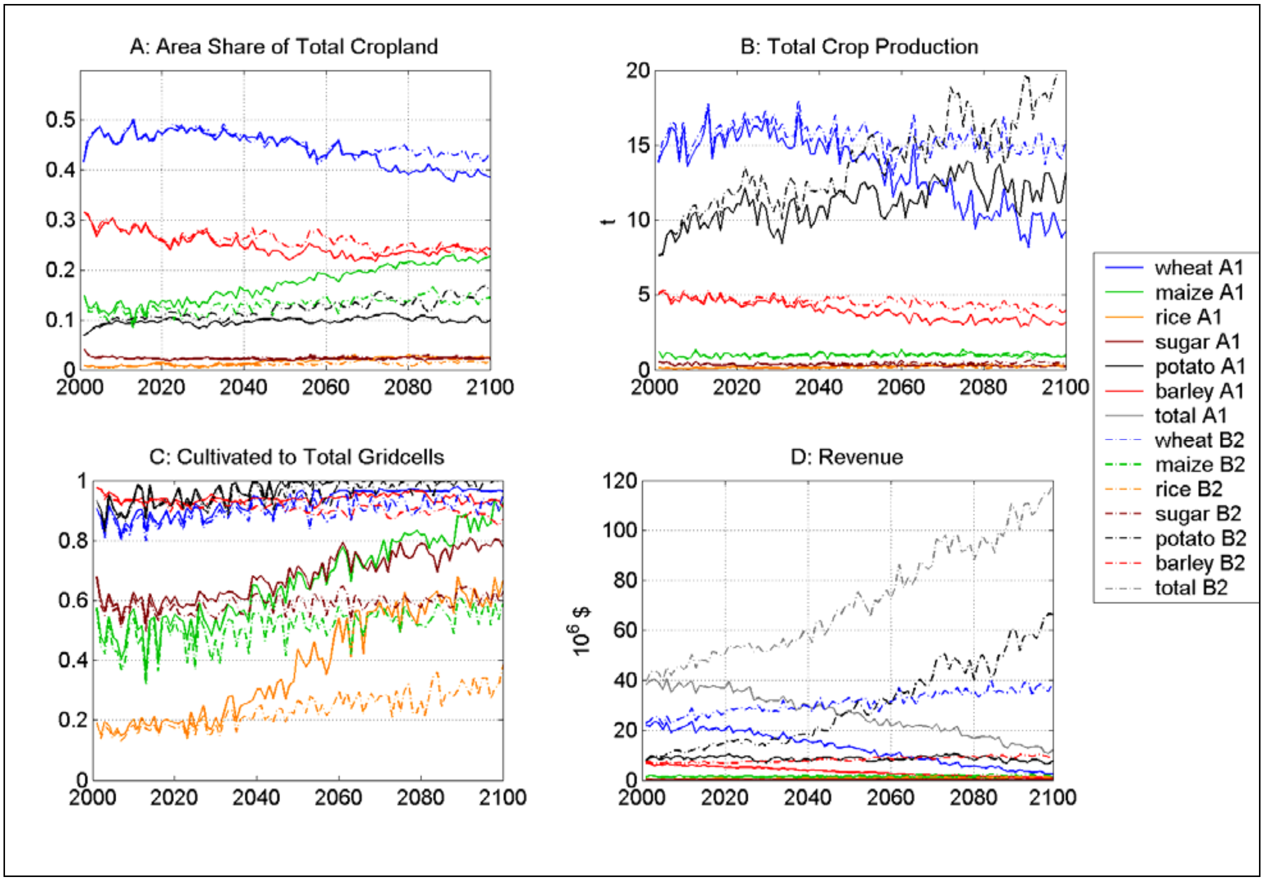

Figure 5: Temporal development of agroeconomic indicators according to KLUM@LPJ. A: Area share of total European cropland; B: Total European crop production; C: Ratio of grid cells, where a crop is cultivated to total grid cells; D: Total European Revenue from crop production (the gray line depicts the summed revenue).

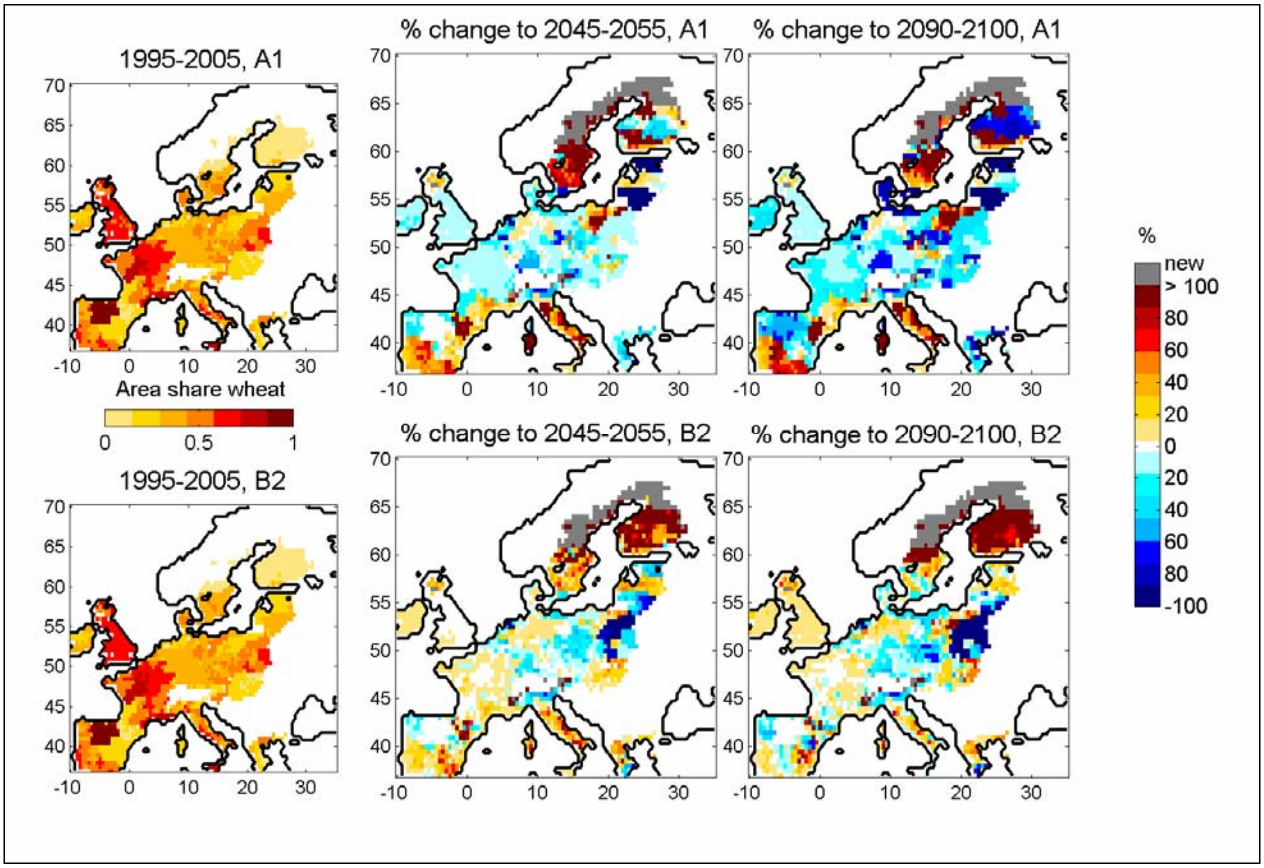

Figure 6: Wheat allocation changes according to KLUM@LPJ. The small left-most plots illustrate the spatial distribution of wheat allocation averaged over the reference period 1995-2005; the remaining plots depict the percentage changes relative to this situation for averages of the periods 2045-2050 and 2090-2100 for scenarios A1 and B2.

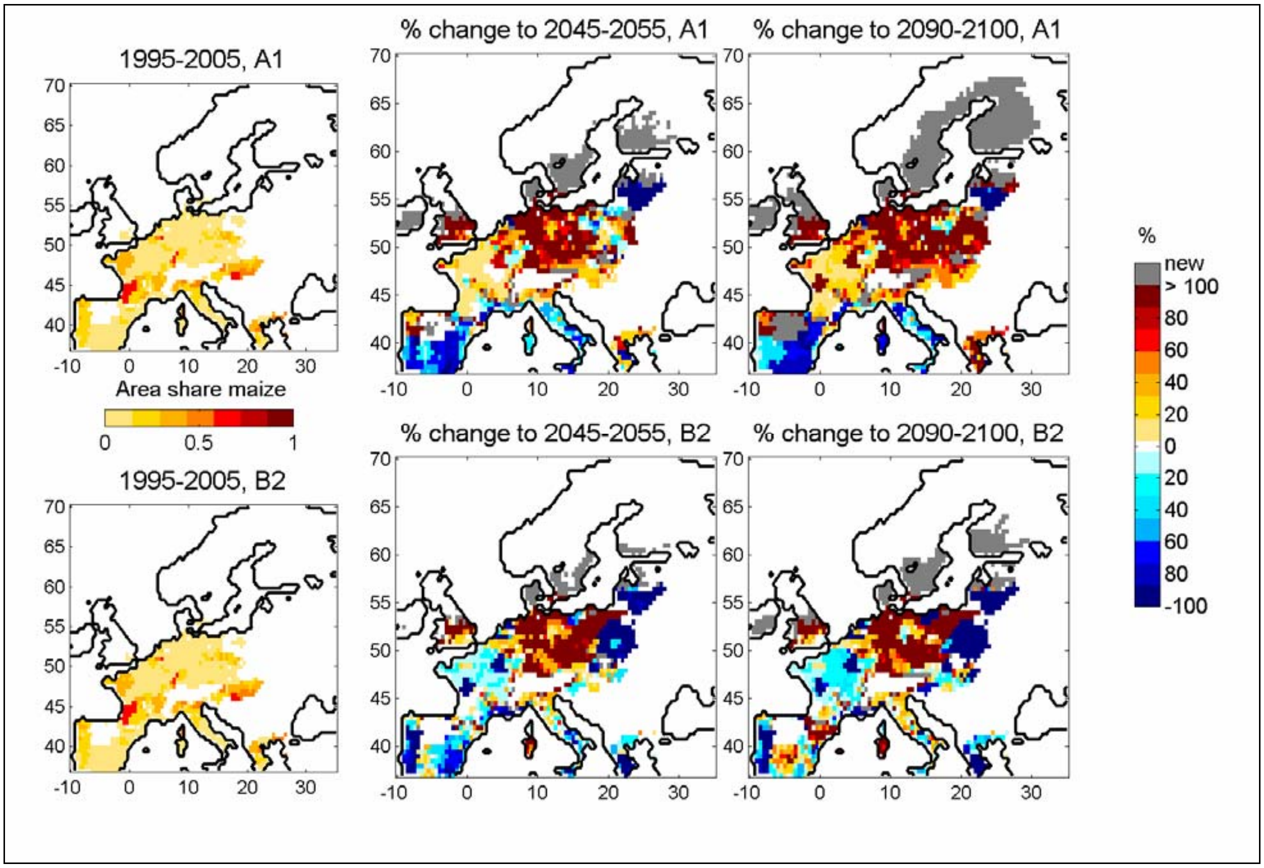

Figure 7: Maize allocation changes according to KLUM@LPJ. The small left-most plots illustrate the spatial distribution of maize allocation averaged over the reference period 1995-2005; the remaining plots depict the percentage changes relative to this situation for averages of the periods 2045-2050 and 2090-2100 for scenarios A1 and B2.

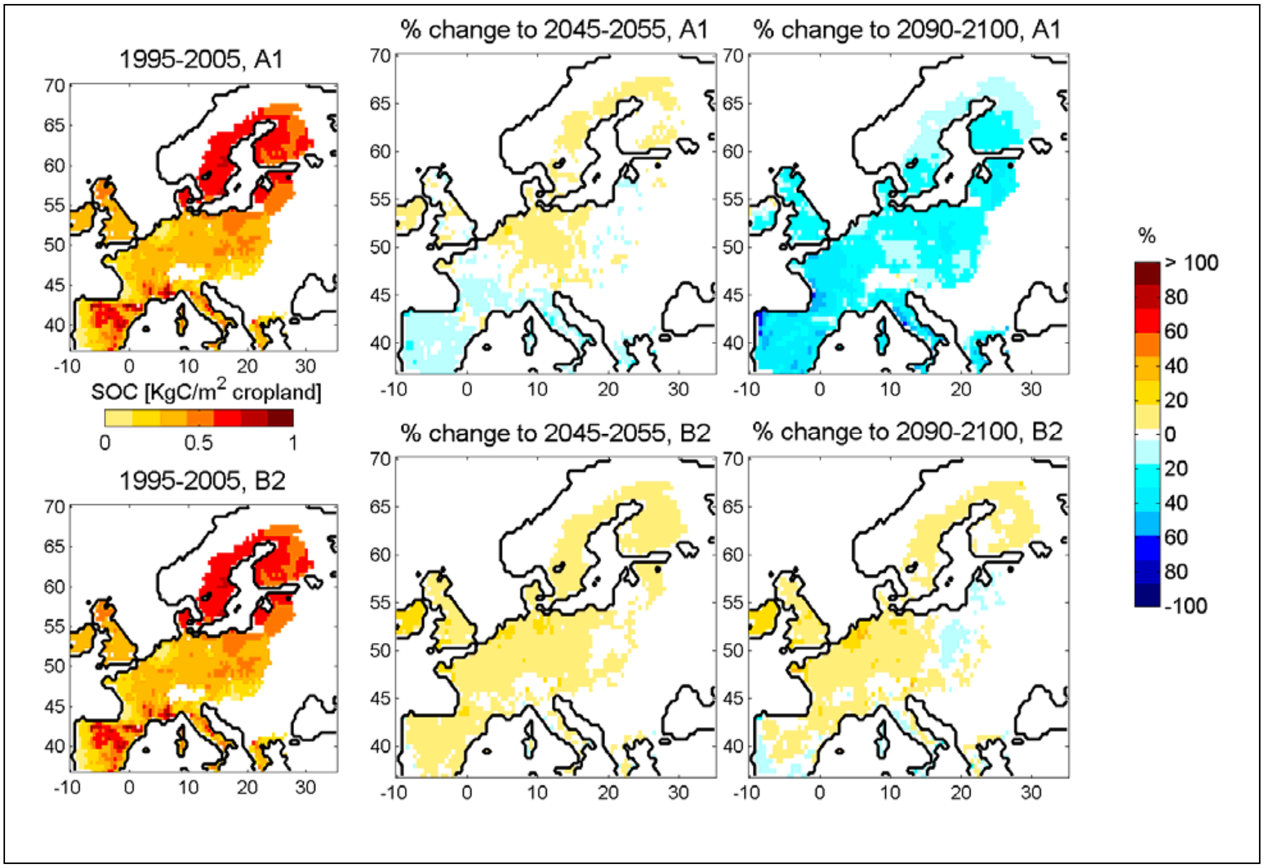

Figure 8: Soil organic carbon changes according to LPJ-C standalone. The small left-most plots illustrate the spatial distribution of SOC averaged over the reference period 1995-2005; the remaining plots depict the percentage changes relative to this situation for averages of the periods 2045-2050 and 2090-2100 for scenarios A1 and B2.

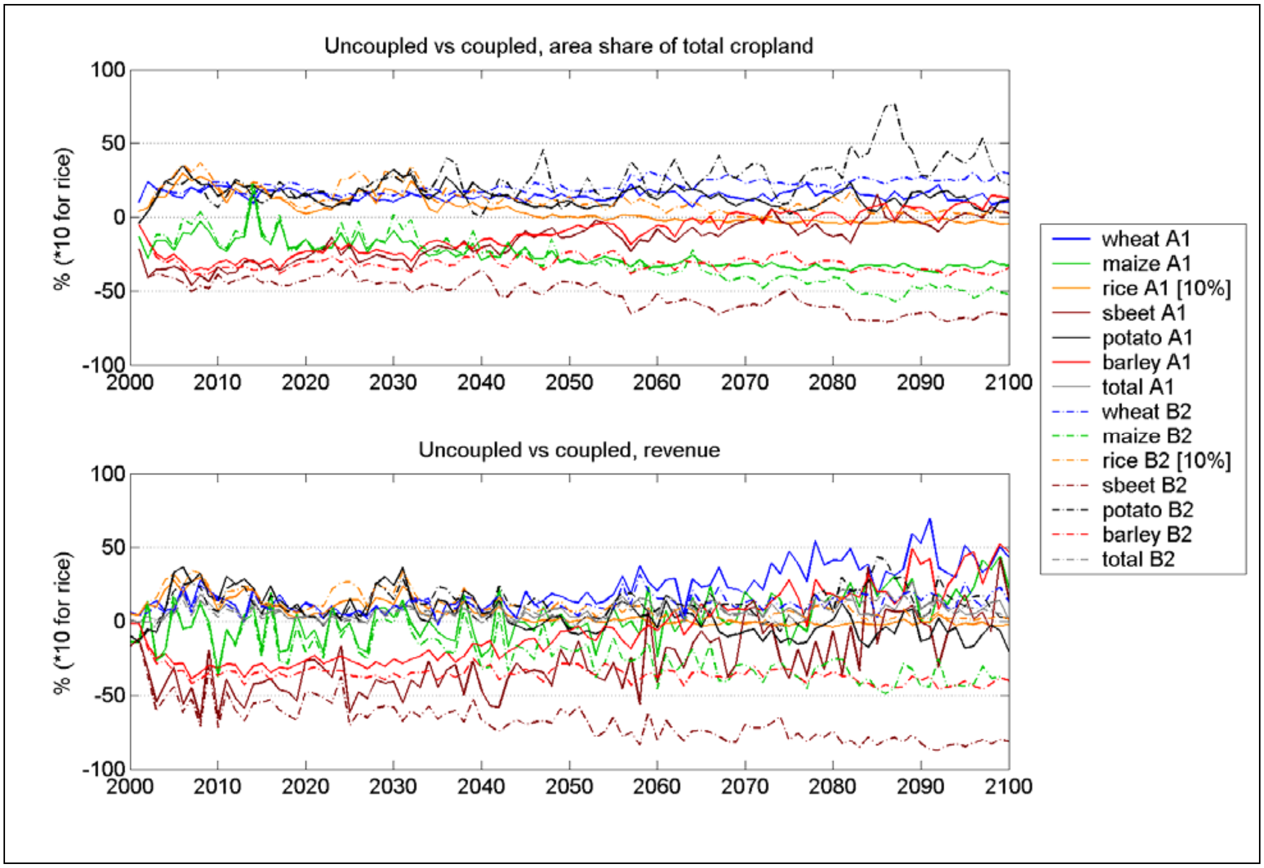

Figure 9: Percentage difference of KLUM standalone versus KLUM@LPJ for European area share (A) and revenue (B). The differences for rice are given in 10% in order to fit in the scheme.

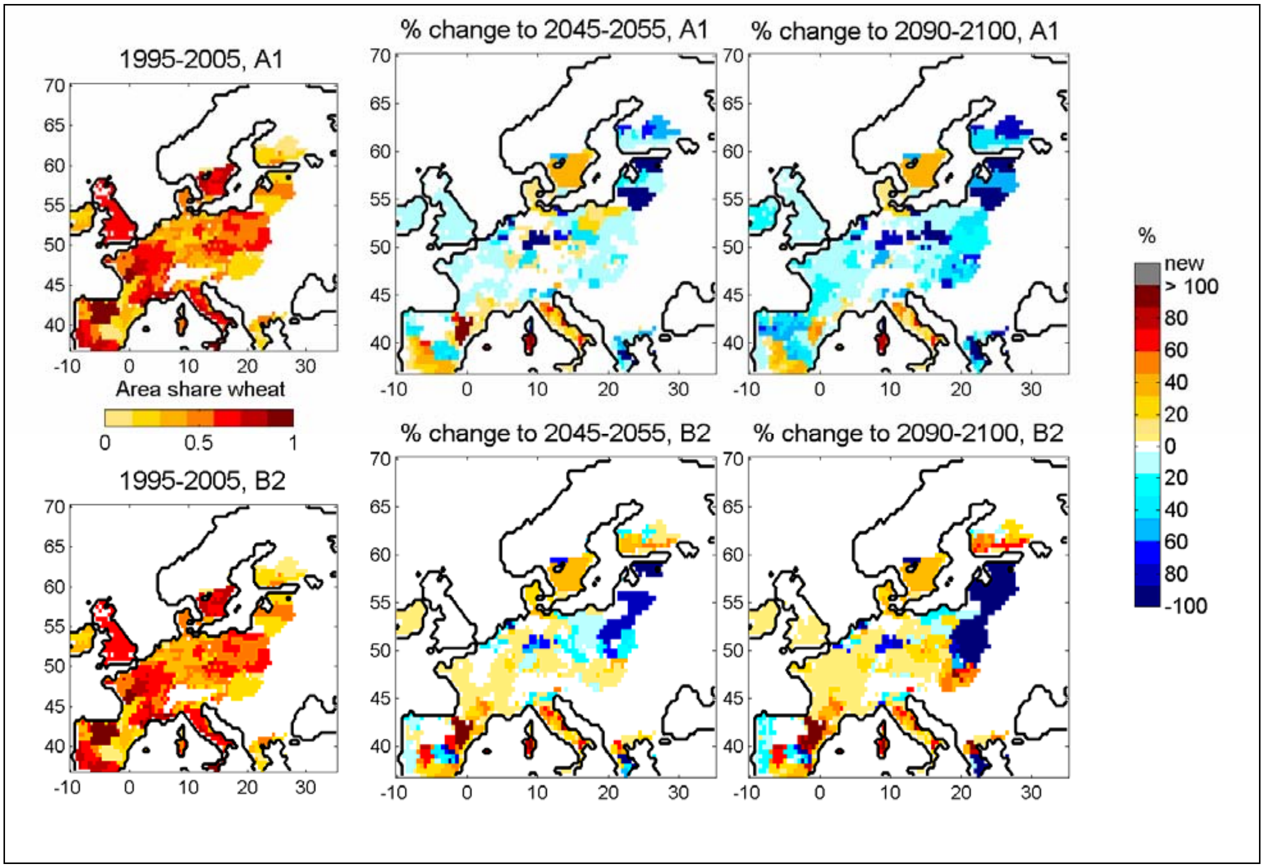

Figure 10: Wheat allocation changes according to KLUM standalone. The small left-most plots illustrate the spatial distribution of wheat allocation averaged over the reference period 1995-2005; the remaining plots depict the percentage changes relative to this situation for averages of the periods 2045-2050 and 2090-2100 for scenarios A1 and B2.

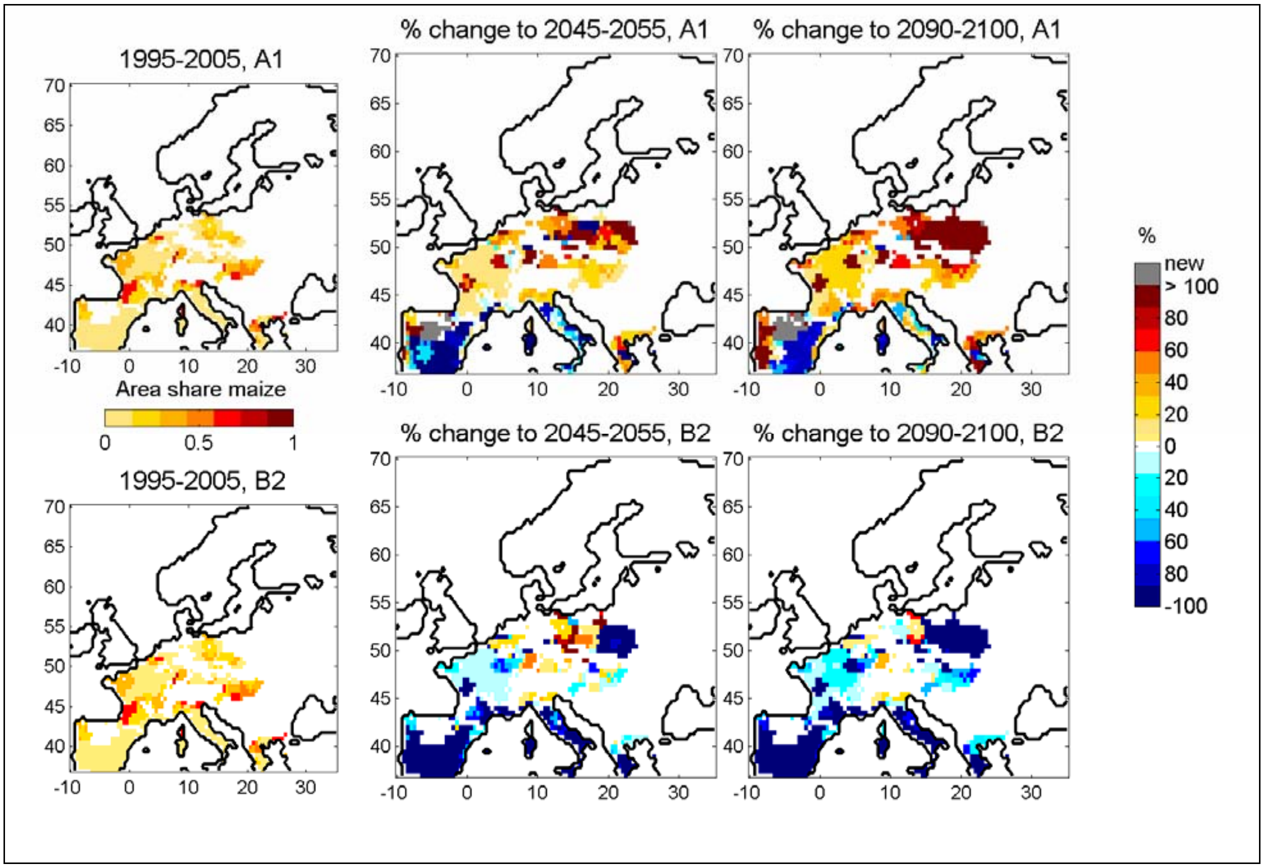

Figure 11: Maize allocation changes according to KLUM standalone. The small left-most plots illustrate the spatial distribution of maize allocation averaged over the reference period 1995-2005; the remaining plots depict the percentage changes relative to this situation for averages of the periods 2045-2050 and 2090-2100 for scenarios A1 and B2.

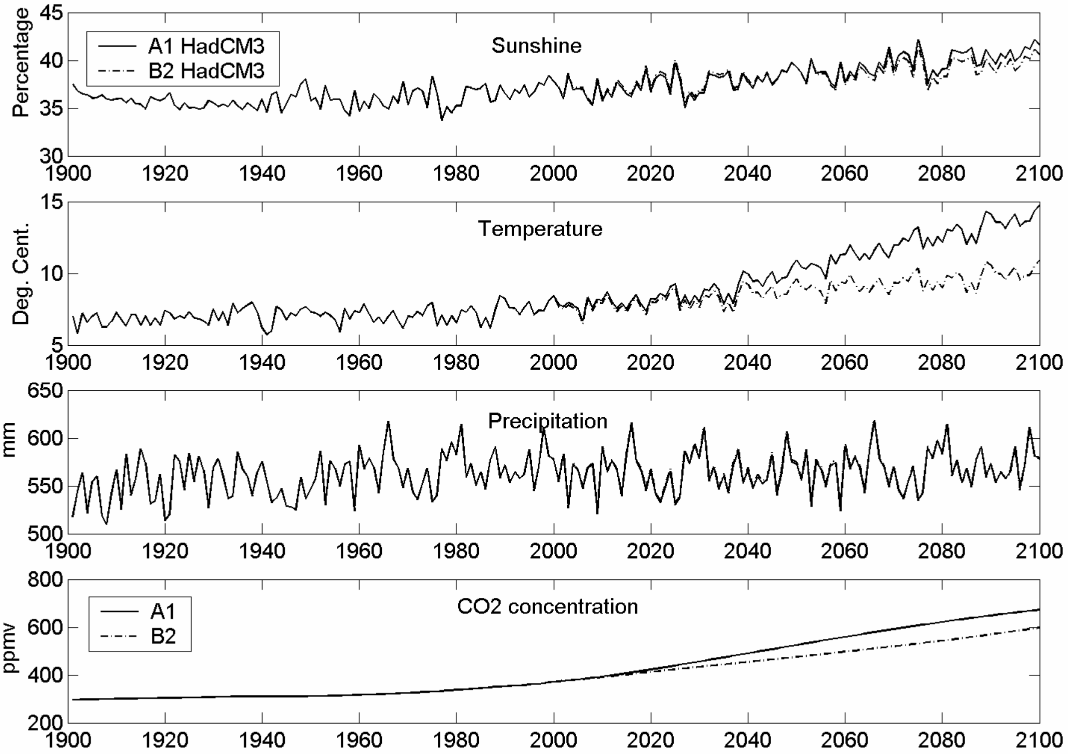

Figure B 1: Total cropland in ha for the different NUTS2 regions. (adopted from (Eurostat New Cronos, 2005))

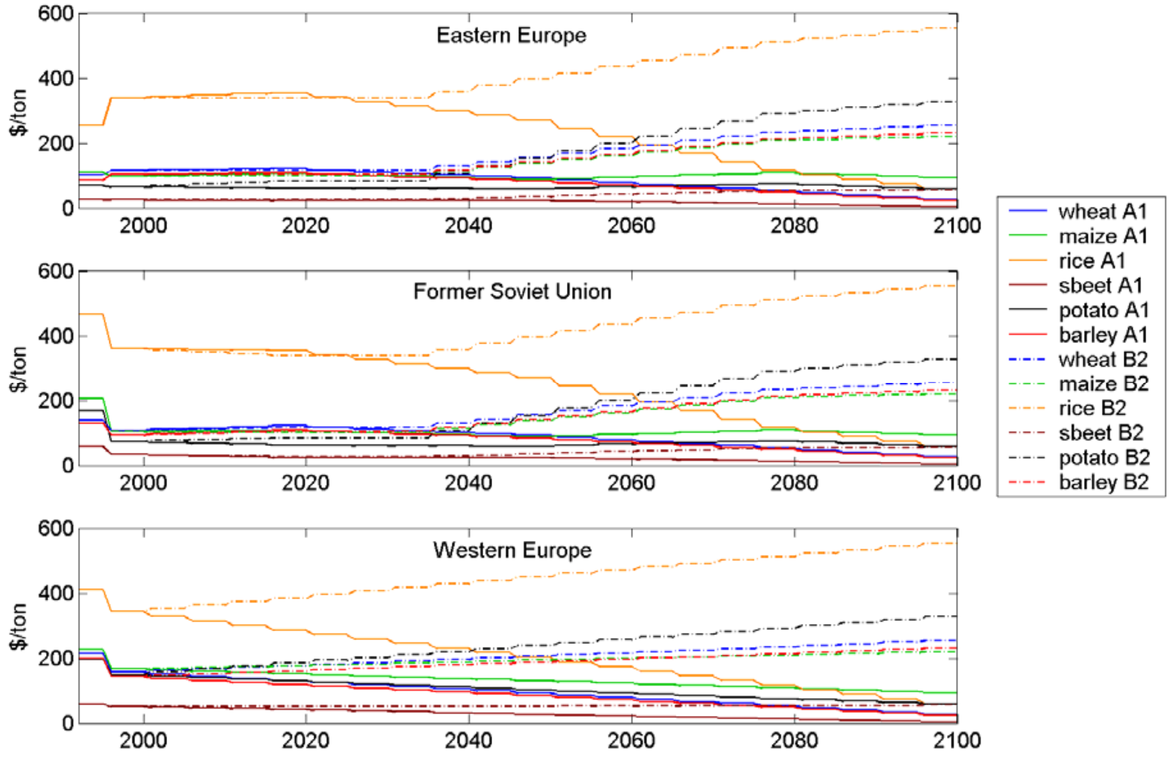

Figure B 2: Price scenario for the different economic regions.

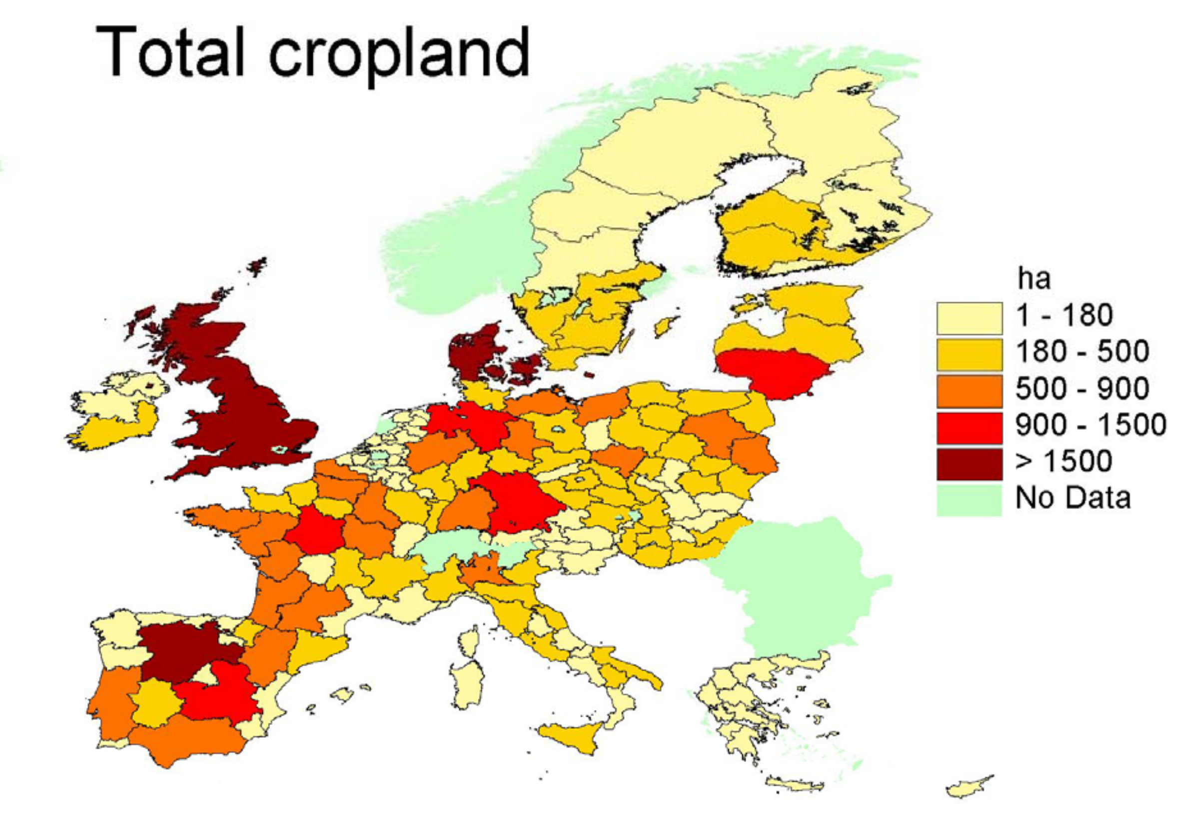

Figure B 3: Climate forcing for the different scenarios averaged over the simulation grid.

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