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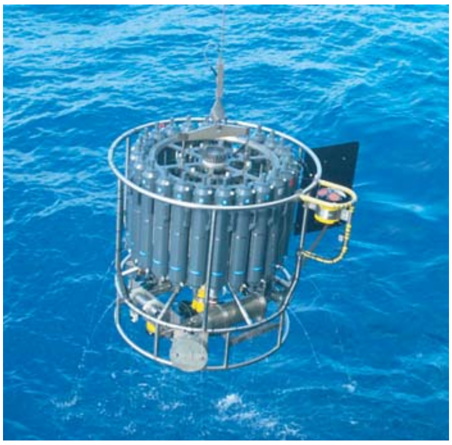
IMPRS

The global agricultural land-use model KLUM

– A coupling tool for integrated assessment –

Kerstin Ellen Ronneberger



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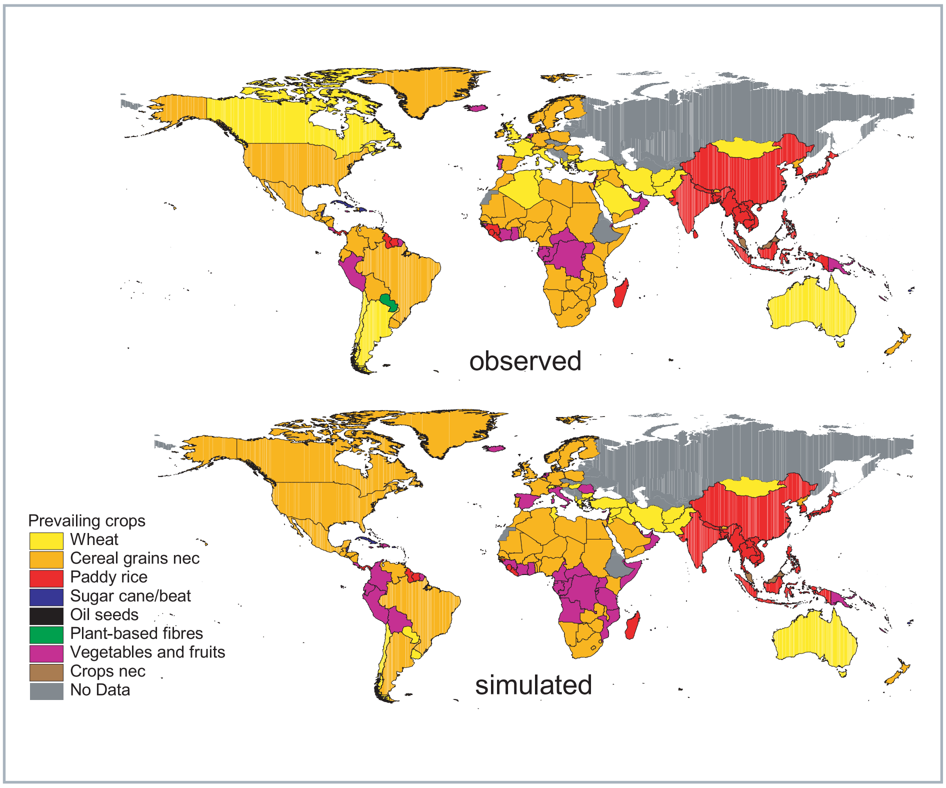

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ABSTRACT

Despite the indisputable impact of human action on global climate, the representation of the interaction between the human and the natural dimension in earth system models is still weak. Models of the economy and the biosphere commonly stand on their own; their mutual impacts are only considered by exogenous scenarios. Land-use decisions are one of the most direct links of antroposhere and biosphere. Land use is target as well as driver of environmental changes, building a vital feedback loop of human societies and the natural environment.

In this thesis, the global agricultural land-use model KLUM (*Kleines* Land Use Model) is developed and the couplings of the model with a global economic trade model as well as with a dynamic vegetation model are described. The aim of the model is to establish a dynamic interface of economy and vegetation in an integrated modeling framework. For this purpose, land allocation algorithm determines the area shares of different crops based on the essential biophysical as a well as economic aspects of agricultural land-use decisions. The developed algorithm is derived by profit maximization, where yield projections enter as a spatially explicit decision factor. The restriction to only the essential parameters as well as the motivationally based approach qualifies the model for long-term predictions, for global analysis and for a dynamic coupling to comprehensive state-of-the-art models of the respective disciplines.

The feedback loop of economic development and agricultural land-use decisions is studied by coupling KLUM to the global computable general equilibrium model GTAP-EFL, an extended version of the established Global Trade Analysis Project model GTAP. The models are linked by replacing the land allocation mechanism of GTAP-EFL with KLUM. Price and management changes, according to GTAP-EFL, and exogenous scenarios of country specific yield values drive KLUM; regionally aggregated changes in area shares of different crops, determined by KLUM are used to update the area-shares in GTAP-EFL. This intimate link establishes a dynamic feedback of country-specific land-use decisions and world-regional economic trade and production decisions. The purely economic representation of crop production in GTAP-EFL benefits from the introduction of biophysical aspects of land-use decisions; the impacts of the changing economy can be projected on agricultural land cover on country level enabling a spatially more explicit analysis of biophysical consequences.

For a spatially explicit analysis of the interaction between land-use decisions, crop growth and organic carbon storage, a C++ version of KLUM is implemented into the dynamic global vegetation model LPJ-C, the Lund Potsdam Jena model for crops. 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 together with exogenous crop prices to drive the land-use decisions; the allocation coefficients for the different crops are used in LPJ-C to scale the carbon entering the soil litter pool. Like this, the effects of a changing economy are projected on the carbon cycle; the environmental changes are projected back on the agricultural sector and can be expressed in economic measures.

In each step of the model development and couplings, the performance is evaluated and relevance and impact of the coupling for the results could be highlighted by means of illustrative future simulations. The results underpin the robustness of the model as well as the importance of land-use changes and their integrated representation for an assessment of climate change impacts.

ZUSAMMENFASSUNG

Trotz des unumstrittenen Einflusses menschlichen Handelns auf das globale Klima, werden die Wechselwirkungen zwischen menschlicher und natürlicher Sphäre in heutigen Erdsystemmodellen immer noch vernachlässigt. Modelle der Ökonomie und der Biosphäre werden zumeist unabhängig voneinander betrachtet und gegenseitige Einflüsse werden lediglich durch exogene Szenarien berücksichtigt.

Die Bewirtschaftung von Land ist einer der unmittelbarsten Einflüsse des Menschen auf die Natur: Landnutzung verändert die Umwelt und wird gleichzeitig von Umweltveränderungen beeinflusst. Als solches stellen die Entscheidungen über die Nutzung von Land ein entscheidendes Bindeglied im Kreislauf gegenseitiger Wechselwirkungen zwischen Mensch und Natur dar.

Diese Arbeit beschreibt die Entwicklung des globalen landwirtschaftlichen Landnutzungsmodels KLUM (*Kleines* Land Use Model) und dessen Kopplung mit einem globalen Weltwirtschaftsmodel sowie mit einem dynamischen Vegetationsmodel.

Ziel des Landnutzungsmodells ist es, in einem integrierten Modellsystem eine dynamische Schnittstelle zwischen Modellen der Ökonomie und der Vegetation zu bilden. Dafür werden im zugrunde gelegten Algorithmus, der die Flächenanteile verschiedener Feldfrüchte bestimmt, sowohl die essentiellen ökonomischen als auch biophysikalischen Aspekte globaler Landnutzungsentscheidungen abgebildet. Der Algorithmus geht aus einer Profitmaximierung hervor in die Ernteertragsprojektionen als ortspezifische Entscheidungsfaktoren eingehen. Der motivationsbasierte Algorithmus, sowie der Verzicht auf große Mengen von Inputdaten ermöglichen nicht nur die direkte Kopplung mit detaillierten Modellen der spezifischen Disziplinen sondern erlauben darüber hinaus langfristige, globale Zukunftsprojektionen.

Die Kopplung von KLUM mit dem allgemeinen ökonomischen Gleichgewichtsmodel GTAP-EFL, einer erweiterten Version des Global Trade Analysis Projekt Models GTAP, gestattet die Simulation und Untersuchung der gegenseitigen Wechselwirkungen zwischen globalwirtschaftlichen Veränderungen und Entscheidungen über die Bewirtschaftung landwirtschaftlicher Flächen. Indem der Landallokationsmechanismus in GTAP-EFL durch KLUM ersetzt wird, wird die rein ökonomische Darstellung von Landnutzungsentscheidungen in GTAP-EFL um biophysikalische Aspekte erweitert. Der Einfluss sich verändernder Wirtschaftsaktivitäten kann länderspezifisch auf die Veränderung landwirtschaftlicher Flächen abgebildet werden. So wird eine feiner aufgelöste Analyse etwaiger Umweltfolgen möglich. KLUM stützt dabei die Simulation der Landnutzungsentscheidungen auf die berechneten Preis- und Bewirtschaftungsveränderungen des GTAP-EFL Modells, sowie auf exogen vorgegebene Ernteertragsszenarien. Die so berechneten Veränderungen der Flächenanteile für den Anbau verschiedener Feldfrüchte werden auf regionale Ebene aggregiert und bestimmen im GTAP-EFL Model den benötigten Landanteil verschiedenener Feldfruchtproduktionen.

Eine ortsabhängige Analyse der Wechselwirkungen von Pflanzenwachstum, Kohlenstoffanreicherung und Landnutzungsentscheidungen wird durch die Integration einer C++ Version des KLUM Models in das dynamische globale Vegetationsmodel LPJ-C (Lund Potsdam Jena for crops) realisiert. In der Kopplung werden die von LPJ-C errechneten feldfruchtabhängigen potentiellen Ernteerträge und die entsprechend von KLUM bestimmten Flächenanteilen ausgetauscht. So wird sowohl der Einfluß einer sich ändernden Wirtschaft auf den Kohlenstoffkreislauf als auch die Auswirkung von Umweltveränderungen auf den landwirtschaftlichen Sektor abgebildet. Die potentiellen Ernteerträge sowie exogen vorgegebene Preisszenarien dienen KLUM als Grundlage

zur Simulation der Landnutzungsentscheidungen. Die so berechneten Flächenanteile der verschiednen Feldfrüchte bestimmen in LPJ-C die Gesamtmenge des organischen Kohlenstoffs, der in das Erdreich übergeht.

Für jeden Schritt der Modellentwicklung wurde eine Evaluierung der Güte des Modellsystems durchgeführt. Darüber hinaus wurden Relevanz der Modellkopplungen und deren Einfluß auf die Resultate durch illustrativen Zukunftsmodellierungen hervorgehoben. Die Ergebnisse spiegeln die allgemeine Stabilität des Models sowie die Bedeutung von Landnutzungsentscheidungen und deren integrierte Darstellung für Folgeabschätzungen des Klimawandels wider.

1. INTRODUCTION

1.1 Land-use as a link in the earth system

Since the middle of the last century the temperature of the Earth's surface has increased by 0.6 ± 0.2C (IPCC, 2001). Comprehensive models of atmosphere, ocean and biosphere are used to explain and understand the development of the climate system and to assess the likelihood and extent of a further warming (IPCC, 2001). The models applied in the forth assessment report of the International Panel for Climate Change (IPCC) have been enhanced by increasing the temporal and spatial resolutions to also capture small-scale processes; atmosphere, ocean and biosphere models have been coupled so as to consider the dynamic feedbacks of the different systems. But - even though a substantial part of the observed global warming is assumed to be a consequence of human activity - the human impact in these models is still considered only by means of external emission scenarios. Impacts of a changing climate on mankind, vulnerability and adaptation possibilities of the socio-economic system are assessed separately, mainly by examining the effect of temperature on different natural and human systems (McCarthy *et al.*, 2001). The dynamic interaction between the human societies and the natural environment are largely excluded from both the analyses.

To understand and asses the feedbacks between the antroposphere and the natural earth system an integrated assessment of socio-economic and natural components and their dynamic interaction is necessary. An increasing number of models of integrated assessment have developed, but they mainly focus on the interplay between simulated greenhouse gas emissions and a simplified development of the climate system; interaction with the biosphere are largely ignored (Tol, 2005). But the interface of human action and the natural system needs to be extended beyond greenhouse gas emissions and temperature responses. A global integrated modeling framework, combing state-of-the-art economy and environmental models is required to appropriately address the joint effects of global climate change.

The most direct impact of humans on their natural surrounding is the use of land for agriculture, forestry, settlement or recreation. Changes in the land use directly influence the terrestrial environment. They govern a large part of greenhouse gas emissions: 10-30% of the current total anthropogenic emissions of CO2 are estimated to be caused by land-use conversion (IPCC, 2001). They influence nutrient, organic carbon and water cycles. They determine landscape design, have an impact on biodiversity and may even alter the albedo. On the other hand, land-use changes affect the social and economic environment. The use of land determines the economic revenue of land-intensive productions. Food security depends on efficient and sustainable use of the available land. Current as well as past land use shapes the social and environmental surrounding of people. Finally, land-use decisions are triggered by environmental properties and motivated by socio-economic drivers, building a vital feedback loop in the interaction between human societies and the natural environment. Thus, to establish a dynamic interface between models of the economy and the biosphere a land-use model gives the ideal link.

1.2 Global land-use modeling

Many important drivers and consequences of land-use change are of global extent. Land-use changes and environmental impacts are often spatially and temporally disjoint (Krausmann, 2004) but interlinked by means of international trade. For these reasons, some of the important impacts and processes of land-use changes need to be addressed on a global scale. Global approaches are still rare, though, for reasons of poor data availability and since many important drivers of land-use decisions, such as land suitability are varying on a rather fine spatial scale.

Current approaches to simulate global land-use changes still tend to over-emphasize either the geographic or the economic aspect and neglect their mutual 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. Allocation decisions are based either on empirical-statistical evidence (e.g. in the family of CLUE models (*Conversion of Land Use and its Effects*), see e.g. (Veldkamp & Fresco, 1996; Kok & Veldkamp, 2001)) or are formulated as decision rules, based on case studies and common sense (e.g. in *Syndromes* (Petschel-Held *et al.*, 1999) and in the *dynamic simulation model of land-use changes in Sudano-sahelian countries of Africa* (SALU) (Stephenne & Lambin, 2001a; Stephenne & Lambin, 2001b)). In both cases the projections are based rather on observed behavior than on underlying economic motivations. This limits their projection horizon and their capability to represent the impact of market interactions, such as economic competition among different land-intensive sectors.

In economic models, land is usually implemented as an input in the production of land-intensive commodities. The models are designed to study impacts on the market and on greenhouse gas emissions of land-using sectors rather than on land-use allocation. The *International Model for Policy Analysis of Agricultural Commodities and Trade* (IMPACT) (Rosengrant *et al.*, 2002), the *World Agricultural Trade Simulation Model* (WATSIM) (Kuhn, 2003) and the *Global Trade Analysis Project, Energy - Land* model (GTAPE-L) (Burniaux, 2002; Burniaux & Lee, 2003) are prominent examples. These models are based on economic motivations, qualifying them for long-term predictions and a dynamic representation of market impacts. Their limitation mainly manifests in the representation of land. Land is treated as homogeneous and space-less, ignoring biophysical characteristics and spatial interactions.

There is a trend in both communities to improve their work by introducing the respective missing aspect into their tools. Global economic models seek to improve their representation of land by dividing the land into different classes, based on geographic assessment. The *Future Agricultural Resources Model* (FARM) (Darwin *et al.*, 1995; Darwin *et al.*, 1996) was one of the first to use the so-called *Agro-Ecological Zone* methodology. According to the dominant climatic and biophysical characteristics, land is subdivided into different classes, reflecting the suitability for and productivity of different uses. Even though this improves the representation of environmental impacts on the economy, still the location of changes and reverse effects on the environment are not simulated.

Global geographic approaches commonly aim to improve their economic rational by introducing economic properties – such as demand – as boundary conditions. In the *Integrated Model to Assess the Global Environment* (IMAGE) (Alcamo *et al.*, 1994; Zuidema *et al.*, 1994; RIVM, 2001) the *Land Cover Model* (an allocation tool based on cellular automata) allocates the commodity demands – calculated by the *Agricultural Economy Model* (Strengers, 2001) – according to land potential on a 0.5×0.5 grid. However, the economic demand module is theoretically weak as trade and market interactions are not dynamically represented. Within the EURURALIS project this weakness was addressed by coupling the IMAGE model to GTAPEM (Hsin *et al.*, 2004), a version of the standard GTAP model (Hertel, 1997), which has an extended agricultural sector. Crop yields and a feed conversion factor, determined by IMAGE are exchanged with production of food and animal products and a management factor (describing the management induced yield changes) as calculated by GTAPEM (van Meijl *et al.*, 2006). The advantage of coupling the two comprehensive models lies in detail and comprehensiveness of process representation. Moreover, this is one of the few approaches, where a feedback between economy and vegetation is at least partly realized. However, the land allocation tool of the coupled framework is still based on empirically estimated rules according to land potential, largely ignoring economic motivations of allocation decisions.

1.3 Objectives and methodology

The aim of this thesis is to develop a global agricultural land-use model, which combines the essential biophysical as a well as economic aspects of agricultural land-use decisions within its land allocation algorithm. The objective is to design a coupling tool to establish a dynamic interface of economy and vegetation in an integrated modeling framework. This is the first approach that offers such a dynamic link for global comprehensive economy and vegetation and crop-growth models in an integrated framework.

Economic profit maximization under risk aversion is used as the basis to derive the cropland allocation algorithm in which crop yields enter as a spatial explicit decision factor. This establishes an interface to map the different temporal and spatial resolutions and concepts of economy and vegetation modeling. Crop prices and crop yields from comprehensive models of the corresponding disciplines are used in their original resolutions. The representation of the land-allocation decisions benefits from the detailed representation of processes in the specialized models. The crop patterns simulated by the land-use model on the spatial resolution of the vegetation model can be directly fed back to determine the land cover in the vegetation model. Aggregated to the regional resolution of the economy model the crop pattern fixes the land endowment for the different crop productions. By exchanging these data in each time-step, the feedback-loop of economy and biosphere can be dynamically represented.

The philosophy of this work is to keep the land-use algorithm as simple as possible in order to avoid the dependency on detailed input data or large computer facilities. Following Einstein, the model is not simpler as possible. Undocumented in this thesis, there was a range of models either too simple or too complicated. This approach is chosen to qualify the model for global application and a dynamic coupling to comprehensive state-of-the-art models of the respective disciplines. The objective is to provide a first approach towards a global integrated framework in order to asses the long-term impacts of global changes. Thus, in order to minimize the bias of long-term projections towards current or departed observed behavior patterns, past observations are solely used for the calibration process; the algorithm itself is derived from theoretical economic motivation instead of directly from past observed behavior.

1.4 Structure of the thesis

The thesis is structured along the development and different coupling-stages of the model. The next chapter sets the scene by reviewing the current state-of-the-art in large scale land-use modeling. Major achievements, deficits and potentials of existing continental to global scale land-use modeling approaches are identified by contrasting current knowledge on land-use change processes and its implementation in models. In order to reflect the current knowledge, summaries of the most important processes of global land-use change are given. Their drivers and consequences and the related feedbacks are outlined in order to study their implementation into current models. Selected land-use modeling approaches are introduced and discussed to sketch the current state-of-the-art. To compare the discussed modeling approaches and their applications, the integration of geographic and economic aspects are used as a guiding principle.

In chapter 3, the development and evaluation of the KLUM model (*Kleines Land Use Model*) is described. An analytical as well as a numerical evaluation of the derived land allocation algorithm is performed in order to guarantee basic functionality and to assess the capabilities and limits of the model. Illustrative future scenarios are used to demonstrate the relevance of land-use changes for economic climate impact estimations. By means of reference scenarios, the importance of the integrated approach within the model is highlighted.

The coupling of KLUM to the global general equilibrium model GTAP-EFL, which is an extended version of the Global Trade Analysis Project model GTAP (Hertel, 1997) is presented in chapter 4. The coupling procedure and related conceptual problems and their handling are outlined and discussed. As the convergence of the two models in the coupled framework turned out to be a problem, a convergence test is performed in order to guarantee the consistency of the results. Again, illustrative future scenarios are used to test the integrity of the coupled system. The effect and relevance of the coupling for the climate impact estimates are assessed by means of uncoupled reference simulations.

In chapter 5 the implementation of KLUM into the dynamic global vegetation model (DGVM) LPJ-C (Lund-Potsdam-Jena model for crops (Criscuolo *et al.*, 2005)) is described. LPJ-C is an expanded version of the standard LPJ model (Sitch *et al.*, 2003) with an added crop growth compartment. The coupling is evaluated by comparing model results with past observations of crop patterns for Europe. A feasibility study for the European area is performed by applying two different IPCC climate change scenarios to the coupled framework and assess the resulting impacts. Again uncoupled reference simulations are used to highlight the relevance and impact of the coupling on the results.

Chapter 6 summarizes, concludes and outlines the areas that warrant further research.

2.1 Introduction

[1] Land use[2] is a crucial link between human activities and the natural environment. Large parts of the terrestrial land surface are used for agriculture, forestry, settlements and infrastructure. This has vast effects on the natural environment. Land use is the most important factor influencing biodiversity at the global scale (Sala *et al.*, 2000). Global biogeochemical cycles (McGuire *et al.*, 2001), freshwater availability (Rosegrant *et al.*, 2002) and climate (Brovkin *et al.*, 1999) are influenced by land use. Closing the feedback loop, land use itself is strongly determined by environmental conditions. Climate (Mendelsohn & Dinar, 1999) and soil quality affect land-use decisions. For example, they strongly influence the suitability of land for specific crops and thus affect agricultural and biomass production (Wolf *et al.*, 2003).

Given the importance of land use, it is essential to understand how land-use patterns evolve and why. Land-use models are needed to analyze the complex structure of linkages and feedbacks and to determine the relevance of drivers. They are used to project how much land is used where and for what purpose under different boundary conditions, supporting the analysis of drivers and processes as well as land-use and policy decisions. Based on this, we define land-use model as a tool to compute the change of area allocated to at least one specific land-use type.

The importance of land-use models is reflected in the increasing emergence of different modeling approaches and applications. Existing reviews try to structure this abundance by focusing on specific types of land-use changes (e.g. intensification, deforestation), specific modeling concepts (e.g. trade models) or by the development of classification systems. Irwin & Geoghegan (2001) classify models according to their degree of spatial explicitness and economic rationale. In a similar, but more elaborated approach, Briassoulis (2000) applies the criterion of modeling tradition in order to distinguish statistical/econometric, spatial interaction, optimization and integrated models (defining integration in terms of consideration of "the interactions, relationships, and linkages between two or more components of a spatial system"). This resembles the approach of Lambin *et al.* (2000) (and also Veldkamp & Lambin (2001)) who evaluate models concerning to their ability to reproduce and predict intensification processes. They classify models as stochastic, empirical-statistical, optimization, dynamic/process-based and, again, integrated approaches where integrated refers to a combination of the other categories. Agarwal *et al.* (2002) compare different approaches to deal with scale and complexity of time, space and human decision-making. Verburg *et al.* (2004) apply six different criteria, e.g. cross-scale dynamics, driving forces, spatial interaction, and level of integration, Li *et al.* (2002) add cross-sectoral integration, feedbacks, extreme events, and autonomous adaptation. Angelsen & Kaimowitz (1999) provide a meta-analysis of 140 economic-based deforestation models. Van Tongeren *et al.* (2001), and similarly Balkhausen & Banse (2004) focus on global agricultural trade models.

In this review, we focus on the state-of-the-art in continental to global land-use modeling. Global land-use modeling approaches are scarce, although the global scale is important for several reasons: First, many important drivers and consequences of land-use change are of global extent and it is desirable to consider them in a consistent

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[1] This chapter is based on (Heistermann *et al.*, 2006)

[2] We define land-use as the "total of arrangement, activities and inputs that people undertake in a certain land cover type" while "land cover is the observed physical and biological cover of the earths land, as vegetation or man-made features" (FAO & UNEP, 1999)

global framework. Secondly, specific processes interlink locations and regions all over the globe: e.g. international trade shifts land requirements from one world region to another, adjacent regions compete for water resources. Furthermore, land-use changes and environmental impacts are often spatially and temporally disjoint (Krausmann, 2004) and thus have to be addressed on an appropriate scale. We focus on land-use models of continental to global scale because these demand specific methodologies that are different from smaller-scale approaches: on the one hand, strategies have to be developed to cope with data limitations. On the other hand, scaling issues have to be addressed appropriately (Veldkamp & Lambin, 2001): processes that are important at smaller scales such as individual decisions by local land users cannot be modeled explicitly on large scales, but their outcome has to be somehow reflected. Abstracting local land-use decision-making to explain regional or global processes has to be seen as a major challenge for large-scale land-use modeling. Potential problems in this context are e.g. discussed by Lambin & Geist (2003) and Geist & Lambin (2004).

Our objective is to provide an overview of land-use modeling approaches at the continental to global scale and to identify major achievements, deficits and potentials of existing land-use models at this scale. We do this by contrasting current knowledge on land-use change processes and the implementation of this knowledge in current models. In order to reflect the current knowledge, we first summarize the most important processes of global land-use change and their drivers and consequences as well as the related feedbacks (Section 2.2). To study the implementation of drivers, consequences and feedbacks into current models, we review existing land-use modeling approaches in Section 2.3. We restrict our scope to modeling approaches that are implemented as computer models, excluding purely mathematical models as well as spreadsheet and accounting approaches. Based on the insights of Sections 2.2 (What is known about land-use change?), Section 2.3 (How is this knowledge implemented in global models?) Section 2.4 identifies the major achievements, deficits and potentials in global land-use modeling, Section 2.5 concludes.

For the review of modeling approaches, we take the integration of geographic and economic approaches as a guiding principle. In our understanding, geographic models allocate exogenous area or commodity demand on "suitable locations", where suitability is based on local characteristics and spatial interaction. In contrast, economic land-use models base the allocation of land on supply and demand of land-intensive commodities, which are both computed endogenously. With integrated we refer to the combination of (i) economic analysis of world markets and policies in order to quantify demand and supply of land-intensive commodities and (ii) the actual allocation of land use to locations based on geographic analysis. Note that we use the term "integrated" in a more narrow sense than e.g. IPCC (2001) or Parson & Fisher-Vanden (1997) in defining Integrated Assessment and also different from Briassoulis (2000) and Lambin *et al.* (2000).

2.2 Processes, drivers and consequences of land-use change

Processes, drivers and consequences of land-use change are intimately linked with each other in many ways (Briassoulis, 2000). Here, we provide a short overview only to facilitate the evaluation of modeling approaches. More detailed reviews can be found in Meyer & Turner II (1994) and Dolman *et al.* (2003). Globally significant land-use change processes include changes in forest cover - mainly in terms of deforestation (Houghton, 1999; FAO, 2003) - and changes in agricultural areas and management

(Geist & Lambin, 2002). Changes in urban areas are of minor importance with respect to spatial extent (Grübler, 1994), although they influence global land-use change through rural-urban linkage (Clark, 1998; Delgado, 2003).

Land-use change[3] is driven by a variety of factors, both environmental and societal, which are also scale-dependant, since changes in the spatial arrangement of land use might be undetected if the resolution of analysis is too coarse or if the extent is too small. Thus, our focus on the continental to global scale has direct implications for the selection of drivers.

Concerning the natural environment, climate (Ogallo *et al.*, 2000), freshwater availability (FAO, 1997; Rosegrant *et al.*, 2002) and soil affect land suitability and thus land-use patterns and are impacted by land-use decisions at the same time (Duxbury *et al.*, 1993; Saiko & Zonn, 2000; van der Veen & Otter, 2001; House *et al.*, 2002; Zaitchik *et al.*, 2002; Lal, 2003). Various characteristics of societies such as their cultural background (Rockwell, 1994), wealth (income) and lifestyle shape the demand for land-intensive commodities (Delgado, 2003). They are also modulated by land use as resources may be limited and typical commodities may be substituted by others. In this respect, the global context is especially important, as local and regional demands can be met in spatially disjoint regions by international trade (Dore *et al.*, 1997; Lofdahl, 1998).

Besides shaping demand, the societal setting also determines land management (Campbell *et al.*, 2000; Müller, 2004) and political decisions (e.g. policy intervention in developed countries and development projects in frontier regions of developing countries (Pfaff, 1999; Batistella, 2001)). Other factors include for instance land tenure regimes, the access to markets, governance and law enforcement. Such factors are known to play a decisive role in local and regional land-use change studies (Angelsen & Kaimowitz, 1999; Geist & Lambin, 2001; Geist & Lambin, 2004). However, their impact on large-scale land-use change is unexplored so far.

2.3 Land-use models

In the following, we will discuss not only different models but also different versions or applications of the same model (as for e.g. the IMAGE model, the CLUE model and different versions of GTAP). We do this to catch the different methodological insights to the issue of continental to global land-use modeling, e.g. by coupling the models to other models instead of using them as a standalone model. On the other hand, we deliberately excluded some global- to continental-scale models[4] from this review, because they do not provide additional methodological insights compared to models already considered in the review.

Our review of land-use models and their applications (see table (2.1)) is structured in three parts. We start with representatives of geographic models. Second, macro scale economic models and their relation to land issues are discussed. And third, we provide an inventory of integrated models. Note that the structures to present geographic and economic approaches differ fundamentally (see table (2.2)): for existing economic models on the global scale, land is not in the focus of interest, but was introduced mainly in order to facilitate an assessment of environmental problems such as climate change. Thus, we discuss the models along general economic modeling

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[3] A driver of land-use change causes in our definition either a change in the total area allocated to a specific land-use type or a change in spatial distribution of land-use types.

[4] Such as, e.g. in EPPA (Babiker *et al.*, 2001) and AIM (Matsuoka *et al.*, 1995).

concepts and strategies to introduce land and land-use dynamics. In contrast, the reviewed geographic models focus on the process of land-use change itself. Thus, we show the key mechanisms to simulate this process, structured by the common approach of empirical-statistical vs. rule/process-based (see e.g. Lambin *et al.* (2000) and Veldkamp & Lambin (2001)): Empirical-statistical models locate land-cover changes by applying multivariate regression techniques to relate historical land-use changes to spatial characteristics and other potential drivers. In contrast, rule/process-based models imitate processes and often address the interaction of components forming a system (Lambin *et al.*, 2000).

2.3.1 Geographic land-use models

Spatially explicit modeling is applied in many disciplines, including both natural and social sciences. However, analyzing the spatial determinants of land use is at the core of geographic science. Geographic land-use studies are mainly concerned with the properties of land, its suitability for different land-use types and its location. Promoted by the introduction of remote sensing and Geographic Information Systems, the application of simulation models boosted, but mostly on local to regional scales. In the following, we will concentrate on geographic models available on large spatial scales.

Empirical-statistical

The CLUE model framework (Veldkamp & Fresco, 1996) was applied and adjusted to several regional case studies, of which two are on the sub-continental scale: for China (Verburg *et al.*, 1999a) and the Neotropics/Tropical Latin America (Wassenaar *et al.*, 2005). The underlying assumption of the CLUE framework is that observed spatial relations between land-use types and potential explanatory factors represent currently active processes and remain valid in the future. The quantitative relationship between observed land-use distribution and spatial variables is derived by means of multiple regression. For this reason, the CLUE model is generally referred to as an empirical-statistical model. Nonetheless, statistical analysis is supplemented by a set of transition rules, which additionally control the competition between land-use types. Land-use changes are driven by estimates of national-scale area demands.

The two CLUE applications pursue different objectives and different strategies to deal with scale problems. CLUE-China follows a multi-scale allocation procedure. Regression analysis on the coarse resolution (96x96 km2) is assumed to reveal general relationships between land use and its determining factors over the whole study region, while finer assessments (32x32 km2) are to capture variability within regions and landscapes (for details see Verburg *et al.* (1999b)).

CLUE-Neotropics focuses on the identification of deforestation hotspots caused by the expansion of pasture and cropland in the Neotropics. It is assumed that the statistical relationship between grid-based explanatory variables and the actual land-use distribution might differ between different socio-economic and agro-ecological settings. Therefore, separate regression relations are established for defined sub-regions with assumed homogeneous conditions. These sub-regions are derived by intersecting the Farming Systems Map for Latin America and the Caribbean (Dixon *et al.*, 2001) with administrative boundaries.

In total, the CLUE approach reflects the complexity of land-use change by applying a broad range of spatial suitability factors. Particularly, it accounts for spatial interaction processes and thus for the dynamic behavior of suitability patterns. This im-

Tab. 2.1. ***Land-use models covered in this review:*** *Overview*

Modeling Framework	**Literature**	**Temporal resolution and coverage**	**Spatial resolution and coverage**	**Main mechanism**	**Motivation**	**Classification**
CLUE-China	Verburg *et al.* (1999b; 1999a)	1-year steps; 1990-2010	*Multi-scale*: (China): 96x96 km grid; 32x32 km grid; subgrid; National level (China)	Observed spatial relations are assumed to represent currently active processes; allocation of area demands based on preference maps (generated through regression analysis)	Assessing the spatial impact of national scale demand trends on the spatial distribution of land-use types	Geographic (empirical-statistical)
CLUE-Neotropics (based on CLUE-S)	Wassenaar *et al.* (2005)(based on Verburg *et al.* (2002))	1-year steps; 1990-2010	*Multi-scale*: (Neotropics): national level, farming systems sub-units, 3x3km; Sub-continental (Neotropics)	see CLUE-China; additionally enhanced spectrum of location factors; using spatial sub-units for regression analysis based on Farming Systems Map	Identifying deforestation hotspots due to the expansion of pasture and cropland	Geographic (empirical-statistical)
SALU	Stephenne & Lambin (2001b; 2001a)	1-year steps; 1961-1997	*Multi scale*: (Sahel); country level; 2.5lat/3.75lon grid; Sub-continental(Sahel zone)	Rule-based representation of the causal chain typical for land-use change in the Sahel zone: transition from extensive to intensive use triggered by land scarcity thresholds	Reconstructing past land cover changes for Sudano-Sahelian countries as input for GCMs	Geographic (rule-/process-based)
Syndromes	Cassel-Gintz & Petschel-Held (2000)	no explicit representation of time	5 min. lon/lat ; Global	Not a land-use model in a strict sense; rather maps present and future susceptibility towards specific land-use changes, in this case deforestation; based on fuzzy-logic	Identifying hotspots with high disposition for current and future deforestation	Geographic (rule-/process-based)
AgLU	Sands & Leimbach (2003)	15-year steps; 1990-2095	11 regions; Global	Partial equilibrium; land share proportional to economic return of the land; joint probability distribution function for yield	Simulate land-use changes & corresponding GHG emissions to feed into integrated modeling framework	Economic

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Land-use models covered in this review: Overview, continued

Modeling Framework	**Literature**	**Temporal resolution and coverage**	**Spatial resolution and coverage**	**Main mechanism**	**Motivation**	**Classification**
FASOM[5]	McCarl (2004); Adams *et al.* (2005)	5-year steps; 2000-2100	*Multi-scale*: 11 US regions (broken down into 63 for agriculture), 28 international regions (for trade), National (USA)	Partial equilibrium; non-linear mathematical programming; endogenous modeling of management; competition of forestry and agricultural sector for land	Studying impacts of policies, technical change, global change on agricultural and forestry sector	Economic
IMPACT[5]	Rosegrant *et al.* (2002)	Comparative static; 1997-2020	36 regions; Global	Partial equilibrium	Analyze the world food situation	Economic
G-cubed (Agriculture)	McKibbin & Wang (1998)	1-year step; 1993-2070	12 regions; Global	General equilibrium + macroeconomic behavior	Exploring the impact of international and domestic stocks like trade liberalization on US agriculture	Economic
GTAPE-L	Burniaux (2002)	Comparative static; baseyear 1997	5 regions; Global	General equilibrium + transition matrix, accounting for the history of land	Exemplify the incorporation of land/land use in GTAP; assessing GHG mitigation policies with focus on land-use impacts	Economic
Global Timber Market Model	Sohngen *et al.* (1999)	1-year steps; 1990-2140	10 regions; Global	Partial equilibrium; welfare optimization with perfect foresight	Studying the impact of set-aside policies and future timber demand on forest structure and cover, timber markets and supply	Economic
GTAPEM	Hsin *et al.* (2004)	comparative static; 2001-2020	7 regions; Global	General equilibrium + refined transformation structure for agricultural land + substitution possibility among primary and intermediate inputs	Improve the representation of the agricultural market in GTAP	Economic

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[5] For FASOM and IMPACT a great variety of different model versions are around. The stated properties might vary between the different versions.

Land-use models covered in this review: Overview, continued

Modeling Framework	**Literature**	**Temporal resolution and coverage**	**Spatial resolution and coverage**	**Main mechanism**	**Motivation**	**Classification**
WATSIM	Kuhn (2003)	1-year steps; 2000-2010	9 regions; Global	Partial equilibrium + quasi dynamic price expectations	Study the influence of trade policy on agricultural sector	Economic
IMAGE Land Cover Module	Alcamo *et al.* (1998)	1-year steps; 1970-2100	*Multi-scale*: 13 world regions, 0.5 grid, subgrid; Global	”Agricultural Economy Model” calculates demands for agricultural and forest products; land is allocated on a rule-based preference ranking	Integrated assessment of Global Change	Integrated
IFPSIM-EPIC	Tan & Shibasaki (2003); Tan *et al.* (2003)	not documented	*Multi-scale*: 32 world regions, 0.1 grid level; Global	Land productivity (based on EPIC) and crop prices (based on IFPSIM) are assumed to be major determinants of agricultural land-use change	Analyzing the relation between land-use patterns and global agricultural markets	Integrated
ACCELERATES	Rounsevell *et al.* (2003)	2000-2050; comparative static	*Multi-scale*: countries; soil mapping units, NUTS2; Europe	Calculation of optimal crop combinations on spatial sub-units; assumes generic farmers who maximize their long term profits	Assess the vulnerability of European managed ecosystems to environmental change	Integrated
GTAP-LEI/IMAGE coupling within EURURALIS	Klijn *et al.* (2005)	10-year steps; 2001-2030	*Multi-scale*: national level, sub-national level (NUTS2), grid level; Global with focus on EU15	Coupling of a variant of GTAPEM (GTAP-LEI) and IMAGE using management factor and food & feed production to update IMAGE and yield and livestock conversion factor to modify production in GTAP-LEI	Assessing impact of different policies on land use in Europe	Integrated
LUC China	Fischer & Sun (2001); Hubacek & Sun (2001)	so far quasi static; 1992-2025	*Multi-scale*: 8 economic regions, 5x5 km grid; National (China)	Combining AEZ assessment, extended I/O-analysis and scenario analysis to develop a spatially explicit production function for a CGE model	Assessing alternative policy scenarios	Integrated
FARM	Darwin *et al.* (1996)	comparative static; 1990-2090	*Multi-scale*: 8 regions, 0.5 lon/lat ; Global	General equilibrium + land and water as primary inputs (imperfectly substitutable) in all sectors; AEZs defined by spatial explicit environmental data	Integrating explicit land and water assessment into CGE, environmental focus on climate change	Integrated

plies the potential of changing suitability patterns to drive land-use changes. Through its multi-scale approach, CLUE is able to reveal scale-dependencies for the drivers of land-use change (Veldkamp & Lambin, 2001). It would thus be desirable to test this methodology for the global scale, too. However, the methodology of regression analysis does not allow for a deeper understanding of the interaction of drivers and processes, which is also acknowledged by the authors. This makes long-term projections difficult, since the empirical relationships cannot necessarily be assumed constant over long time periods. On the other hand, the empirical analysis might help in identifying key processes and thus facilitate the understanding of system behavior.

Rule-based/process-based

The SALU model (Stephenne & Lambin, 2001b) is a zero-dimensional model designed to capture the characteristic processes in the Sahel Zone. It has been applied by Stephenne & Lambin (2001a) in order to simulate spatially explicit changes of land use on very coarse resolution (by dividing the Sahel region into eight independent sub-regions). It provides an appealingly simple approach to endogenously deal with agricultural intensification by focusing on a sequence of agricultural land-use changes not only typical for the Sahelian region: agricultural expansion at the most extensive technological level is followed by agricultural intensification once a land threshold is reached. Exogenous drivers are human and livestock population, rainfall variability and cereal imports. In Sahelian agriculture, intensification mainly takes place as a shortening of the fallow cycle, compensated by additional inputs such as labor and fertilizer, and by the expansion of cropland at the cost of extensive pasture (nomadic grazing). This results in the sedentarization of livestock and overgrazing of remaining pastures (desertification).

This causal chain was recognized as also being relevant in other poorly developed parts of the world (Cassel-Gintz *et al.*, 1997), which inspired the syndromes concept. Petschel-Held *et al.* (1999) define a syndrome of global change as a ”non-sustainable pattern of civilization-nature interaction”. Cassel-Gintz & Petschel-Held (2000) applied the syndromes concept to provide global-scale patterns for the occurrence of and susceptibility to deforestation. Deforestation in this context is seen as a consequence of the *Overexploitation Syndrome*, the *Sahel Syndrome* and the *Dust-Bowl Syndrome* (the last two are described in Cassel-Gintz *et al.* (1997) and Ldeke *et al.* (1999)). The syndromes approach does not simulate the area allocated to specific land-use types and thus does not fit into our general definition of land-use models. Instead, it provides spatially explicit information about present and future susceptibility towards specific land-use changes. For this purpose, it distinguishes between current intensity of a syndrome and future disposition towards a syndrome. Methodologically, it combines spatially explicit and quantitative data sets with qualitative reasoning by applying the concepts of fuzzy logic. The procedure also accounts for typical tandems and causal chains by considering that a high current intensity of one syndrome (e.g. the Overexploitation Syndrome) together with a high future disposition for another syndrome (e.g. the Sahel Syndrome) might promote deforestation. Thus, the syndromes approach provides information where specific land-use changes might occur. This could basically be integrated into a quantitative framework in order to model actual land-use changes.

Tab. 2.2. ***Selected properties of large-scale land-use models:*** *Double-headed arrows represent bidirectional feedbacks; single-headed arrows represent causal chains that lack a feedback.*

Modeling Framework	**Land use/cover types**	**Land-use change processes**	**Land-using Sectors**	**Land-using Commodities**	**International trade**	**Feedbacks/ causal chains**
CLUE-China	Cropland, forest, grassland/pasture, horticulture, urban, unused	De-/Reforestation, agricultural expansion/abandonment, urban growth	-	-	-	Spatial interaction enables dynamic preference maps
CLUE-Neotropics	Cropland, forest, grassland/pasture, shrub, unused	See CLUE-China	-	-	-	See CLUE-China
SALU	Cropland, forest, grassland/pasture, unused	Deforestation, agricultural expansion/abandonment, intensification	-	-	-	Land scarcity ⇒intensification ⇒ degradation ⇒ land scarcity
Syndromes	Forest, other	Deforestation	-	-	-	-
AgLU	-	De-/Reforestation, agricultural expansion/abandonment	Agriculture (crops, commercial biomass & livestock), forestry	3 agricultural (one each), 1 forestry	Unilateral	Land use ⇔ commodity prices climate ⇒ land use
FASOM	-	De-/Reforestation, agricultural expansion/abandonment, intensification/extensification	Agriculture (crops, biofuel & livestock), forestry	52 agricultural (24 crops, 2 biofuel, 26 livestock), 20 forestry	Unilateral	Climate ⇒ land use Land-use/management change ⇔ price and cost changes
IMPACT	-	Agricultural expansion/abandonment	Agriculture (crops and livestock)	16 (6 livestock, 10 crops)	Unilateral	Land use ⇔ commodity prices
G-cubed (Agriculture)	-	-	Agriculture (crops and livestock)	4 (3 crops, 1 livestock)	Bilateral	Land use ⇔ commodity prices
GTAPE-L	-	De-/Reforestation, agricultural expansion/abandonment urban growth	Agriculture (crops and livestock), Forestry, Others	3 agricultural (2 crops, 1 livestock) 1 forestry	Bilateral	Land use ⇔ commodity prices

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Selected properties of large-scale land-use models, continued

Modeling Framework	**Land use/cover types**	**Land-use change processes**	**Land-using Sectors**	**Land-using Commodities**	**International trade**	**Feedbacks/ causal chains**
Global Timber Market Model	-	Forest-management change	Forestry	1 forestry	No trade modeled	-
GTAPEM	-	Intensification/ Extensification	Agriculture (crops and livestock)	10 (8 crops, 2 livestock)	Bilateral	Land use ⇔ commodity prices
WATSIM	-	-	Agriculture (crops and livestock)	18 (12 crops, 6 livestock)	Bilateral	Land use ⇔ commodity prices
IMAGE Land Cover Module	Cropland, forest, pasture, urban, 14 biomes incl. forest	De-/Reforestation, agricultural expansion/abandonment, urban growth	Agriculture (crops and livestock), Forestry, Energy	7 food crops, 4 biofuel crops, grass and fodder, 1 forestry	Unilateral (based on self-sufficiency ratios)	Land use ⇔ climate, land scarcity ⇔ commodity demand
IFPSIM-EPIC	Agriculture	Agricultural expansion/abandonment	Agriculture	Not documented	Unilateral	Land use ⇔ commodity prices
ACCELERATES	Agriculture	Agricultural expansion/abandonment	-	12 crops	-	-
GTAP-LEI/IMAGE coupling within EURURALIS	Cropland, forest, pasture, urban, 14 biomes incl. forest	De-/Reforestation, agricultural expansion/abandonment, urban growth Intensification	Agriculture (crops and livestock)	10 (8 crops, 2 livestock)	Bilateral in GTAP-LEI, unilateral in IMAGE	Climate ⇔ Land use ⇔ commodity prices, production specification, land scarcity ⇔ yield, commodity demand, land price
LUC China	Cropland, grassland, forest	De-/Reforestation, agricultural expansion/abandonment, urban growth	Agriculture (crops and livestock) forestry, others	Not clearly documented	No international trade	Environmental conditions ⇒ future scenarios ⇒ production function specifications (theoretically ⇒ environment)
FARM	-	De-/Reforestation, agricultural expansion/abandonment, urban growth	Agriculture (crops and livestock), forestry, others	4 Agriculture (3 crops, 1 livestock), 1 forestry, 8 others	Bilateral	Climate ⇒ land use

2.3.2 Economic land-use models

Studies of land use and land-use changes have a long history in economic theory. Strictly speaking, (agricultural) land-use studies are the origin of economic science. However, the perception of land in mainstream economics has changed tremendously from the only source of "real" production (Physiocrats) to just another primary factor (neoclassical theory, Hubacek & van den Bergh (2002)). Considerations explicitly including land are now treated in specific economic sub-disciplines that are interested in the land-intensive sector such as Agricultural and Land Economics, Environmental and Resource Economics and, more recently, New Economic Geography.

In recent years, the rising interest in science-based assessment and treatment of environmental problems has created a new incentive to reintroduce land into standard economic models as a direct link between economy and environment. In the following, we are introducing models that are examples of the latter tendency. All of them include additional details in their land-use sectors to study the impact of environmental changes on future economic welfare. However, in a strict sense these are not land-use models. Except for the AgLU model (Sands & Leimbach, 2003), these models focus on changes in market structure for land-intensive goods or land-use emissions, but not on allocation of land.

Motivation and major characteristics of economic land-use models

Economic science deals with the optimal allocation of scarce resources under the assumption that profit or abstract properties such as welfare are maximized. The same focus applies to the land-use sectors. Market structures are analyzed to understand land-use decisions. This mainly limits the analysis to aspects expressible in monetary terms. Most global economic land-use models are equilibrium models, aiming to explain land allocation by demand-supply structures of the land-intensive sectors. The main mechanism is to equate demand and supply under certain exogenously defined constraints. Besides data tables of in- and output of all included commodities, the most important parameters are elasticities. These describe consumer preferences and the feasibility on the producer's side by determining the impact of input changes on output or input of other commodities. On the broadest level computable general equilibrium models and partial equilibrium models can be distinguished. In partial equilibrium models (PEM) only a subset of the markets is modeled with explicit demand and supply functions, whereas the remaining markets are parameterized (or ignored). An important implication of this approach is the assumption that the markets of interest are negligible for the rest of the economy, since feedbacks with other sectors are largely ignored. In computable general equilibrium models (CGE) all markets are modeled explicitly and are assumed to be in equilibrium in every timestep. These models are based on a very rigid theoretical framework, which guarantees market closure. All money-flows are traceable through the whole economy and the structure provides the emergence of feedback effects between sectors (for more detail on CGEs see Ginsburgh & Keyzer (1997) and Hertel (1999)).

Examples of partial equilibrium models are IMPACT (Rosengrant *et al.*, 2002) and WATSIM (Kuhn, 2003), modeling only the agricultural sector, the Global Timber Market Model (Sohngen *et al.*, 1999) describing the forestry sector, AgLU (Sands & Leimbach, 2003; Sands & Edmonds, 2004) and FASOM (McCarl, 2004; Adams *et al.*, 2005) which include both the agricultural and forestry sectors. The high resolution of the analyzed sector allows for an in-depth analysis of the respective markets or, due to its simpler market structure, an integration within an integrated modeling framework (as in the case of AgLU).

GTAPEM (Hsin *et al.*, 2004), GTAPE-L (Burniaux, 2002; Burniaux & Lee, 2003) and the G-cubed model[6] (McKibbin & Wang, 1998) are examples of CGEs. CGEs are often used to analyze the effects of changes in single sectors on the entire economy and vice versa. GTAPEM and GTAPE-L are used to analyze the economic impacts of greenhouse gas emissions and climate change. G-cubed was originally developed to study the impact of global environmental problems on the economy and later extended by inclusion of more detailed agricultural markets in the USA to assess the effects of trade liberalization. For more details on the PEM and CGE land-use models see van Tongeren *et al.* (2001) and Balkhausen & Banse (2004).

Economic land-use models differ in sectoral and regional resolution (see tables 2.1 and 2.2) and in the representation of trade and land. A realistic implementation of international trade is important to properly reproduce food and timber markets. The representation of trade in PEMs is often limited to raw or first-stage processed goods. This excludes processed food products, which account for an increasing share of the world market (van Tongeren *et al.*, 2001). More general, the main issue concerning international trade is whether goods are treated as homogenous or heterogeneous, distinguished by producer and origin. Assuming homogenous goods implies that neither bilateral trade flows nor intra-industrial trade can be represented appropriately. A common way to introduce bilateral trade is the Armington approach, where goods are differentiated according to their origin. More details on trade can be found in Hertel (1999) and van Tongeren *et al.* (2001).

In the next section, however, we concentrate on the supply side of land-intensive goods and the treatment of land in the different models since the focus of this paper lies on land allocation.

Land in economic models

In economic models, land is usually allocated according to its relative economic return under different uses. In CGEs, this is commonly achieved via a competitive market of land-intensive products. In G-cubed and GTAPEM land is only used for agricultural production, whereas GTAPE-L land is also used for forestry and a so-called "others" sector, interpreted as urban land. In PEMs, area is a direct function of own and cross prices and exogenous trends (as in IMPACT and WATSIM), or the result of an optimization of welfare and/or profit (as in the Global Timber Market Model and FASOM). In AgLU, the share of land for a certain use is proportional to its expected relative profit.

Management practices can be simulated by defining the production of land-intensive commodities as a function of primary factors such as land and labor, and intermediate inputs such as fertilizer and machinery. In order to lower parameter requirements,in CGEs intermediate inputs are commonly modeled as not substitutable to primary factors. This means e.g. that a decrease in land cannot be outbalanced by additional use of fertilizer, implying that intensification and disintensification cannot be represented endogenously (Hertel, 1999). Of the introduced CGEs, only GTAPEM explicitly models the substitution between intermediates and primary factors. Of the introduced PEMs, the Global Timber Market Model and FASOM endogenously simulate man-

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[6] G-cubed really is a mixture of CGE and a macroeconomic model. However, the implication for the agricultural sector is minor.

agement changes. FASOM optimizes over a discrete choice set of alternative management practices, whereas the Global Timber Market Model endogenously determines a management-intensity factor.

An important aspect for the treatment of land in the production process is the heterogeneity of land. The productivity of land can vary across products, management, regions and time. The main reasons for these differences are biophysical characteristics of land, such as climate and soil. A way of introducing heterogeneity into CGEs is to loosen the common assumption that land is perfectly substitutable towards an imperfect substitutability of land between different uses and sectors. In GTAPE-L the standard GTAP model (Hertel, 1997) is modified such that land is modeled as imperfectly substitutable between the different uses. GTAPEM refined this structure by adopting the land allocation structure of the policy evaluation model (OECD, 2003), distinguishing land in the production structure of the agricultural sector even further into miscellaneous agricultural land, rice and the group field crops and pastures. For these, three different elasticities of transformation are defined, reflecting that certain transformations are more inert than others. The disadvantage of such a non-linear treatment of land in the production functions of CGEs is that land cannot be measured in physical units of area but instead is measured in the value added to the production. This complicates the interpretation of the resulting land allocation.

In partial equilibrium models, land is commonly treated as homogenous. AgLU and FASOM are exceptions. AgLU assumes a non-linear yield distribution decreasing in land. This reflects the assumption that the most productive land is used first, whereas more and more unproductive land has to be utilized for further use, decreasing the average yield per hectare. By introducing a joint yield distribution function, where the yields of different uses are correlated, the conversion possibility from one use to another is characterized. Climate change and technological growth have been introduced by changing the yield distribution (Sands & Edmonds, 2004). FASOM distinguishes four different classes of land mainly based on the slope of land. For timberland, ownership is also a criterion influencing land suitability. Land-allocation changes are only allowed for non-public land. Here, industrial and non-industrial timberland is distinguished according to its production and conversion possibilities. Climate impacts have been studied by introducing externally estimated climate induced yield changes (Alig *et al.*, 2003). The so-called Agro-Ecological Zones (AEZ) methodology (Darwin *et al.*, 1995; Fischer *et al.*, 2002) different classes, which are defined by the dominant climatic and biophysical characteristics. This approach allows an inclusion of environmental changes as e.g. climate change by altering the distribution of land among the different classes. In GTAPE-L the inclusion of AEZ is designated, but not yet realized. An extended version of the GTAP database includes land-use and land cover data, allowing the definition of several AEZ (Lee *et al.*, 2005).

GTAPE-L captures another aspect of the land heterogeneity by introducing a so-called land transition matrix, tracking all land transformations among the sectors. This distinguishes land according to its history, which is quite unique in economic models. So far, however, the used transition matrix has entries solely for Europe and the USA for only two transformation processes each.

A further aspect of land, not yet touched by any of these models, is the geographic location. To properly introduce geographic location of land, the inclusion of space would be necessary. However, the required existence of an unique equilibrium in macro-economic equilibrium models prohibits the inclusion of increasing returns to scale. Without increasing returns to scale, the scale of production is not defined and thus production is distributed equally over space, hampering any notion of location (Jaeger & Tol, 2002). For a more technical discussion on the topic see Greenhut & Norman (1995a; 1995b; 1995c), Fujita *et al.* (1999), Surico (2002) and Puu (2003).

Dynamics in economic models

Land-use change is a highly dynamic process. Land-use decisions do not only depend on current and past uses, but also on future expectations - especially in slow producing sectors such as the forestry sector, where long-term planning is essential. In economics, comparative static (equilibriums that are independent of each other), recursive dynamic (previous equilibriums may influence subsequent ones) and fully dynamic (all equilibriums for all time-steps solved simultaneously) models are commonly distinguished.

The obvious drawback of comparative static models is that they are not capable of describing any kind of time path and forward-looking behavior. This makes these models rather inappropriate e.g. for detailed forestry studies, since this sector is governed by long-term decisions. GTAPEM and GTAPE-L are representatives of this group of models. In recursive dynamic models, forward-looking behavior can be implemented by assuming rational expectations based on past experience, as in WATSIM, where the economic agents expect that prices will not change. More often, however, time-dependent variables are updated exogenously. In IMPACT for example, income growth and population, as well as area- and yield growth trends are updated according to exogenous assessments.

In fully dynamic models the time path of variables is based on the assumption of an intertemporarily optimizing agent with perfect foresight. Like this, not only immediate welfare is optimized (as in recursive dynamic models) but also optimal welfare, defined over the whole period, is guaranteed. Apart from the tedious implementation and calibration of such models, their greatest deficit in respect to integrated modeling is the bi-directional notion of time, which hampers online coupling with other models. G-cubed, FASOM and the Global Timber Market Model are fully dynamic models with perfect foresight.

To appropriately model the forestry sector, the inclusion of future expectations is required, which excludes most of the CGEs. But even among the PEMs, agricultural models are more common than forestry models and very few model both sectors. AgLu and FASOM are such exceptions including both sectors in a dynamic fashion and modeling the market competition between them. FASOM simulates the competition for the land among the sectors via a perfectly competitive market. In AgLU land is distributed among forestry and agriculture proportionally to the respective expected economic return. Forward-looking behavior is implemented by equating only one future market at each timestep to determine the expected price for timber in the harvesting year.

2.3.3 Integrated land-use models

Both economic and geographic land-use models have strengths and weaknesses. Economic equilibrium models can consistently address demand, supply and trade via price mechanisms. They are limited in accounting for supply side constraints, in reflecting the impact of demand on actual land-use change processes and in representing behavior not related to price mechanisms. On the other hand, geographic models are strong in capturing the spatial determination of land use and in quantifying supply side constraints based on land resources. They are more flexible in describing the behavior leading to specific allocation patterns. However, they lack the potential to treat the interplay between supply, demand and trade endogenously. In the following, we will show a selection of models and model applications which try to make up for the deficits of the disciplinary approaches. For all of these models, this is done by coupling existing economic optimization models with existing tools for spatially explicit evaluation and allocation of land resources (except IMAGE and the IIASA LUC model for China which were rather developed from scratch). The discussed integrated models have different foci: while the IMAGE model, the coupled IFPSIM/EPIC system and the ACCELERATES framework rather focus on the spatially explicit allocation of land-use, the FARM model and the IIASA LUC China framework rather use spatially explicit evaluation of land resources in order to account for supply side constrains. The coupled GTAP-LEI/IMAGE system tries to reconcile these two foci within one framework.

The IMAGE model (Alcamo *et al.*, 1994; Zuidema *et al.*, 1994; RIVM, 2001) is a complex framework of dynamically coupled sub-models, providing an interlinked system of atmosphere, economy, land and ocean. The so-called Terrestrial Environment System (TES) deals with land-use and land-cover change. Within TES, the Agricultural Economy Model (Strengers, 2001) calculates per capita food demand, using "land-use intensities" as surrogates of food prices. Land-use intensities are the amount of land required to produce a unit of food product. Hill-shaped regional utility functions yield a utility value for a given diet. The maximization of the utility function to an optimal diet is constrained by a land budget. This is the area needed to produce food at preference levels, reduced by factors depending on income, average potential production and technology. Trade is introduced by exogenously prescribing self-sufficiency ratios for each of the 13 world regions. For timber demand, available forest area at a timestep is considered as surrogate for timber prices. Per capita timber demand is thus computed as a function of income and forest area. The Land Cover Model is based on a rule-based preference ranking of the grid cells and serves to allocate the commodity demands on a 0.5 longitude/latitude grid according to land potential. The assessment of land potential for agriculture takes into account neighborhood to other agricultural cells, potential productivity (based on AEZ methodology, (FAO, 1978)), distance to water bodies and human population density. A management factor accounts for discrepancies between potential and actual yield. If demand in a specific timestep cannot be satisfied by suitable land, this information is fed back to the Agricultural Economy Model where the available land budget is reduced by a scarcity factor and a new optimal demand vector is calculated (iterative procedure).

In total, the IMAGE model has several unique features. First, it is the only model which considers the feedback between land-use change and climate change in both directions. Second, information about land scarcity from the allocation module is fed back to the economic demand module for agricultural commodities. And finally, the competition between the important land-use/cover types is included (albeit simplified and quite ad hoc).

Another approach is applied by the land-use choice module (Tan *et al.*, 2003), which dynamically links the IFPSIM global partial equilibrium model (Oga & Yanagishima, 1996) to the EPIC model (Williams, 1995). This approach accounts for the agricultural sector only and has two major characteristics: (i) land-use decisions are based on price information provided from IFPSIM (ii) supply is not calculated within IFPSIM but results from the land-use and yield distribution of the previous time-step. The land-use choice module is a discrete logit choice model operating on a 0.1 grid: in an utility function it considers profit for a specific crop (derived from crop yields and prices) as well as a set of socio-economic variables (population density, accessibility). Crop yields are simulated by a global version of the EPIC model (Tan & Shibasaki, 2003). It should be noted that this approach has yet to be tested and is not applied so far. However, the implementation of a dynamic feedback between the global market of agricultural commodities and the price based decisions of local farmers would add an important aspect to endogenize market driven land-use decisions.

One objective of the ACCELERATES framework is to assess the change in agricultural land use on the European level, as a consequence of climate change and European policies (Rounsevell *et al.*, 2003; ACCELERATES, 2004). For this purpose, the SFARMOD farm model (Annetts & Audsley, 2002) determines the optimal crop combinations on spatial sub-units (which are based on soil mapping polygons). It emulates farmers' behavior to maximize their long-term profits within the constraints of their situation, taking account of uncertainty in prices and yields. The constraints (water-, temperature- and nitrogen-limited crop yields, sowing and maturity days and the number of workable days) are provided by the ROIMPEL model (Rounsevell, 1999). This is an agro-climatic, process-based simulation model, which is linked to GIS-based soil/terrain information and GCM-derived grid values of climate variables. Besides these constraints, the optimization procedure is driven by exogenously determined crop prices, the cost structure for management operations and historical variability in prices and yields. Altogether, this can be seen as a bottom-up procedure where the regional land-use distribution is a result of optimized local decisions (similar to the EPIC/IFPSIM framework). However, the degree of macro-economic integration is very low. The SFARMOD model is designed to better reflect farmers' decision making than a regression model would do, however, it might be too detailed to be adapted to the global scale.

An AEZ based approach to modify crop yields according to biophysical factors is applied by the FARM model (Darwin *et al.*, 1995; Darwin *et al.*, 1996). The comparative static CGE is based on GTAP, but includes land as primary input to all producing sectors and water as primary input for crops, livestock and services. Water as well as land is modeled as imperfectly substitutable between the sectors and allocated in a perfect competitive market. 6 different AEZs are distinguished according to the length of growing period, which is considered as an appropriate proxy for crop suitability. The impact of climate change on crop productivity is accounted for via a shift in the water endowments and the alteration of the distribution of land across the AEZs. The FARM model was one of the first economic models to use spatially explicit environmental datasets in order to distinguish different land classes and to include the effects of climate change on land allocation. The inclusion of water and its endogenous allocation is unique among CGEs.

The coupling of GTAP-LEI (a version of the GTAPEM) and the IMAGE model within the EURURALIS project (van Meijl *et al.*, 2006) aims at an even further integration. In GTAP-LEI, GATPEM has been extended by a more elaborate formulation of demand in the animal feed processing sector and by a land supply curve, representing the increase of land prices when land becomes scarce. In the coupled framework, GTAP-LEI replaces the Agricultural Economy Model (Strengers, 2001) of IMAGE. Total crop production, as calculated by GTAP-LEI, is interpreted as demand and allocated on grid level by IMAGE as described above. In GTAP-LEI yield is determined by an exogenous trend and by the impact of endogenous management changes, which are modeled as the substitution of primary and intermediate factors (see section 2.3.2). The exogenous trend is supplied by IMAGE, where changes in potential yield are modeled as a result of climate change and assumptions on technological progress. The impact of endogenous management change on yields (as modeled in GTAP-LEI) is fed back to IMAGE and used as the management factor described above. This is so far the only approach which couples a full-blown economic land-use model with a full-blown integrated assessment model. The advantage of coupling these models stands against the risk of producing redundancies and inconsistencies, as there is e.g. a land allocation mechanism in both models. As an additional part of the methodology applied within EURURALIS, the land-use patterns computed by the coupled IMAGE/GTAP-LEI models are disaggregated for Europe to a 1-km^2 grid using the CLUE model. Since this step is not influencing the integration of economic market analysis and the geographic assessment, we do not provide more detail on this.

The IIASA LUC model for China (Fischer & Sun, 2001; Hubacek & Sun, 2001) aims at a similar degree of integration, proposing a combination of an AEZ assessment, an input-output analysis and a CGE. The depth of the integration in this approach is remarkable - but it may also hamper its implementation which is still pending. The resulting CGE would not only exchange exogenous parameters with an environmental model but actually synthesize economic and geographic thinking within its theoretical foundation. Future land-use scenarios have been developed by using an extended input-output (I-O) model and spatially explicit measures of land productivity and land availability. An enhanced AEZ assessment model was utilized to provide these measures. By means of empirical estimation the agro-environmental characterization of a spatially explicit production function can be gained from the produced scenarios. This function as well as the projected I-O tables are proposed as the basis of a not yet developed CGE model.

2.4 Major achievements, deficits and potentials

Choosing and classifying relevant modeling approaches is an ambivalent task. On the one hand our focus on land allocation models excluded some approaches towards an integration of economy and environment. E.g. Perez-Garcia *et al.* (2002) is one of the few integrated approaches, where forestry is in the focus of interest. Land and land allocation, however, is not explicitly modeled (or at least not documented). On the other hand, the differentiation into integrated or economic models was not always straightforward. FASOM, for instance, uses EPIC simulation results to include some environmental impacts for agricultural production; GTAPE-L offers a certain degree of integration by including land history, which is a spatial aspect of land; and AgLU not only accounts for certain biophysical characteristics of land, it also is a tool designed to establish a feedback loop with the integrated assessment of greenhouse gas emission reduction strategies model ICLIPS (Toth *et al.*, 2003). We decided, however, that the economic basis or the contribution to the economic aspect in these models outweighs the integration aspect. Finally, our aim was to choose a set of representative approaches characterizing the current state-of-the-art. This excludes some modeling approaches which are very similar to the selected ones – though we do not claim these approaches to be irrelevant or less useful.

Each type of land-use change of major importance at the global scale (see section 2.2) is covered in at least one of the reviewed models. However, not all models include all major types of land use and are – especially in the case of economic land-use models – rarely designed to primarily model land-use changes and the related processes. At the global scale, the EURURALIS framework still addresses land-use changes most explicitly while most global economic models consider land only as an input to production; Syndromes is not intended to allocate land and IFPSIM/EPIC only considers major crops. On the continental scale all the selected models or model applications have an explicit focus on land-use changes (e.g. CLUE, SALU, ACCELERATES, LUC China, FASOM). Concerning FASOM, CLUE-China and CLUE-Neotropics, the applied methodologies could basically be applied to the global scale, too, while ACCELERATES and SALU are rather tailored for regional application and LUC China is not even fully applied within China.

Concerning the reviewed geographic models land is commonly modeled as a carrier of ecosystem goods such as crops or timber. They focus on the dynamics 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 (CLUE) or formulated as decision rules, based on case studies and common sense (Syndromes, SALU). Empirical-statistical approaches can account for a large choice of suitability factors, spatial interaction and thus dynamic suitability patterns. Beyond, they can explicitly account for scaling issues by performing the statistical analysis on different scales and thus revealing scale dependencies of drivers. Rule-based models are based on a certain understanding of land-use decisions. Thus, they are able to reproduce causal chains (e.g. explaining intensification and degradation in the Sahel Zone), the synergetic interaction of drivers and processes or the impact of governance (Syndromes approach). However, upscaling of decision-making processes is not explicitly discussed in the reviewed modeling studies (see below).

In contrast to the geographic approach, economic models focus on drivers of land-use change on the demand side. They represent trade, which shifts land requirements from one world region to another. However, the actual impact of trade on land-use changes is rarely explicitly addressed in the reviewed studies. Land is usually implemented as a constraint in the production of land-intensive commodities and the focus is more on the outcome of land use than on its allocation. The economic competition of different uses within one sector is represented endogenously. The simulation of management changes as well as the competition among different sectors are supported by the structure of such models but seldom actually included. This strongly limits the representation of land-use change processes (see table 2.2). Land is often utilized in one sector only, but even the inclusion in several sectors does not guaranty a proper representation of land-use changes. FASOM and AgLU are the only economic models that provide an appropriate framework to model competition and resulting changes between two land-intensive sectors (agricultural and forestry). But as partial equilibrium models (and FASOM additionally due to its regional focus) their representation of global trade is limited. The inclusion of management changes or technological progress is hampered by the models' internal representation of the production process (see section 2.3.2) and data availability. The inclusion of a production structure allowing for substitution of primary and intermediate goods in GTAPEM, however, is a first step towards a better representation of management changes in CGEs.

Current integrated land-use modeling approaches provide evidence that some of the intrinsic deficits of geographic and economic approaches can be overcome to a certain extent. Several strategies of integration can be identified: Some studies employ a land allocation scheme, which uses demand or price information from economic models to update land-use patterns in detailed environmental models (ACCELERATES, IFPSIM/EPIC). The land-use choice model in the EPIC/IFPSIM approach determines the supply side outside the trade model and thus allows for a dynamic feedback between land-use patterns and global demand. IMAGE computes demand internally without external price information. It is the only model which accounts for the feedback of land scarcity on demand although the economic demand module is theoretically weak, as also admitted by its author (Strengers, 2001).

The coupling of IMAGE and GTAP-LEI in the EURURALIS project aims to improve on this weakness. It enhances the economic foundation of the IMAGE land-use model and improves the representation of land supply in the GTAPEM version. Beyond, a first step towards a representation of the relation between land scarcity and intensification has been achieved by implementing a land supply curve in GTAP-LEI. The remaining integrated approaches focus on improving the representation of the supply side within a general equilibrium approach by considering spatially explicit environmental information: In FARM, different land types are distinguished and evaluated (AEZ methodology) whereas in IIASA LUC China the entire supply function is planned to result from environmental and economic analysis. In addition, these models also refine their land allocation mechanism. FARM for instance, includes land in all sectors, enabling competition for land[7]. Additionally, a competitive market for water is implemented, which improves the representation of management.

Despite these achievements, the full potential of integrating economic and geographic approaches seems not to be fully explored, yet. For the coupling of different modeling approaches as in the EURURALIS framework, the advantages of process detail stands against the risk of inconsistencies and redundancies. The reviewed models lack endogenous approaches to determine whether food demand will be satisfied rather by expansion of agricultural area than by the intensification. Beyond a more detailed representation of agricultural management, including the feedback with soil and water is also needed. Irreversibly degraded soil or the exhaustion of freshwater resources are major constraints on future land use, that have not yet been tackled sufficiently by any land-use model. Admittedly, there are several models which consider irrigation and FARM even includes the competition for water among water-intensive sectors. However, water resources are not bound to environmental processes in these models, so that no feedback loop is established. Yet, it should be critically assessed whether all these issues can be addressed within one single framework or rather in related scenario storylines.

Other methodological challenges are still ahead. The problems associated with different time-scales and dynamics are often ignored. Environmental studies operate on large temporal scales of up to 100 years or even more. Studies including human behavior are designed to operate on smaller time scales, typically ten to twenty years. Predominantly, the parameterization of human reactions and behavior makes long-term projections highly uncertain, as it is mainly based on current or past observations. This also holds true for the economic approach which uses motivation based theory instead of observed behavior. The same applies for spatial scales. How can human behavior be described at a continental to global scale? Individual behavior cannot be simply transferred to the continental or global scale. Empirical geographic models implicitly account for scale effects by using regression techniques on the scale of application. Rule-based models have more problems in generalizing local behavioral patterns to large scales. The Syndromes approach suggests a way to base such up-scaling tasks on large-scale process patterns (called Syndromes). However, large-scale modeling studies rarely explicitly address the scaling issue. There could be some potential in combining empirical-statistical approaches with rule- or process-based settings in order to explore

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[7] But the comparative static setting prohibits an inclusion of planning based on foresight for the forestry sector.

scale dependencies of drivers while employing explicit process description.

Moreover, the interpretation of parameters can differ tremendously among different models. An obvious example is the representation of land in CGEs as value added for the production. A simple mapping from dollars to hectares will not be sufficient to account for the different underlying interpretations.

2.5 Conclusions

Global land-use modeling approaches are scarce in spite of the importance of the global context for land-use change processes. Current approaches to continental and global land-use modeling bear the potential to model land-use dynamics but still need further efforts since land-use is rarely the primary objective of these models. The strength of economic models is the description and quantification of drivers on the demand side. They provide a structure to represent the competition among different sectors, changes in management and technology and demand shifts due to trade or policy interventions. Geographic models explicitly address information on fundamental constraints on the supply side and allow for path dependence by tracking inventories of land and their productive potential. Beyond, they are flexible and open to integrate socio-economic drivers and their synergies (Geist & Lambin, 2002; Lambin *et al.*, 2003). Integrated models seek to combine these strengths in order to make up for the intrinsic deficits of both approaches and thus to assess the feedbacks between terrestrial environment and global economy.

But despite the achievements and individual strengths of the selected modeling approaches, core problems of global land-use modeling have not yet been resolved. Scaling issues are rarely explicitly discussed. Models need to address several land-use types and their drivers simultaneously in order to account for their competition. Beyond, the inclusion of feedbacks between society and environment are needed and call for further efforts in integrated land-use modeling. For a new generation of integrated large-scale land-use models, a transparent structure would be desirable which clearly employs the discussed advantages of both geographic and economic modeling concepts within one consistent framework and avoids redundancies. For this purpose, suitable access points for model coupling need to be identified.

3.1 Introduction

[1]

The global agricultural land-use model *Kleines*[2] *Land Use Model* (KLUM) was developed to establish a link between biosphere and economy in a global integrated assessment model (IAM). We reduce the risk of redundancies and inconsistencies by *outsourcing* the allocation process from the specified models. At the same time we benefit from the comprehensive process representation of the specialized models by utilizing their output for the allocation process. Feeding back the allocation pattern to the larger models completes the feedback loop of economy and vegetation.

The *Agricultural and Land Use model* AgLU (Sands & Leimbach, 2003) and the *land-use choice module* (Tan *et al.*, 2003) follow a similar approach. The AgLU model, a global partial equilibrium model, is used to provide a feedback between the climate and economic core models of the *Integrated Assessment of Climate Protection Strategies model* (ICLIPS) (Toth *et al.*, 2003). Based on gross domestic product (GDP) and carbon price of the economic model, land is allocated according to proportional revenues of the possible uses. The resulting carbon emissions are calculated and fed back to the climate model. Biophysical characteristics of land are considered via a joint probability distribution, which determines the productivity of land. Still, this approach neither links land-use changes to specific geographic locations nor does the probabilistic representation of land productivities capture the true variability of land within a region or allows for a feedback to a vegetation model.

In KLUM we represent geographic location and biophysical heterogeneity of land by using spatially explicit yields, as can be calculated by a vegetation model. The allocation is determined on the resolution of the biophysical input, which enables the direct utilization of the results in the vegetation model.

The *land-use choice module* is a more geographically based approach to couple the global partial equilibrium model IFPSIM (*International food policy simulation model*) (Oga & Yanagishima, 1996) to the crop growth model EPIC (*Erosion Productivity Impact Calculator*) (Williams, 1995). Based on potential yields, as calculated by EPIC, and market prices as determined by IFPSIM, the utility of different land-use alternatives is calculated. From this, the land-use choice module chooses the set of alternatives with highest utility by means of logistic regression. The resulting allocation is calculated on a 0.1×0.1 grid resolution. Analogously to common geographic approaches, the regression technique allows for an easy inclusion of other than monetary factors influencing land-use patterns but the ad-hoc definition of utility limits the long term predictability.

We derive the allocation algorithm of KLUM from a maximization of profit. This explicit motivationally based approach ensures validity also for long-term predictions. The model replaces the internal allocation mechanism of the economy model that solely provides the equilibrium prices for the optimization. The aggregated allocation can be fed back as production-specific land endowments to the economy model.

In the next section we present the model structure, outline the underlying assumptions and describe the implementation. We document the calibration and a thorough evaluation of the model performance by means of analytical as well as numerical analysis in section 3.3. Section 3.4 discusses the impacts of climate change on economic growth. Section 3.5 concludes.

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[1] This chapter is based on (Ronneberger *et al.*, 2005)

[2] German for *small*, avoiding the acronym *SLUM*

Tab. 3.1. ***Crop aggregation of KLUM*** *adopted from (GTAP, 2005).*

Aggregate	Description
Paddy rice	Paddy rice
Wheat	Wheat
Cereal grains nec	Maize(corn), Barley, Rye, Oats, Other cereals
Vegetables and fruits	vegetables, Roots and Tubers, Fruits, Nuts
Oil seeds	Oil seeds and oleaginous fruits
Sugar cane/beets	Plants used for sugar manufacturing
Plant-based fibres	Raw vegetable materials used in textiles
Crops nec	Flowers, vegetable-, fruit- and flower-seeds, spice crops etc.

3.2 The model

KLUM runs on an exchangeable spatial resolution and with 1 year time-steps. The model is designed for global coverage and a possible time horizon of several centuries. The allocation decision in each spatial unit is independent of adjacent units and preceding allocations. The size of the spatial units is flexible. Decisive parameters for the allocation process are crop prices and crop yields. Calibrated parameters are cost parameters and risk aversion. For this study, the model is calibrated according to data of FAOSTAT (FAOSTAT, 2004) and World Development Indicators (World Bank, 2003) to reproduce the allocation of 8 different crop aggregates (see table 3.1) for 181 countries (see appendix table A1).

3.2.1 Purpose and basic underlying assumptions

We design the model as an interface between biosphere and economy in a global integrated assessment model. Its objective is to reproduce the key-dynamics of land allocation to capture the characteristic trait of the feedback-loop between vegetation and economy. Thus, the focus lies on simplicity and efficiency in order to guarantee computational feasibility as well as to facilitate structural interpretation of model performance and results.

In the developed model the maximization of achievable profit is assumed to be the driving motivation underlying the simulated land-use decisions. In each spatial unit we calculate and maximize the expected profit per hectare in order to determine the most profitable allocation in this unit. Thereby risk aversion as well as decreasing return to scales are assumed. The sum of these separately optimized allocations is equivalent to the global optimal allocation.

By using spatially explicit yields in the optimization, the results account for geographic and biophysical heterogeneity of land and assure the spatial detail required for a data exchange with a global state-of-the-art vegetation model. Prices instead are defined on a regional level, to enable coupling to a state-of-the-art world trade model.

3.2.2 Implementation

We derive the allocation algorithm by maximizing the achievable profit per hectare of each spatial unit. Profit per hectare π of one grid-cell is represented by:

$$\pi = \sum_{k=1}^{n} \left(p_k \alpha_k l_k - \tilde{c_k} \bar{L} l_k^2\right) - \gamma \mathbb{V}\mathrm{ar}\left[\sum_{k=1}^{n} (p_k \alpha_k l_k - \tilde{c_k} \bar{L} l_k^2\right] \tag{3.1}$$

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 area $\bar{L}$ 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

$$\begin{aligned} C \quad &= \quad \sum_{k=1}^{n} \mathcal{C}_k(L_k) L_k \\ \text{with} \quad & \mathcal{C}_k(L_k) = \tilde{c_k} L_k, \forall k \in \{i \ldots n\} \\ \Rightarrow \quad C \quad &= \sum_{k=1}^{n} \tilde{c_k} L_k^2 \end{aligned} \tag{3.2}$$

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

The second term of equation (3.1) represents the risk aversion of the representative land-owner and implicitly accounts for crop rotation considerations. To minimize the risk, monoculture is avoided in favor of a crop mix. We quantify the perception of riskiness by the temporal variance of the expected profit, weighted by a risk aversion factor $0 < \gamma < 1$.

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

$$\max[\pi] \qquad \text{s.t.} \textstyle\sum_{k=1}^{n} l_k \leq 1$$

$$\Rightarrow l_i = \frac{\frac{1}{2} \sum_k \frac{\beta_i - \beta_k}{c_k + \gamma \sigma_k^2} + 1}{\sum_k \frac{c_i + \gamma \sigma_i^2}{c_k + \gamma \sigma_k^2}} \tag{3.3}$$

where for convenience $\beta_k = p_k \alpha_k$ displaces the profitability of crop k, $\sigma_k^2 = \mathbb{V}\mathrm{ar}[\beta_k]$ displaces the respective variance; $c_k = \tilde{c_k} \bar{L}$. The temporal variability of total costs is assumed to be negligible compared to the variability of prices and productivities.

In the applied model, cost parameters and risk aversion factors for each spatial unit are determined by calibration. Variances are calculated from five preceding time-steps (initialized by the variance of the complete time-horizon). For the allocation decision of time t, prices and yields of time $t-1$ are assumed to be decisive. Prices are defined for world-regions in 5-year time-steps, reflecting the temporal and spatial structure of common state-of-the-art global trade models. Yields are defined on a finer spatial resolution and on a yearly basis, analogous to common state-of-the-art vegetation models. To account for memory effects, we calculate the decisive yield $\alpha(t)$ as the weighted mean of the actual yield $\tilde{\alpha(t)}$ of the respective and the decisive yield of the preceding time-step $\alpha(t-1)$:

$$\alpha(t) = (1-m)\alpha(t-1) + m\tilde{\alpha}(t) \tag{3.4}$$

In current simulations, m is set to 0.3 since this gives a reasonable fit to the data. We apply the same relationship to the variance.

To avoid negative allocation, negative shares are set to zero and the allocation process is repeated for the remaining crops.

3.3 Calibration and validation

As emphasized we base the derived algorithm on the assumption that profit maximization is a predominant driver of human induced land-use changes. Below, we assess the validity of this assumption as well as the suitability of the developed model for its purpose.

As a first step, we inspect the derived algorithm analytically concerning its mathematical dynamics to assure the agreement with intuitive logic. Secondly, we evaluate the model numerically to assess the performance and to identify potentials and limits. For this, we use the calibrated model to reproduce historical land-use changes and compare the results to observed data with respect to temporal and spatial accordance.

3.3.1 Algorithm dynamics

The major drivers of land allocation in KLUM are profitability β and its variability σ^2 of each crop. In the following we study the impact of changes in a crop's β_i and σ_i^2 on its own land-share l_i and the remaining crop's land-shares $l_{j\neq i}$. Solving the respective derivatives of the allocation algorithm equation (3.2.2) yields:

$$\frac{\partial l_i}{\partial \beta_i} = \frac{1}{2}\frac{\sum_{k\neq i}\frac{1}{c_k+\gamma\sigma_k^2}}{\sum_k \frac{c_i+\gamma\sigma_i^2}{c_k+\gamma\sigma_k^2}} > 0 \tag{3.5}$$

$$\frac{\partial l_i}{\partial \sigma_i^2} = -l_i\gamma\frac{\sum_{k\neq i}\frac{1}{c_k+\gamma\sigma_k^2}}{\sum_k \frac{c_i+\gamma\sigma_i^2}{c_k+\gamma\sigma_k^2}} < 0 \tag{3.6}$$

$$\frac{\partial l_j}{\partial \beta_i} = -\frac{1}{2}\frac{\frac{1}{c_j+\gamma\sigma_j^2}}{\sum_k \frac{c_i+\gamma\sigma_i^2}{c_k+\gamma\sigma_k^2}} < 0 \tag{3.7}$$

$$\frac{\partial l_j}{\partial \sigma_i^2} = l_i\gamma\frac{\frac{1}{c_j+\gamma\sigma_j^2}}{\sum_k \frac{c_i+\gamma\sigma_i^2}{c_k+\gamma\sigma_k^2}} > 0 \tag{3.8}$$

The results are intuitive: an increase in a crop's profitability increases its own and decreases the remaining land-shares; an increase in a crop's riskiness decreases its own and increases the remaining land-shares. The total amount of changes naturally adds up to zero.

Furthermore, interpreting σ^2 as a measure of riskiness, the results show that the effect of riskiness depends on the allocated share. $\tilde{l} = \frac{1}{2\gamma}$ marks the share of land for which a change in riskiness and a change in profitability are valued equally; for shares greater than $\tilde{l}$, riskiness is valued higher than profitability whereas for shares lower than $\tilde{l}$, profitability is more influential than the risk. Restricting the risk aversion parameter to be $0 < \gamma < 1 \Rightarrow \tilde{l} \geq 0.5$ implies that at most riskiness dominates for crops planted at more than half of total cropland. Calibration exercises with unbound γ support the assumed restriction. Only for very few countries (mostly countries with problematic data) risk aversion exceeds the value of one. For calibration with bound γ for nearly all countries $\gamma < 0.5 \Rightarrow \tilde{l} > 1$, implying that in the respective country profitability always dominates risk (see Appendix Table A2).

Tab. 3.2. ***World regions in KLUM.*** *The affiliation of countries is presented in the Appendix table A1*

Acronym	Name
USA	USA
CAN	Canada
WEU	Western Europe
JPK	Japan and South Korea
ANZ	Australia and New Zealand
CEE	Central and Eastern Europe
FSU	Former Soviet Union
MDE	Middle East
CAM	Central America
SAM	South America
SAA	South Asia
SEA	Southeast Asia
CHI	China, North Korea & Mongolia
MAF	Mediterranean Africa
SSA	Subsaharan Africa
SIS	Small Island States

3.3.2 Numerical assessment

For the numerical assessment we use the available data of FAOSTAT (FAOSTAT, 2004) for the time-period 1966-1997 on yield, prices and harvested area. We aggregate the data of 134 available crops to 8 aggregates[3] (as shown in table 3.1). Prices are standardized to constant US dollars based on year 1995, by means of GDP data and inflation-rates as documented in the World Development Indicators (World Bank, 2003)[4]. Excluding countries with data for less than 6 years or 1 crop-aggregate leaves us with 163 countries for the validation exercise (see Appendix table A1). For the moment, we prefer the national resolution to a sub-national grid-resolution as consistent data are readily available. Prices are aggregated to 16 regions (see table 3.2) and averaged over 5 years in order to imitate the coupling situation in most IAMs, where economic trade models commonly operate on coarse spatial and temporal resolution. We assume the total available land $\bar{L}$ to stay constant during the simulation.

For every country we use the first half of the available time-period for calibrating risk-aversion and cost parameters. For this, we minimize the sum of mean-squared-errors of model results and observed data [5]. In the optimization the cost parameters $\tilde{c}_{k\in\{1\dots n\}}$ are restricted to be positive and in the same order of magnitude as the revenues $\beta_{k\in\{1\dots n\}}L_{k\in\{1\dots n\}}$ (notation as in preceding equations); risk aversion parameters are forced to satisfy $0 < \gamma < 1$. In order to study the performance of the calibrated model we use the data of the second half of the available time-period to calculate the evolving crop-pattern and we compare the results to the observed data on harvested area.

Figure 3.1 - 3.3 highlight different aspects of the model performance. In Figure 3.1

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[3] In the aggregation yields are weighted by the crop's area share and prices by the crop's production share

[4] For some countries WDI (2001) had to be used due to the local currencies choice in the FAOSTAT data

[5] The optimization was done by means of the LSQNONLIN function of MATLAB 6.1

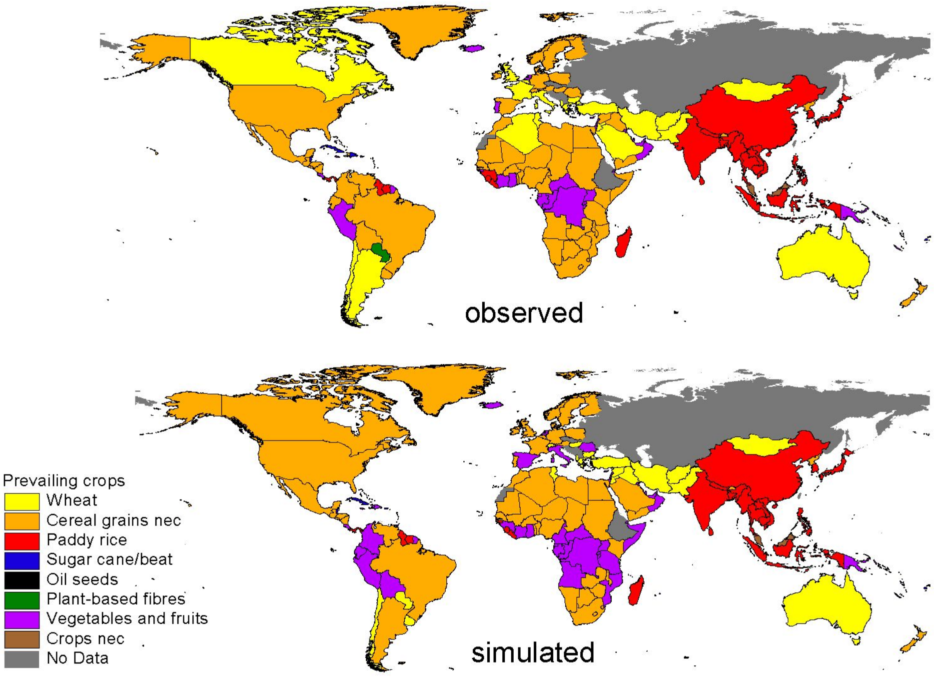

Fig. 3.1. ***Reproduction of crop pattern with KLUM:*** *The pattern of prevailing crops for the validation period.*

we compare the global pattern of prevailing crops for modeled and observed allocation. 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.

In order to evaluate the sub-national patterns, we depict the percentage deviation of simulated from observed means in figure 3.2 and the correlation of model results and observed data in figure 3.3. We do this for *wheat*, *rice* and *cereal grains nec*. The agreements 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 emphazise units where the depicted crop exceeds a certain relevance with respect to the cultivated area share, we highlight countries with a respective land share $l \geq 0.1$.

All figures show a good agreement 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 3.3. Falsely predicted prevailing crops are often a result of similar price and/or yield structure for two crops (such as wheat and cereal grains for price and yield in Canada, or the price of cereal grains and vegetables and fruits in Subsaharan 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.

Tab. 3.3. ***Number and percentage of false predicted prevailing crops per region.*** *Observed and simulated prevailing crop on regional aggregation.*

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	2/5	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/beets	Sugar cane/beets
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

Even though the highest percentage of failure occurs in Canada, Western Europe and South America, only for Canada and Mediterranean Africa the prevailing crop has been falsely predicted on a regional aggregation of area and area shares.

The deviations of simulated and observed means 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 *cereal grains nec* are in best agreement 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. 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 comparably bad reproduction 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.

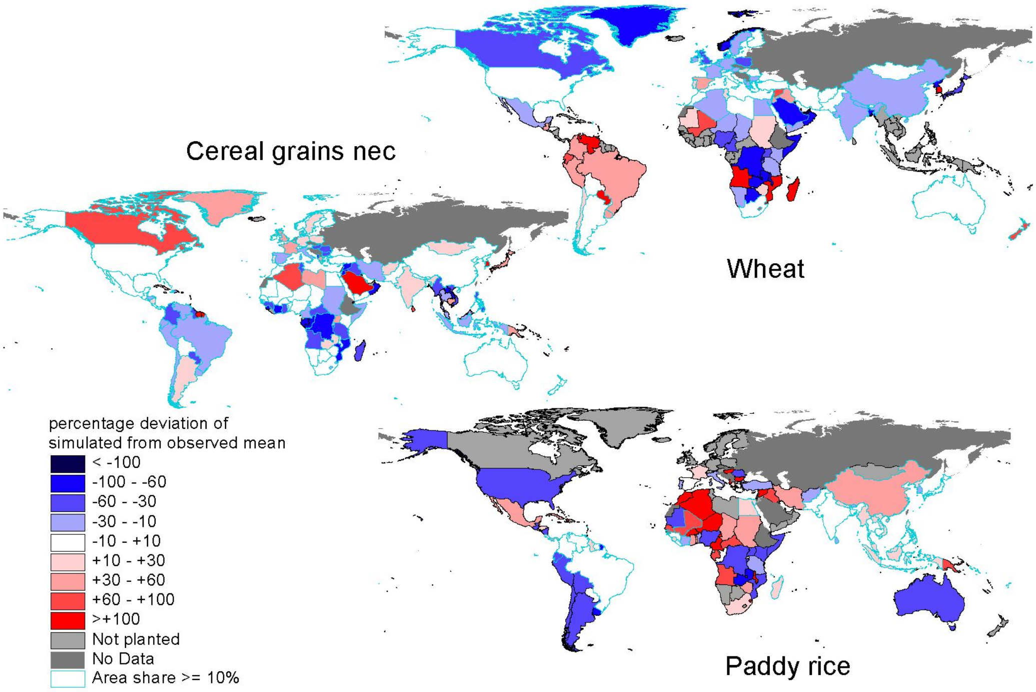

Fig. 3.2. ***Spatial exactness of KLUM:*** *The percentage deviation of mean area share over the validation period for model results to observed data.*

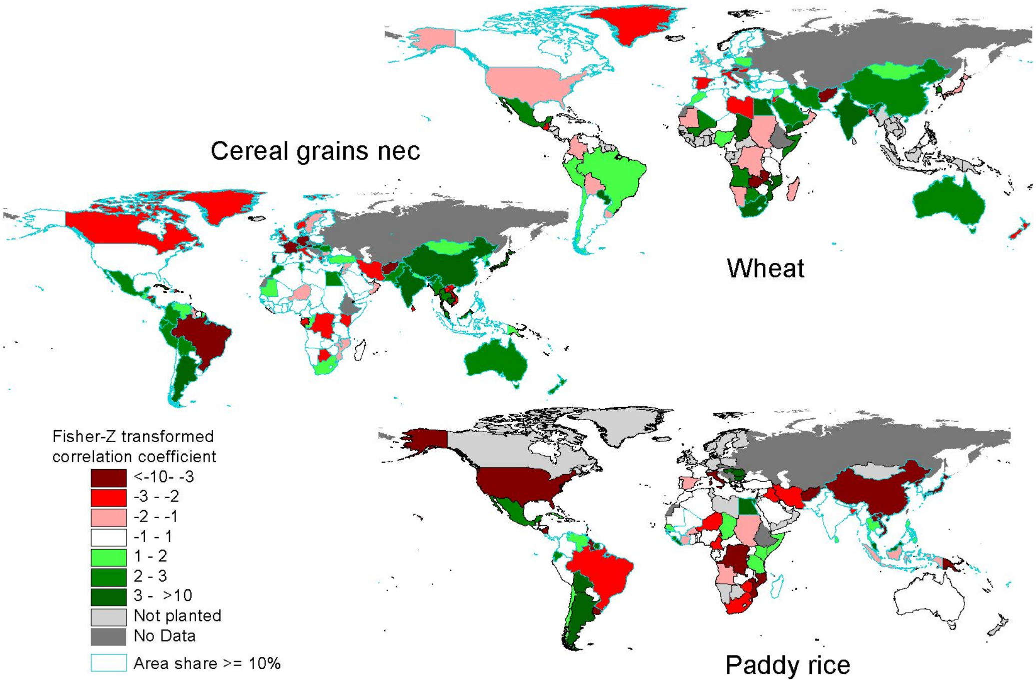

Fig. 3.3. ***Temporal accuracy of KLUM:*** *The Fisher-Z-transformed correlation coefficients over the validation period of model results and observed data.*

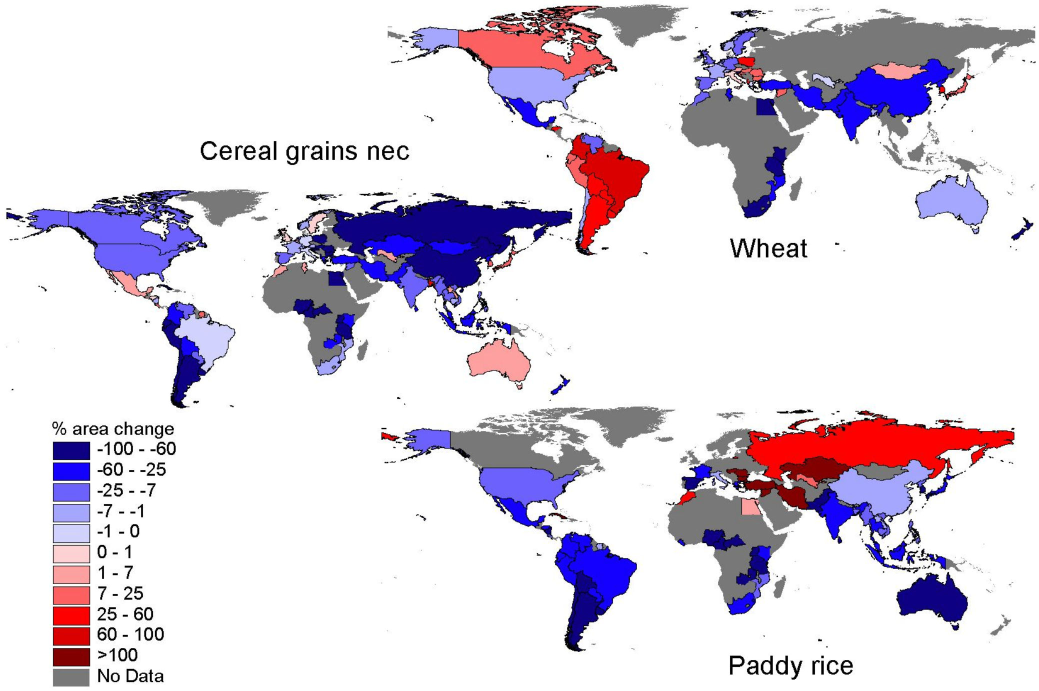

Fig. 3.4. ***Climate change impacts on crop allocation:*** *Percentage area changes 1997-2050 for wheat, cereal grains nec and paddy rice under climate change (scenario A).*

3.4 Future scenarios

Tan & Shibasaki (2003) present 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) [6] to quantify monthly minimum and maximum temperature and precipitation. Adaptation is taken into account by means of changing planting dates.

Based on their estimates for 2050 we determine yields under climate change of *wheat*, *paddy rice* and *cereal grains nec*, to simulate the effects of a changing climate on crop allocation (see appendix Figure B1). We use the predictions of yield changes in maize to adjust the yields of *cereal grains nec*, 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. Prices are assumed to develop with a continued linear trend, as estimated from past years. For future simulations the model is calibrated with the complete dataset, which also includes countries with less than 6 years of data (see Appendix Table A1). We determine the optimal allocation of the 8 crop aggregates for the 83 countries used in Tan and Shibasaki's study for 1997 and 2050. In the simulation the variances σ^2 are set to the temporal average of past variances. Potential productions of the remaining crop aggregates are assumed to continue on the level of 1997.

In Figure 3.4, we depict the resulting area changes for *wheat*, *paddy rice* and *cereal*

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[6] Provided by the Intergovernmental Panel on Climate Change (IPCC)

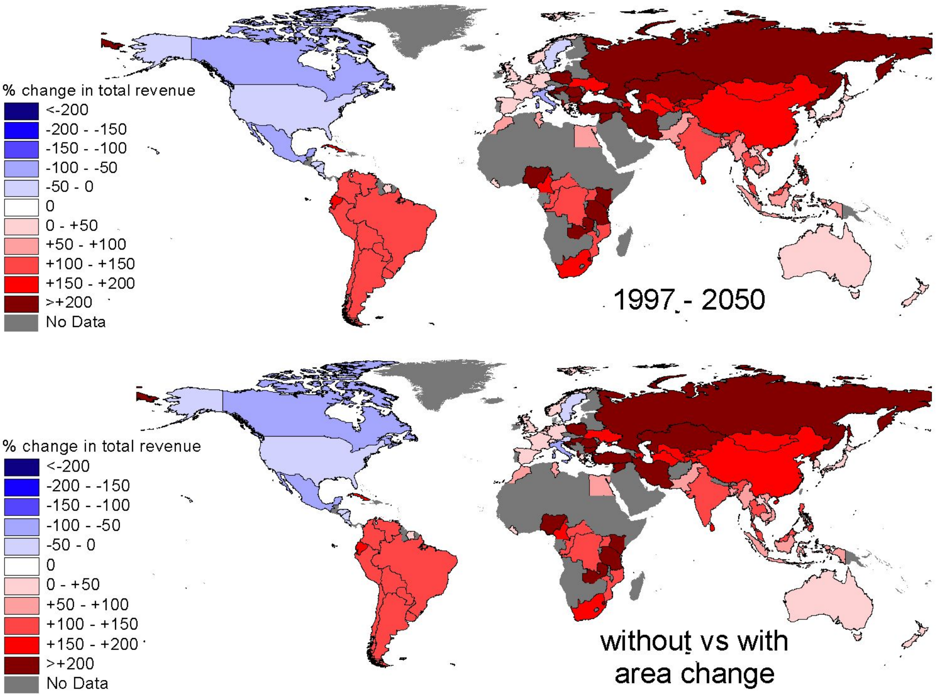

Fig. 3.5. ***Impacts of climate change on revenue:****(scenario A); The upper graph shows the percentage changes in revenue under consideration of the simulated area changes. The lower picture shows the differences in of revenue changes with and without the consideration of area changes expressed in percentage of the former.*

grains nec. They show a decline in area for all 3 depicted crops in nearly all countries. Especially the area in *cereal grain* production is reduced up to complete disappearance in countries of the Eastern Block. The greatest increase of area for *cereal grains nec* can be found in Bangladesh and Japan by 20–32% . For *wheat*, area increases in South America by up to 75% , in Canada by some 7% and in Eastern Europe and Japan by up to 55% . The greatest decrease of area for *wheat* takes place in Africa, where it partly vanishes to zero and South Asia/China, where the area is nearly halved. Also *paddy rice* cultivation tends to disappear in Africa and is strongly reduced in most other countries. However, in the Former Soviet Union and the Middle East, the area share of *paddy rice* increases by up to 150–166% (Hungary and Kazakhstan). The area changes reflect a shift in total global crop production away from major crops, such as wheat, paddy rice, other cereal grains and also oil seeds towards minor crops, such as vegetables and fruits, sugar crops, plant based fibres and other crops (see Table 3.4).

To quantify the impacts of climate change, Figure 3.5 shows changes in total revenue from crop production from 1997 to 2050. Strong gains govern the overall picture. Only North America, Sweden and Italy show losses in revenue. They range from -12% to -73% (USA and Italy). Greatest gains are achieved on the Asian continent where for many countries revenue is up to quintuple. Some African and South American countries double or even triple there revenue of crop production. Compared to this, the gains of about 2–50% obtained in Western Europe are modest.

To highlight the importance of land-use changes for these impact assessments, the lower graph of Figure 3.5 presents percentage differences of revenue changes calculated

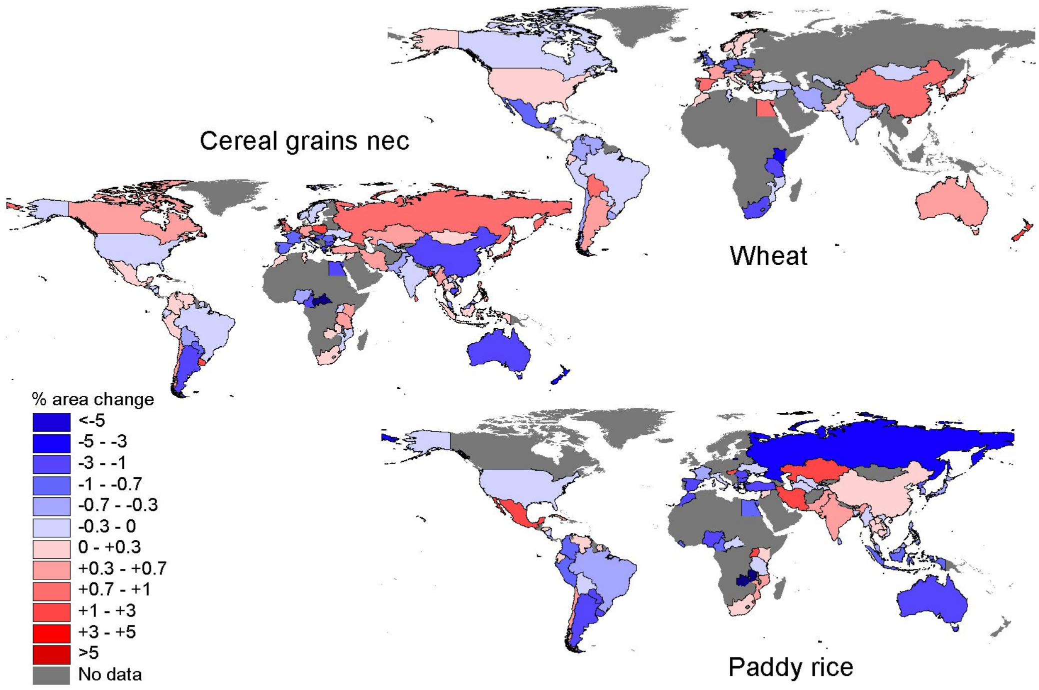

Fig. 3.6. ***Impacts of climate change, ignoring price changes:*** *Percentage area changes 1997-2050 for wheat, cereal grains nec and paddy rice under climate change (scenario B). Blue depicts negative, red positive changes*

with and without area changes. For nearly all the simulated countries losses are overestimated whereas gains are underestimated, if area changes are not taken into account. For a few, mainly wealthy countries, such as Switzerland, Germany, Japan and Australia, even the sign of predicted revenue change varies between the different estimates (depicted in dark blue). For all these countries estimates including area changes predict a gain in revenue, whereas the estimates ignoring area changes predict losses.

Besides the simulation of future allocation under climate change (scenario A), we run two diagnostic scenarios - one, in which only yields change and prices are kept constant (scenario B) and one, where prices change and yields are kept constant (scenario C). The results of the diagnostic scenarios show that the projected effects of climate change on revenue and crop allocation are mainly a result of the assumed price changes. They exceed the applied yield changes by up to 2 orders of magnitude. Figure 3.6 shows the changes in area for scenario B as a reference for the impact of the yield changes. The pattern considerably differs from the predictions of scenario A (Figure 3.4). Besides the fact that for all depicted crops area changes are naturally much lower than in scenario A, additionally the occurrence of decreases and increases is more balanced. However, decreases still dominate the picture. For *paddy rice*, we find most increases of area in the Asian countries but also in some South African and South and North American countries. Besides in Zambia, the decrease of area is largest in the Russian Federation, which stands in strong contrast to the predicted increase in area for this country in scenario A. For *wheat* the production in Europe and South America seems to move from the north to the south (Scandinavia is an exception). Whereas the greatest decrease in area for *wheat* can be seen in the South African countries, great increase

Tab. 3.4. ***Impacts of climate change on crop production:*** *Percentage change of total global production 1997-2050 for all simulated crops (scenario A).*

Crop	Scenario A %	Scenario B %
Wheat	-12.84	+0.18
Paddy rice	-21.62	-0.12
Cereal grains nec	-39.95	-0.10
Vegetables and fruits	+78.41	+0.09
Sugar cane/beets	+54.66	-0.09
Plant-based fibres	+43.16	+0.09
Oil seeds	-9.74	-0.17
Crops nec	+44.60	+0.17

can be observed in New Zealand and China. This again stands in contrast to the gains of these countries, predicted in scenario A. In contrast to *wheat*, for *cereal grains nec* the production seems to move from the south to the north (again Scandinavia is an exception). Among others, great increases in area are expected in Poland, which in scenario A is one of the countries where wheat production disappears. The decrease in area is greatest in Central Africa, which is in accordance with predictions of scenario A.

Also in scenario B we observe a shift of global crop production (Table 3.4). However, the global production changes are smaller than in scenario A and the pattern is different. Paddy rice, other cereal grains and oil seeds production declines in favor of wheat, other crops, fruits and vegetables and plant-based fibres. The increase is highest for global wheat production, in contrast to the predicted decrease of wheat production in scenario A. For sugar crops the decline in global production in scenario B stands in contrast to the increase in scenario A.

The pattern of resulting revenue changes is notably different as well for scenario B compared to scenario A (see Figure 3.7). In contrast to the prevailing gains in revenue of scenario A, in scenario B more countries experience a loss in revenue. Gains mainly occur in South Asia, South Africa and North Europe, but also Canada and Mexico and Kazakhstan strongly gain from climate change. Losses govern the rest of the global pattern.

The pattern of percentage differences of revenue change without area changes to those with area changes is not as straight forward as for scenario A. For nearly all South American countries, for the USA, China and Australia and some African and European countries, losses are over- and gains are underestimated when ignoring area changes. But for larger parts of Eastern Europe and the former Soviet Union, gains are overestimated and losses are underestimated. In contrast to scenario A, in scenario B rather for poorer countries such as Cameroon, Uganda and Zambia the revenue-change predictions differ in sign if area changes are ignored.

The results of the different scenarios also show that the allocation change under simultaneous price and yield changes differ from the linear sum of allocation change under sole price and sole yield changes. In Figure (3.8) the percentage differences of the summed allocation change of scenario B and C to the allocation change of scenario A are shown exemplary for *wheat*, *paddy rice* and *cereal grains nec.* We find that the differences are highest for *cereal grains nec.* They range from +255% up to -142%, implying that some changes even differ in sign. However, most deviations are in the

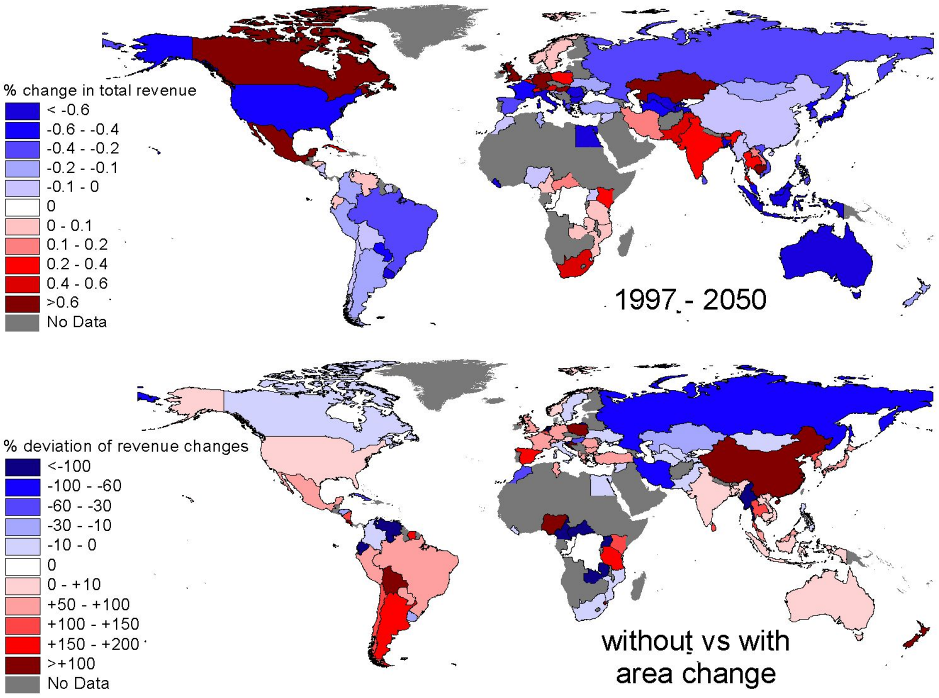

Fig. 3.7. ***Impacts of climate change on revenue, ignoring price changes:*** *(scenario B) The upper graph shows the percentage changes in revenue under consideration of the simulated area changes. The lower picture shows the differences in of revenue changes with and without the consideration of area changes expressed in percentage of the former.*

range of up to ±10%. For *paddy rice* area changes are overestimated by the simple sum of price and yield effected changes for large parts of the world. For *wheat* and *cereal grains nec* the picture is more diverse. However, it can be noted, that in many countries an overestimation of the change in area allocated to *wheat* comes along with an underestimation of the area change in *cereal grains nec*, and vice versa. This indicates that especially the representation of competition among similar crops is weak, if price and yield interactions are ignored.

3.5 Discussion and conclusion

Studying environmental impacts on the economy and vice versa requires an effective representation of land-use as the essential link of biosphere and economy. We present a global agricultural land-use model, made to dynamically couple global state-of-the-art vegetation and economy models. In order to capture the economic as well as the biophysical aspects of land-use decisions the model is motivated by profit maximization, where yields enter as a spatially explicit decision factor. The restriction to only the essential parameters as well as the motivationally based approach qualifies the model for long-term predictions and online coupling.

The evaluation of the model shows that the derived algorithm is capable of reproducing essential dynamics of land-use decisions, theoretically as well as practically. The dynamics of the derived algorithm are in line with intuitive logic. Global, as well as

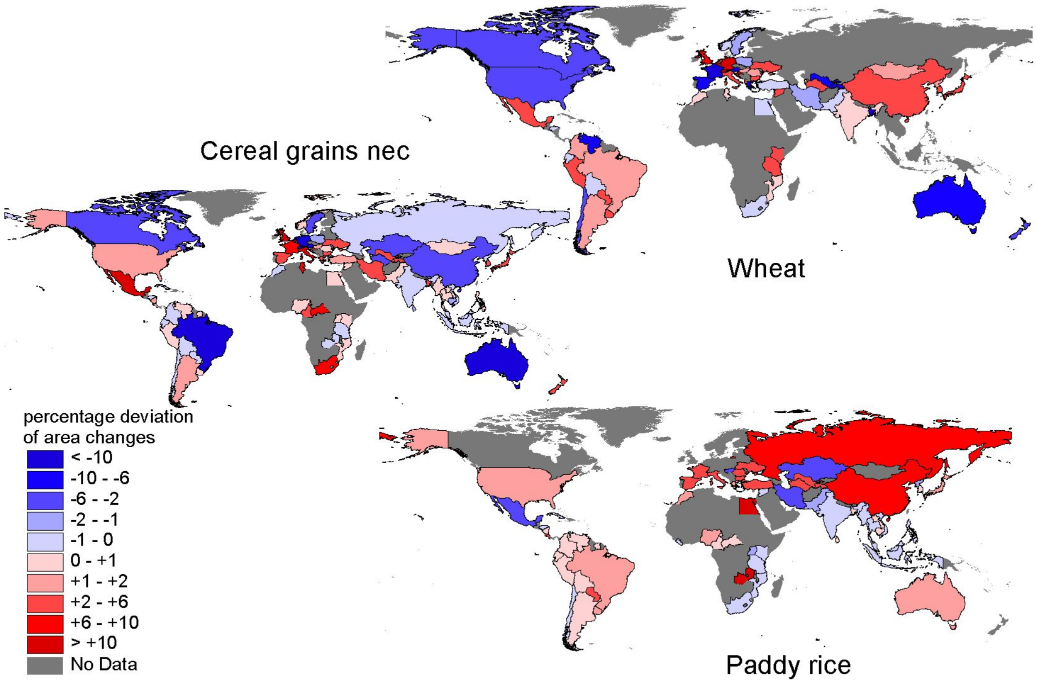

Fig. 3.8. ***Nonlinearity of price and yield effects:*** *Percentage differences of summed allocation-changes of scenario B and C from the allocation-changes under scenario A. For blue countries area changes are underestimates, for red countries the changes are overestimated if effects of price and yield are simply summed up.*

national past allocation patterns can be reproduced with good agreement. False predictions are often a consequence of impacts that do not necessarily show up in price and yield data, such as political changes or local habits. A more flexible cost structure could improve the capability of the model to better adapt to extreme changes.

The partly weak temporal agreement of the model results with observation indicates that the causal timing of profitability impacts is not as straight forward as assumed in the model. Obviously, the time-lag between a change in price or yield and its effect on the allocation can vary for crop, country and even in time. The good agreement of simulated and observed means, however, shows that only the exact timing of the impact is problematic whereas in average profitability changes have the expected effect on the crops allocation. The comparably poor performance of the model for the African continent can be interpreted in two ways; on the one hand the influence of existence farming in Africa is still much greater than in developed countries (Collier & Gunning, 1999), on the other hand data sources for Africa are often inconsistent and doubtful which makes a sound evaluation difficult.

Altogether the evaluation results suggest that despite the weaknesses the trends of global crop allocation are sufficiently reproduced for a global analysis or a data exchange with global economy and vegetation models, respectively.

Simulations of crop allocation under climate change project a large decline of major crops (such as wheat, paddy rice and other cereal grains) in favor of minor crops (such as vegetables and fruits, sugar crops and plant-based fibres) for most countries around the world. Increases are concentrated for wheat in South America and for paddy rice in the Former Soviet Union. KLUM predicts an increase of total revenue of crop production mainly everywhere, save North America. The increases are notably greater in developing than in developed countries. These predictions, however, are mainly determined by the price scenario, which dominates the much smaller yield changes. The pattern of only yield induced impacts looks fundamentally different: whereas positive and negative area changes are more balanced than in the first scenario, the changes in revenue are mainly negative. For some regions we find a shift of wheat production to the South and of other cereals to the North, indicating that wheat is replaced in northern countries by maize or other cereal grains.

The chosen linearly extrapolated price trends imply that minor crops, (such as vegetables and fruits, sugar crops and plant-based fibres) gain in price in comparison to major crops (such as wheat, paddy rice and other cereals). The prices of the minor crops have been increasing or slowly decreasing over the reference years, whereas for major crops prices have been declining more rapidly. In Asian countries and the Eastern Block, and to a lesser extent also in African countries, prices have been increasing in the reference period for all or at least most of the crops (again with the tendency to increase faster for minor crops). This explains the great gains on the Asian continent, in comparison to moderate gains or even losses of the developed world.

Assuming that the chosen price and yield projections are realistic, the results of the 3 different scenarios suggest that price changes will dominate or even outweigh the impacts of climate change. Yet, it should be noted, that the estimates of yield changes of Tan and Shibasaki are rather low, compared e.g. to changes of Rosenzweig *et.al.* (1993), which are similar in sign but up to tenfold in magnitude. Our price extrapolations assume on the one hand, that prices are not affected by climate change and on the other hand, that they are independent of market development: according to these trends the majority of people would change their diet from common grains to fruits, vegetables, sugar crops and plant based fibres. Both implications are rather unlikely. So, the results emphasize once more the necessity to model the complete feedback loop of economy and environment, in order to capture feedbacks of prices and productivities as well as feedbacks and competition among different economic productions and sectors. The importance of a proper inclusion of land-use changes in impact calculations is pointed up by the presented deviations of calculations with and without area changes. Monetary impacts can be underestimated by more than 200%, and even differ in sign, if land-use changes are ignored.

In a more balanced scenario of prices and yield changes not only the picture of changes would alter but also the effect on the decision of joint price and yield changes would increase. Even for the unbalanced scenario a strong non-linearity in the summed effect of price and yield changes can be detected; the effect is greatest for *cereal grains nec*, which is the crop with the greatest yield changes. Especially the representation of competition among similar crops suffers from an separate inclusion of price and yield effects on allocation. This emphasizes the importance to include economic as well as biophysical aspects of land-use change decisions in a common framework, as done in KLUM.

All things considered, the developed model proves as a step in the right direction. Already the offline simulations allow for interesting dynamics and outline the importance of an appropriate inclusion of land-use changes into simulations of future development. To gain an insight into the dynamics of the feedbacks between economy, land-use changes and vegetation, the most important next step is to couple KLUM to a global economic trade model and a global vegetation model. An increase of the spatial resolution, as well as a change to a grid-pattern is planned, to match the spatial resolution of common vegetation models. Moreover, to allow for commonly not planted crops to conquered new regions, calibration-parameters for such crops need to be found.

4. COUPLING THE ECONOMY: KLUM@GTAP

4.1 Introduction

[1]

This chapter presents the coupled system KLUM@GTAP of KLUM with the 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[2]. 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). 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 has 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 in chapter 5 we use KLUM on a 0.5 × 0.5 degree grid (for Europe only). The second difference is that KLUM@GTAP does not have land classified by different productivity, but that productivities vary continuously over space, again allowing the direct coupling to large scale

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[1] This chapter is based on (Ronneberger *et al.*, 2006a)

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

Tab. 4.1. ***Regional aggregation of KLUM@GTAP.*** *The respective regions of KLUM are given in the second column (compare Table A1)*

KLUM@GTAP	KLUM	Region
USA	USA	USA
CAN	CAN	Canada
WEU	WEU	Western Europe
JPK	JPK	Japan and South Korea
ANZ	ANZ	Australia and New Zealand
EEU	CEE	Central and Eastern Europe
FSU	FSU	Former Soviet Union
MDE	MDE	Middle East
CAM	CAM	Central America
SAM	SAM	South America
SAS	SAA	South Asia
SEA	SEA	Southeast Asia
CHI	CHI	China, North Korea & Mongolia
NAF	MAF	North Africa
SSA	SSA	Subsaharan Africa
ROW	SIS	Rest of the World

crop growth models to simulate implications of environmental changes. In GTAP-AEZ, a change in e.g. climate or soil quality requires an elaborate reconstruction of the land 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.

In the next section we outline the basics of GTAP-EFL and the changes applied to 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 4.3 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 4.4 outlines the different simulation setups. The results of these simulations are presented in section 4.5. Section 4.6 summarizes and concludes.

4.2 The models

4.2.1 GTAP-EFL

In order to assess the systemic general equilibrium effects of climate change on agriculture and land use, we use a multi-region world CGE model called GTAP-EFL, which is a refinement of the GTAP-E model (Burniaux & Truong, 2002). Basically, in the GTAP-EFL model finer industrial and regional aggregation levels are considered (17 sectors and 16 regions, reported in Table 4.1 and in the Appendix Table A3). Furthermore, in GTAP-EFL a different land allocation structure has been modeled for the coupled procedure.

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 (Appendix 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 (imperfectly mobile) and natural resources are industry-specific. The national income is allocated between aggregate household consumption, public consumption and savings (Appendix Figure A2). 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 land input is exogenously fixed at the regional level; it is imperfectly substitutable among different crops or land uses. Indeed a transformation function distributes land among 5 sectors (rice, wheat, other cereals, vegetables & fruits and animals) in response to changes in relative rental rates. Substitutability is equal among all land-use types. Only for the coupled procedure, in the GTAP-EFL model sectoral land allocation becomes exogenous and consequently the total land supply change becomes endogenous. 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 on the value of land in region r, all evaluated at market prices.

4.2.2 Modifications on KLUM

For the coupling, we calibrate KLUM to 4 crop aggregates: wheat, rice, other cereal crops and vegetables & fruits so as to match the crop aggregation of GTAP-EFL. 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 (Table 4.1). 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. Costs are adjusted for the total amount of agricultural area to guarantee the consistency of results on different scales (see below). For all countries the cost parameters as well as the risk aversion factor are determined in the calibration and are hold constant during all simulations.

Adjustment of the cost parameters in KLUM

The assumption of decreasing returns to scale 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[3]. 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 an 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:

$$c_a = c_b \frac{L_b}{L_a} \tag{4.1}$$

where L_b and L_a represent the total agricultural area of unit b and of the original unit a, respectively. This procedure assures that under identical conditions, the spatial resolution does not impact the result.

4.2.3 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 $\partial\alpha_i$ by adjusting the change qo_i of the total production of crop i by the change in its harvested area $qoes_i$, according to:

$$\partial\alpha_i = \frac{qo_i - qoes_i}{1 + qoes_i} \tag{4.2}$$

The coupling can be divided into 3 methodologically different procedures: a convergence test, a baseline simulation transferring both model to the future and the simulation of the impact of climate change (see Figure 4.1).

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 GTAP-EFL is shocked with an uniform increase of 2%[4]. 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 4.3 for further details).

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[3] In the present study a spatial unit refers to one country.

[4] 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.

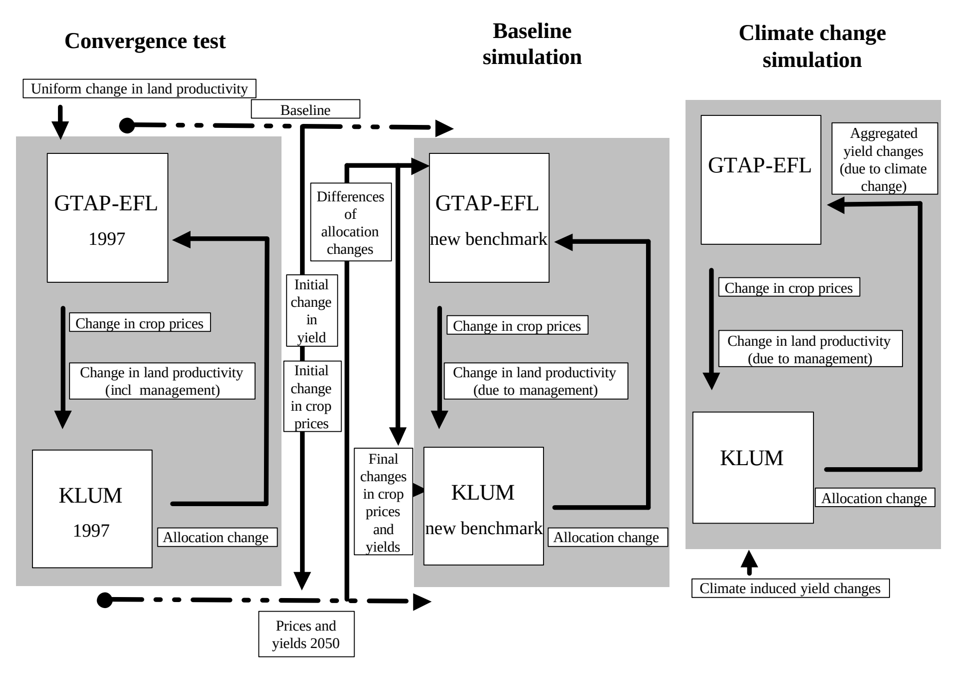

Fig. 4.1. ***The coupling scheme of KLUM@GTAP:****The coupling can be divided into 3 different procedures. For further details see the description in the text.*

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 is thus effectless for the simulation 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; the land allocation in the benchmark is thus adjusted to that in KLUM. The results of this simulation mark the final benchmark of the future situation. Corresponding price and yield changes are used to adjust prices and yields in KLUM to the final situation consistent with the benchmark. To test the consistency a similar loop as in the convergence testing is started. The allocation changes of KLUM relative to the primarily calculated future allocation is fed back to GTAP-EFL in the final benchmark. The resulting price and yield changes are again imposed on KLUM in its final benchmark. Consistency is assured if prices, yields and allocation changes eventually converge to zero.

Climate change simulation To simulate the relative impact of climate change we impose a climate change scenario over an afore 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 4.2) 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.

4.3 Convergence

To assure 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, in combination with the "rigid structure" of the CGE model 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 solving 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 situation of harvested area in 1997 of GTAP-EFL and KLUM are presented in Table 4.2. Since the units used in the GTAP model are not specified, we present the allocation as shares of the total crop area of the respective region in the respective model. The global totals per region and crop are given as share of total global cropland in the respective model (stated in the lower right corner of the Table). Obviously, regional 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 GATP-EFL is only half of the share used in KLUM. Contrary, vegetables & fruits use twice as much global cropland in GTAP-EFL than in KLUM. Considering that the quantities in GTAP-EFL originally represent the monetary value of cropland this distortion is understandable. But for the coupled framework this means that e.g. small absolute changes in the area share of vegetables & fruits of KLUM translate into large absolute changes in GTAP-EFL. Also the shares of total area used in the different regions differ notably. Whereas in GTAP-EFL large shares of total global cropland are situated in Western Europe, South Asia and the USA, only the largest areas of cropland in KLUM is also harvested in South Asia; other major shares can be found in 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, e.g. the trade structure is impacted by the regional distribution of resources. Thus, relatively small changes of aggregated absolute allocation in e.g. Western Europe

Tab. 4.2. ***Initial shares of harvested areas in GTAP and KLUM.*** *The emphasized totals are relative to total global cropland (as quoted in the lower right corner, KLUM's quantity is given in 1000 ha). The region specific crop shares relate to total cropland in the respective region.*

Crop	Rice		Wheat		Cereal Crops		Vegies & Fruits		**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	**0.096**	**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**	**965,573**	**268,948**

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 all model parameters in order to re-establish a new initial stable equilibrium consistent with the entire observed situation of 1997. This would be a major task due to the "rigid structure" of the model, and it would be arbitrary without land price data.

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 $ESBV$. 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-added* (see e.g. (Hertel, 1997) for more details). We conduct convergence loops with ten iterations each for the original and appropriately increased elasticities $ESBV$.

Results of the convergence test

A first set of simulations (not presented here) revealed that price, yield and area-share-changes for the region *Rest of the world* diverged quickly and distorted the performance of the complete system, preventing the existence of a common equilibrium. This region encompasses the "remaining" 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 coupling experiment. No data is exchanged between KLUM and GTAP-EFL for this region in any of the presented simulations.

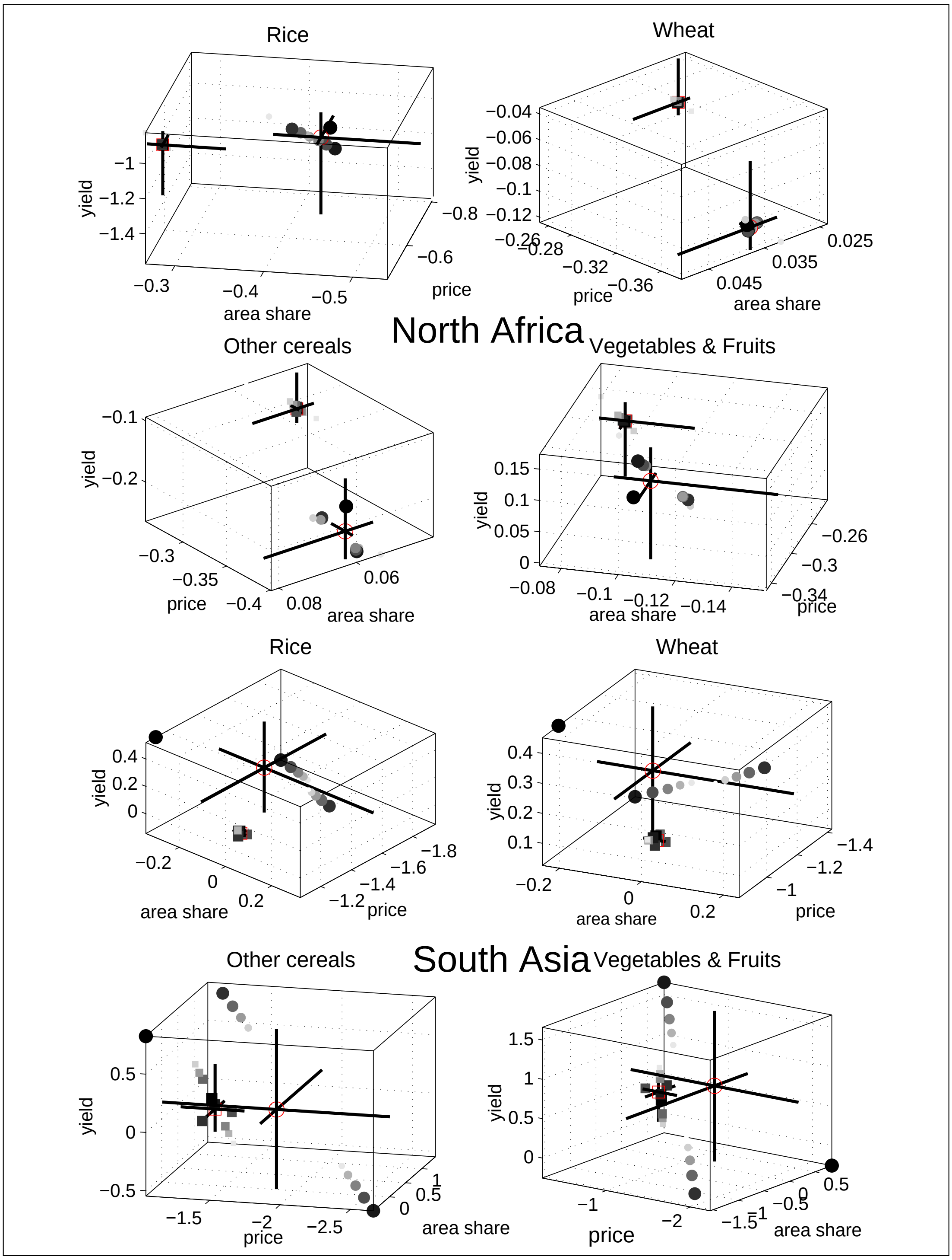

Fig. 4.2. ***Results of the convergence test for North Africa and South Asia:*** *The plots depict the space spanned by the percentage changes in price, yield and area-share. Round markers: results under doubled elasticity; Square markers: results under tripled elasticity. With proceeding iteration size 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 4.2 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. For doubled elasticity a strong divergence of the iterating values can be observed in both regions for all crops. Only the results for wheat 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 4.2); only wheat 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, making it one of the potentially largest crop producers. North Africa instead is one of the smallest producers in terms of harvested area (compare Table 4.2). 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 4.2 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.

4.4 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 *baseline* 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 *cc 2050*.

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 *cc 1997*.

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 *uncoupled* simulations). In both models we use the benchmark equilibrium 2050 of the *baseline* 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

Tab. 4.3. ***Changes in the economy until 2050:*** *Percentage changes in economic key indicators 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

exogenous price and management changes according to the *uncoupled* GTAP-EFL. Like this the KLUM model describes a partial equilibrium situation.

More detail on the explicit assumptions and used data are given in Appendix B.

4.5 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.

Baseline scenario

The changes according to the baseline scenario in CO2 emissions and GDP (Table 4.3) and crop production (Table 4.4) are positive in the order of several hundred percent for all regions. For emissions, GDP and crop production the growth is up to 1.5-4 times stronger in currently developing regions, such as Subsaharan Africa and China, than in developed 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 4.3). Negative changes appear in Africa, the Middle East, South America, the Former Soviet Union and Europe. They are largest for Western Europe. The reason may be found in the fact that in Western Europe the land productivity increases much less than in the other countries; in fact, it is nearly one order of magnitude smaller than in the other regions. Crop prices generally decrease by around 20-60% for all regions and crops (Table 4.5). 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. Accordingly, also these trends are greater for the developing

Tab. 4.4. ***Impacts on crop production*** *For the baseline and the cc 2050 scenario the percentage changes according to KLUM@GTAP are given. Column cc 1997 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	-6.92	-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.& Fruits	baseline	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
	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

than the developed regions, but less pronounced than for the parameters discussed above.

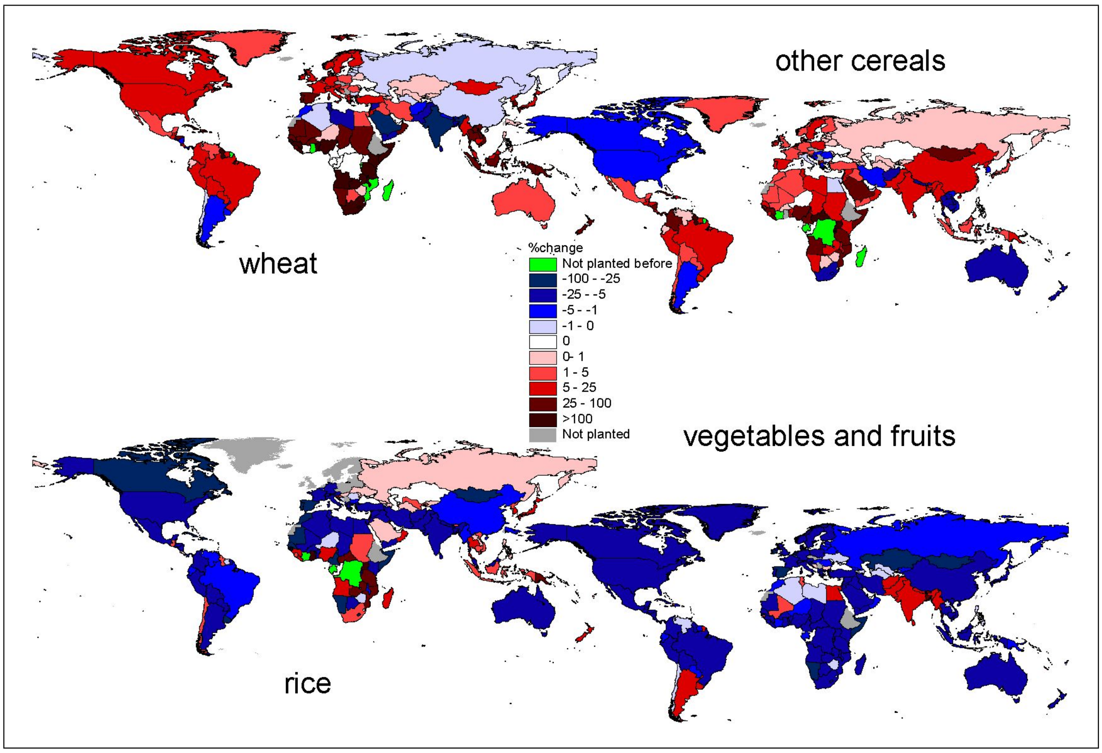

Fig. 4.3. ***Cropland allocation changes until 2050:*** *Percentage changes in cropland allocation in the baseline simulation according to KLUM@GTAP. In gray countries the crop is either not planted or no data is present.*

Impact on the cropland allocation are pictured in Figure 4.3. The plots suggest that vegetables & fruits are largely replaced by wheat and other cereals. Only in South Asia and some countries of Central America and North Africa the area share for vegetables & fruits is increased. Also rice cropland is strongly reduced in most countries. Only in the Former Soviet Union, South East Asia and a number of Subsaharan 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; Argentinia decreases its area share for both crops.

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). 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 4.4 and Table 4.4 and 4.5. 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

Tab. 4.5. *Impacts on crop prices.* *For the baseline and the cc 2050 scenario the percentage changes according to KLUM@GTAP are given. Column cc 1997 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.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	-45.56	-58.32	-43.75	-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 & Fruits	baseline	-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
	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	70.0	n.a.	166.7	91.7	1050.0	33.3	184.6	-12.5	133.3	63.6	150.0

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 4.4); 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.

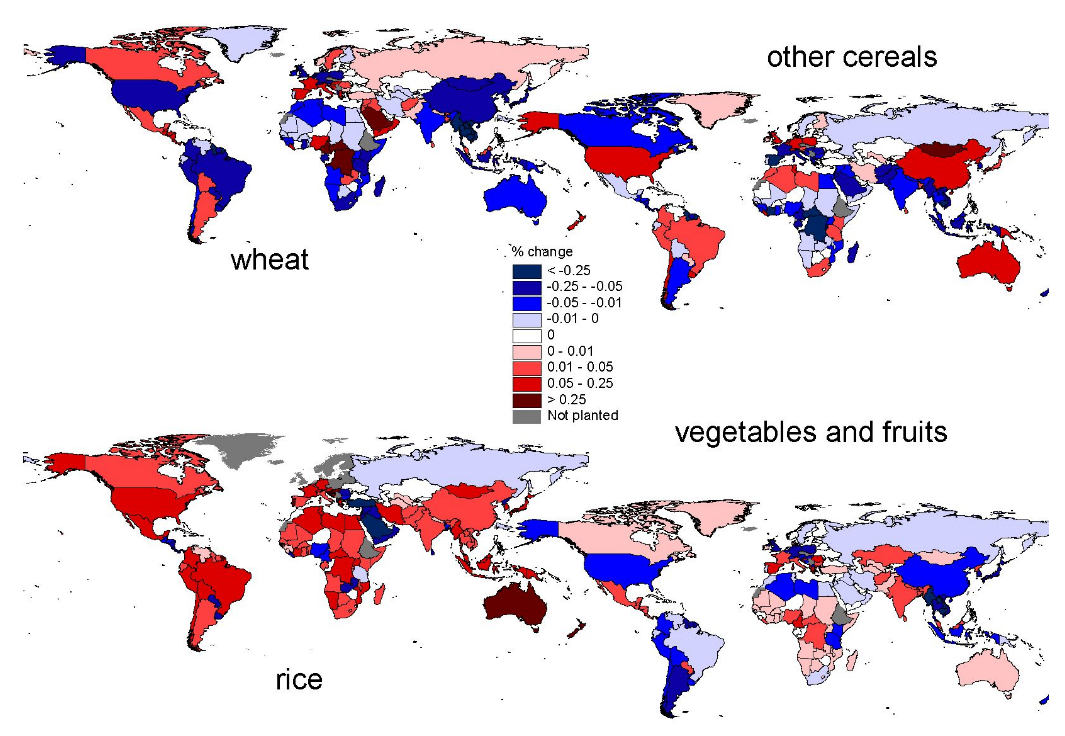

Fig. 4.4. ***Climate change impacts on cropland allocation:*** *Percentage changes in cropland allocation in the climate change scenario relative to 2050 (cc 2050) according to KLUM@GTAP. In gray countries the crop is either not planted or no data is present.*

The crop production changes by and large explain the pattern of losses and gains observed for GDP and welfare (Figure 4.5, 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 Subsaharan Africa, Canada and Western Europe: all regions where also for crop production the increases prevail. Generally CO2 emissions change in accordance with GDP. Only the USA, the Former Soviet Union, and Eastern Europe are notable exceptions. In these regions, the "composition" effect dominates the "size" effect; that is, in terms of emissions the change in the production mix to more carbon intensive goods dominates the total loss in production. 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

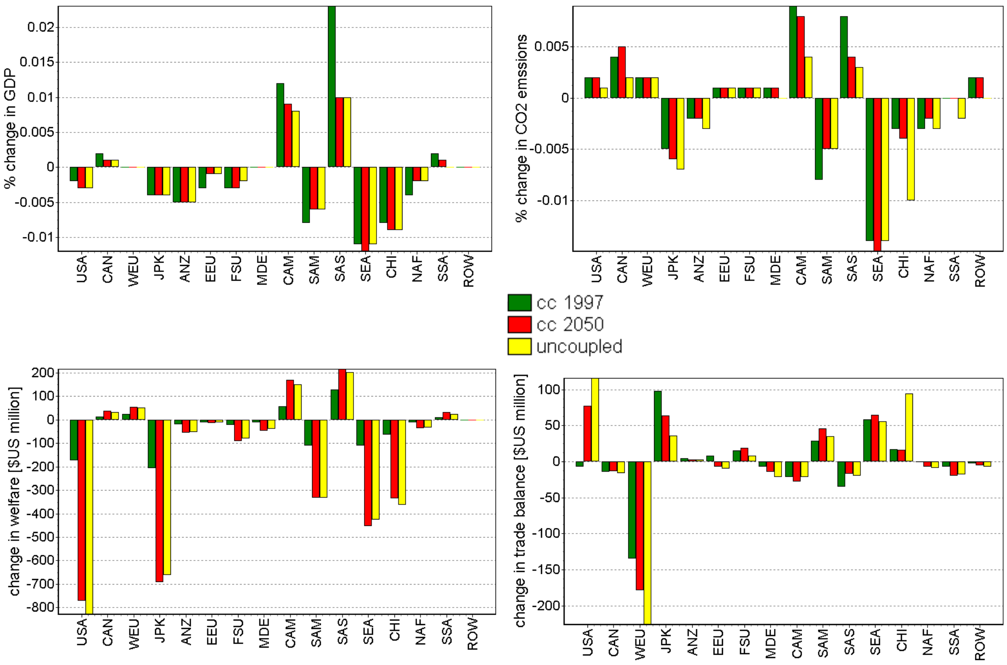

Fig. 4.5. ***Climate change impacts on the economy:*** *Changes in economic indicators according to the different climate change simulations. The cc 2050 and cc 1997 simulations are performed with the coupled system. The uncoupled simulation is performed with GTAP-EFL standalone.*

terms of trade, WEU shows the highest losses.

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 *cc 1997* (where the climate scenarios is imposed on the current situation) to those of scenario *cc 2050* (where the climate change scenario is applied to the baseline benchmark of 2050). Figure 4.6 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 4.4 and 4.5). 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 *cc 1997* simulation (green bars in Figure 4.5). 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,

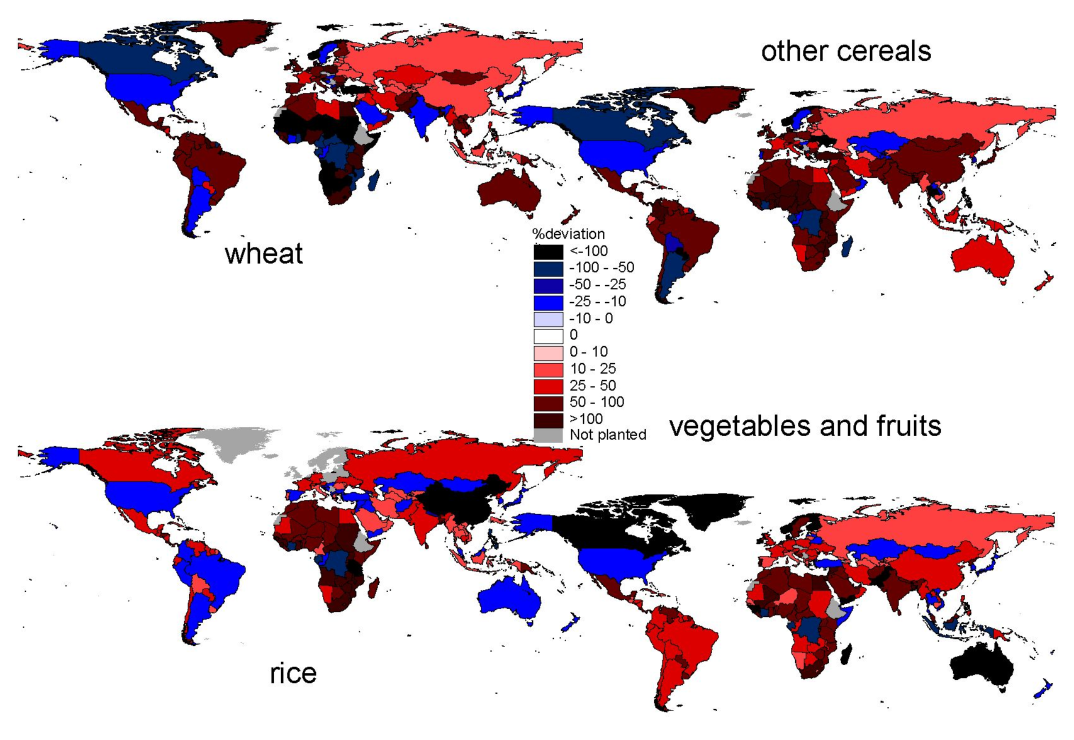

Fig. 4.6. ***Effect of the baseline scenario on simulated climate impacts:*** *Climate impacts relative to the current situation (cc 1997) are compared to those estimated relative to the baseline (cc 2050). The differences are expressed in percent of the latter. In gray countries the crop is either not planted or no data is present.*

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.

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 GTAP-EFL standalone; feedbacks, though, are excluded.

GTAP-EFL - standalone

The resulting land allocation changes of GTAP-EFL standalone differ from the results of the coupled system simulation by several hundred up to thousand percent (shown in Table 4.6); 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

Tab. 4.6. ***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.*

%	Rice	Wheat	CerCrops	VegFruits
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	-372.73	-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.

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 to be affected by climate change directly; these changes result from the indirect impacts on allocation. Even though the region *Rest of the world* 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 4.5, 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.

KLUM - standalone

The percentage differences of land allocation changes in KLUM standalone to KLUM@GTAP are in the range of $\pm 10 - 100\%$, reaching up to several hundred percent (Figure 4.7). 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

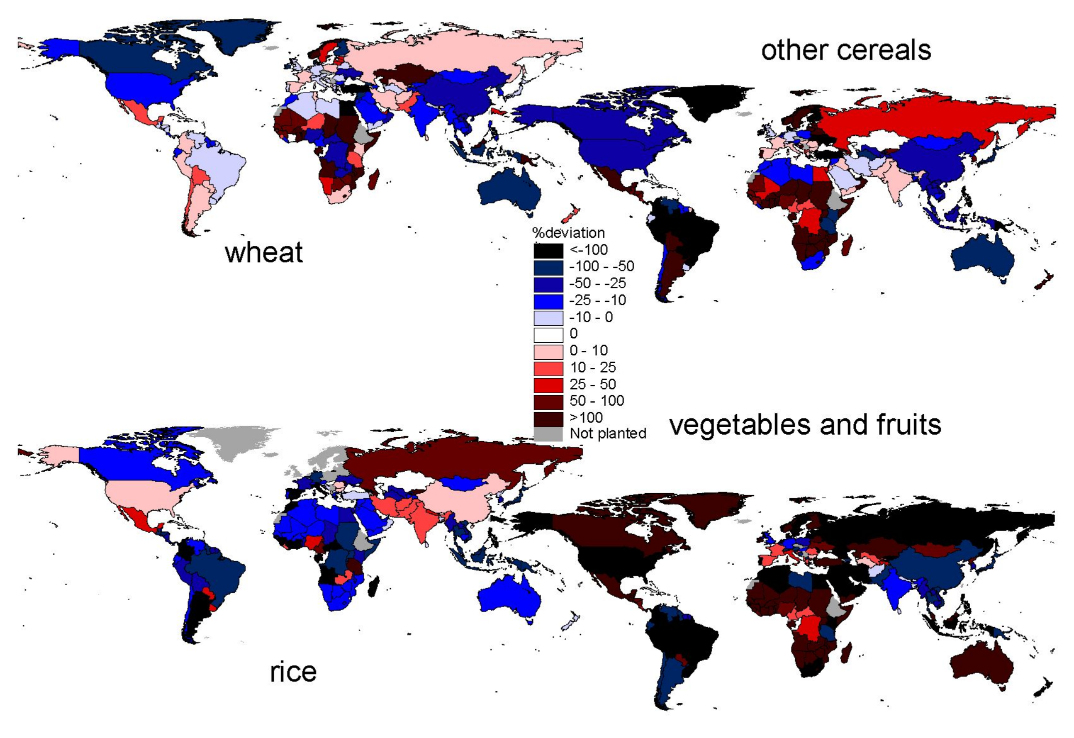

Fig. 4.7. ***Effect of the coupling on simulated climate impacts:*** *Climate impacts according to KLUM standalone (uncoupled) are compared to those of KLUM@GTAP (cc 2050). The differences are expressed in percent of the latter. In gray countries the crop is either not planted or no data is present.*

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.

4.6 Summary and Conclusion

We present in this chapter 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 projection of more spatial explicit and 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 chapter 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 tremendously 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 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 chapter we illustrate that plausible estimations of climate change impacts are still feasible under the afore mentioned 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 Subsaharan 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: emissions 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 a dynamic 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.

5.1 Introduction

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In this chapter, we include KLUM 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.

Similar to the SFARMOD-ROIMPEL approach, this framework provides a link between dynamically modeled yield projections and economic motivated agricultural land-use decisions. In SFARMOD-ROIMPEL 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. 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.

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 0.8C 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 4-6C 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. We

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[1] This chapter is based on (Ronneberger *et al.*, 2006b)

assess the impact and relevance of the coupling on the simulation results by reference simulations with the uncoupled models. 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.

In the following section, we outline the characteristics of the two models and describe the coupling procedure. Section 5.3 introduces the experimental design. Section 5.4 presents a comparison of model results and observations. In Section 5.5 we present and discuss the results of future and reference simulations. Section 5.6 summarizes and concludes.

5.2 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.

5.2.1 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 10C) a medium ($0.03yr^{-1}$ at 10C) and a fast one ($0.35yr^{-1}$ at 10C). 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.

5.2.2 Modifications on KLUM

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[2] 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 Chapter 3, 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 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 former chapter Section 4.2.2. 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[3] 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 Vstsverige, the calibration of stra 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.

5.2.3 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 5.1).

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[2] 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).

[3] 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

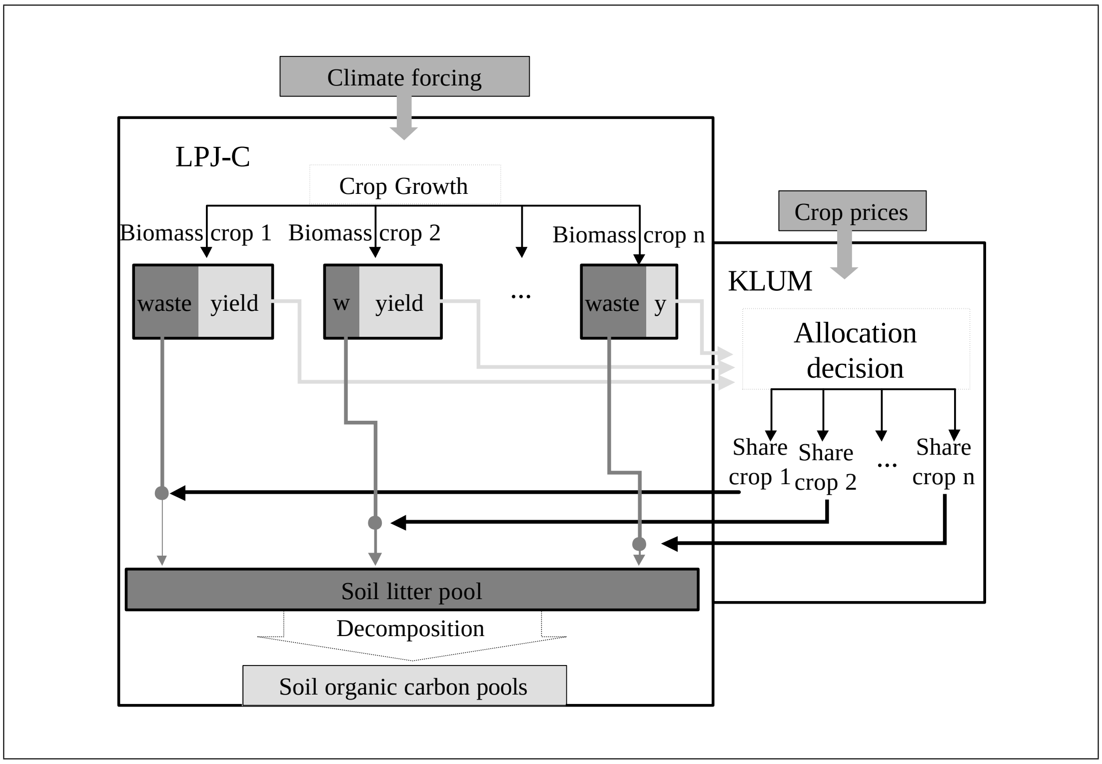

Fig. 5.1. ***Coupling scheme of KLUM@LPJ:*** *The share of total biomass stored in the human edible part of the crop are used in KLUM as potential yield, the rest of the plant's biomass is scaled by the calculated area share and enters the soil litter pool for further decomposition.*

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.

5.3 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

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and Eszak-Alfold (Hungary) as they give a better fit than all western European regions.

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 irrelevant 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 and coupled to an economy model. 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 5.2.2). 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).

5.4 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 5.2. 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 (see 3.3. 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.

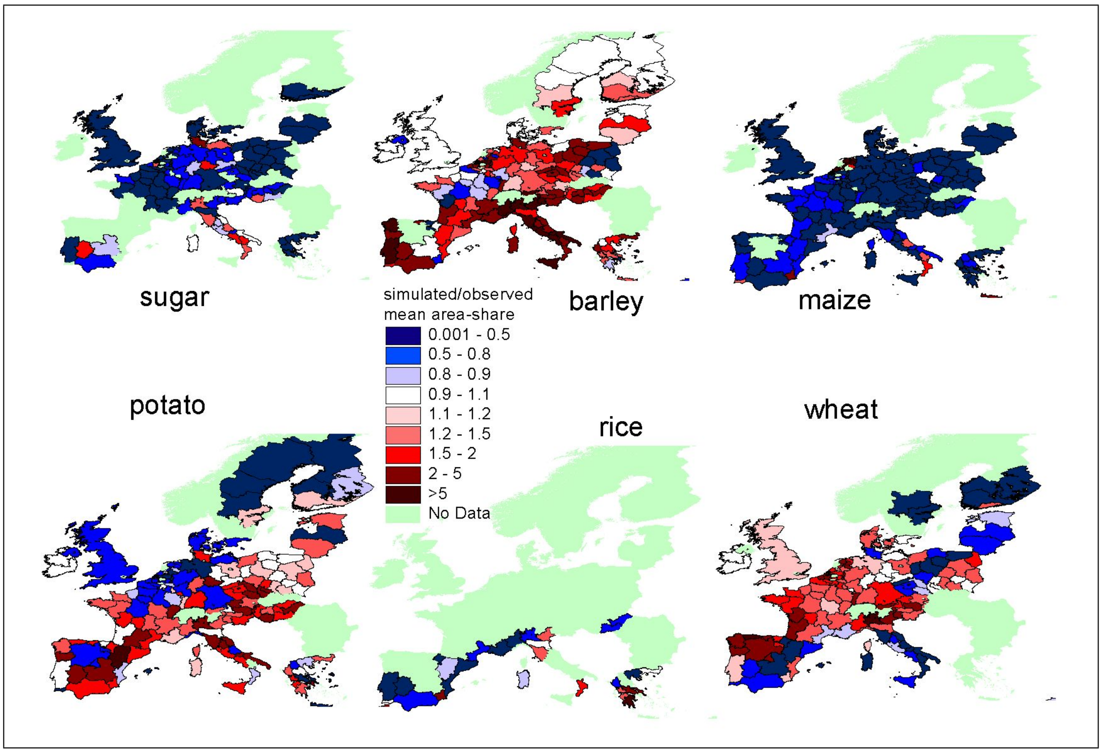

Fig. 5.2. ***Ratio of simulated and observed area share for the year 2000.*** *The values are compared on NUTS2 level; simulated values are averaged over the grid cells within one NUTS2 region.*

5.5 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.

5.5.1 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 5.3-A the temporal development of mean carbon biomass per cropland area at harvest time. Figure 5.3-B shows the mean ratio of storage organs over total biomass weighted by area share, reflecting the changes in carbon allocation within the plant[4]. The ratio of grid cells where maturity is reached to total grid cells (Figure 5.3-

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

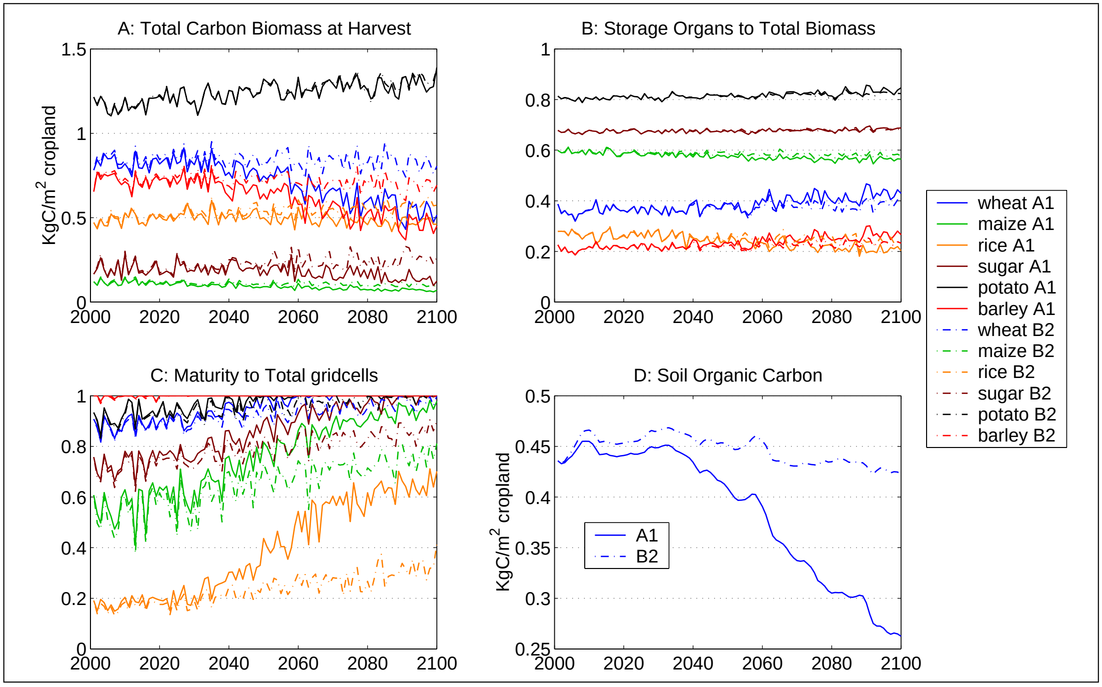

Fig. 5.3. ***Temporal development of indicators describing the natural system according to KLUM@LPJ.*** *A: Mean total biomass at harvest time; B: Mean of the ratio of a crop's storage organs to total biomass; C: Ratio of gridcells, where full maturity is reached to total grid cells; D: Mean soil organic carbon*

C) describes the spread of the potential growing area. The mean soil organic carbon (SOC) per area of cropland is shown in Figure 5.3-D. The spatial pattern of the soil organic carbon changes are depicted in Figure 5.4.

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 5.3-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 5.3-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 5.3-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.

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

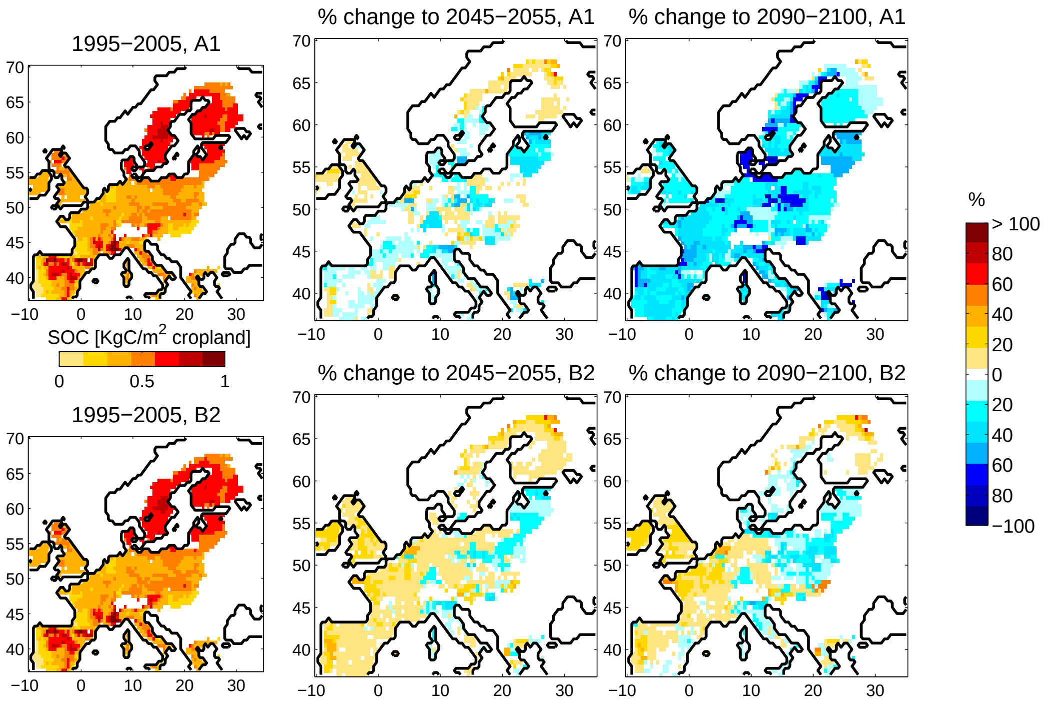

Fig. 5.4. ***Soil organic carbon changes according to KLUM@LPJ.*** *The small left-most plots illustrate the spatial distribution of SOC averaged over the reference period 1995-2005; the remaining plots depict the percentage changes relative to this situation for averages of the periods 2045-2050 and 2090-2100 for scenarios A1 and B2.*

& 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 5.4) 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 5.5-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 5.5-C). The spatial pattern of allocation changes are depicted in Figure 5.7 for maize and in Figure 5.6 for wheat. To quantify the effects on the European crop sector, the development of crop production and the corresponding revenue are presented in Figure 5.5-B and 5.5-C, respectively.

We reveal a general increase of the allocation share for maize and potatoes and a decrease for barley and wheat (Figure 5.5-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 5.5-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%

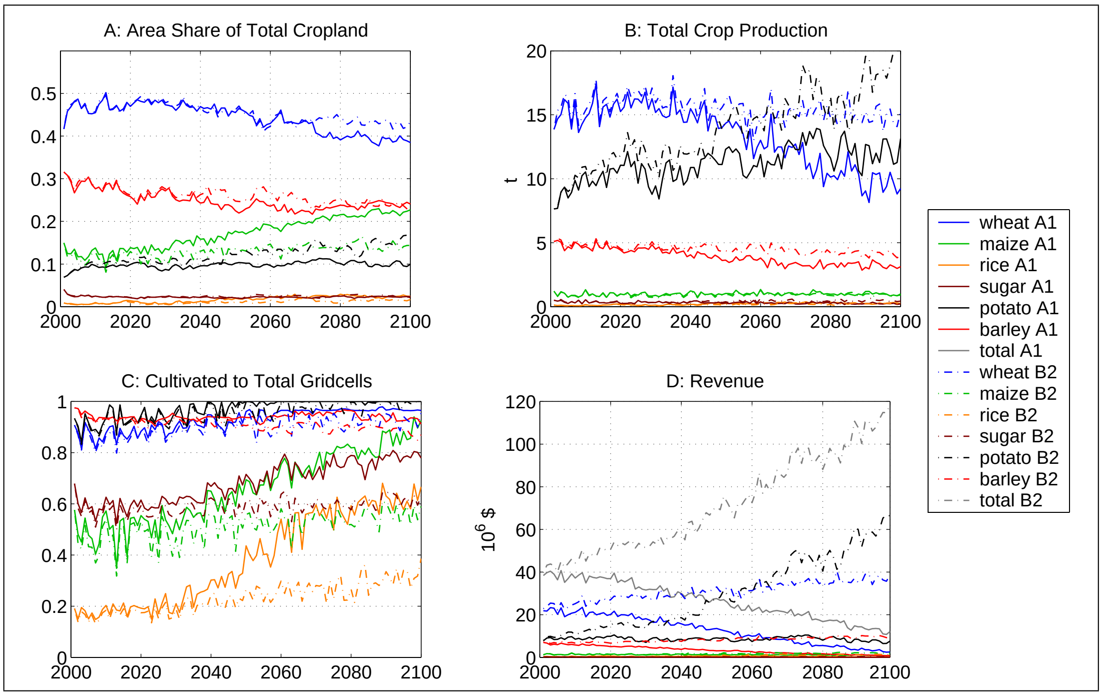

Fig. 5.5. ***Temporal development of agroeconomic indicators according to KLUM@LPJ.*** *A: Area share of total European cropland; B: Total European crop production; C: Ratio of grid cells, where a crop is cultivated to total grid cells; D: Total European Revenue from crop production (the gray line depicts the summed revenue).*

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 5.3-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 5.3-A and 5.3-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 5.6) reveals that the decrease in the total area share of wheat (Figure 5.5-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 5.7): 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.

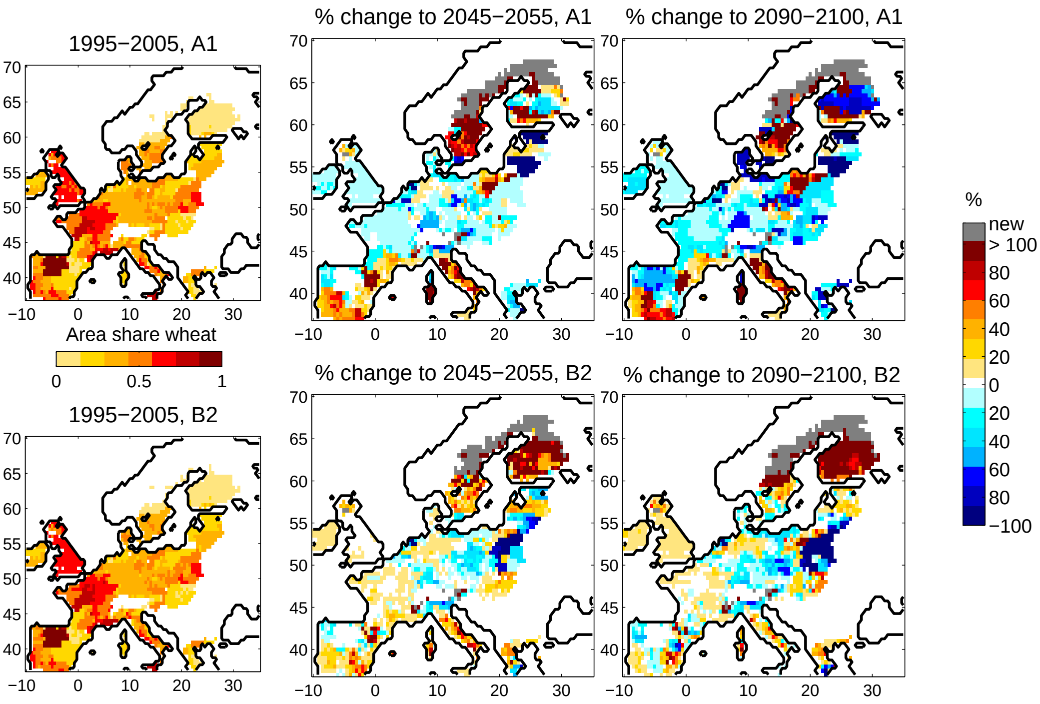

Fig. 5.6. ***Wheat allocation changes according to KLUM@LPJ.*** *The small left-most plots illustrate the spatial distribution of wheat allocation averaged over the reference period 1995-2005; the remaining plots depict the percentage changes relative to this situation for averages of the periods 2045-2050 and 2090-2100 for scenarios A1 and B2.*

5.5.2 *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 5.8 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 5.3-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 5.9-A shows the differences

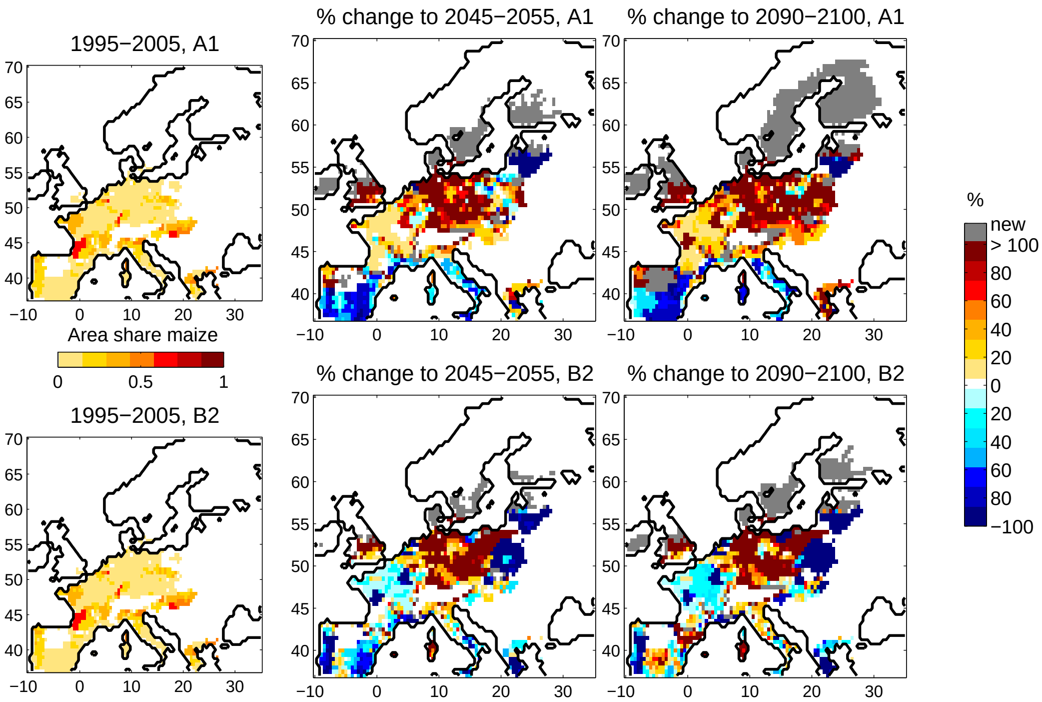

Fig. 5.7. ***Maize allocation changes according to KLUM@LPJ.*** *The small left-most plots illustrate the spatial distribution of maize allocation averaged over the reference period 1995-2005; the remaining plots depict the percentage changes relative to this situation for averages of the periods 2045-2050 and 2090-2100 for scenarios A1 and B2.*

of the area shares of uncoupled to coupled simulation for all crops; 5.9-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 understimated. Towards the end of the simualtion, 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 Figures 5.10 and 5.11, respectively. For both crops in scenario A1, the extent rather than the general pattern of changes differ from the coupled simulation (compare Figures 5.6 and 5.7). For wheat, the uncoupled KLUM generally underestimates the extent of changes in scenario A1, without affecting the sign. For maize, the largest differences

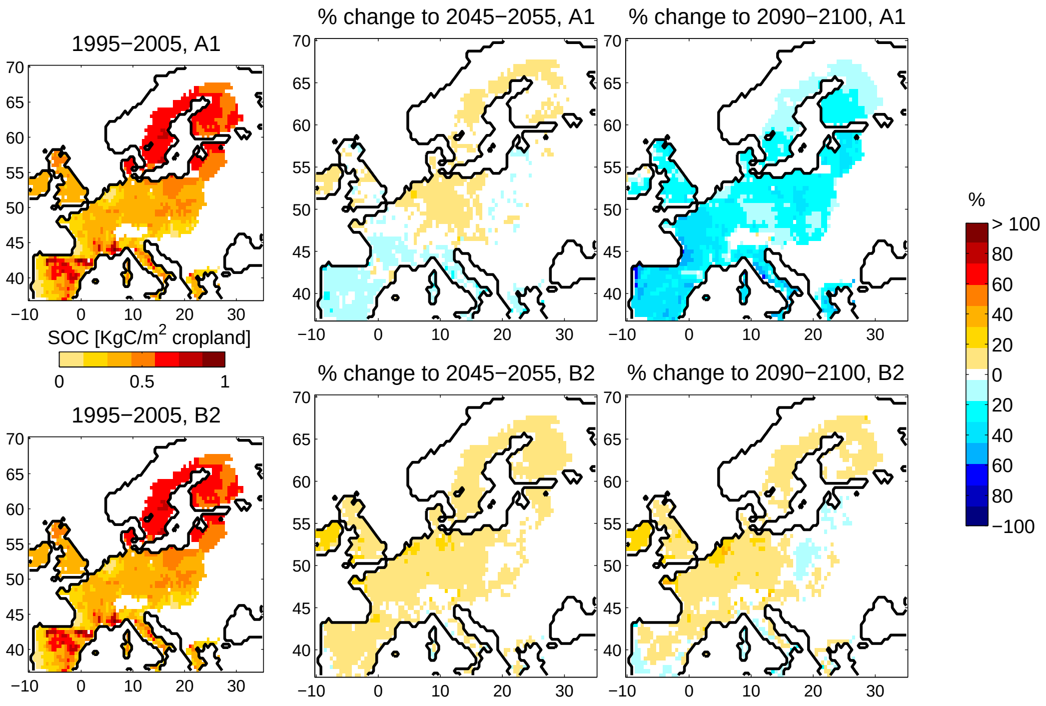

Fig. 5.8. ***Soil organic carbon changes according to LPJ-C standalone.*** *The small left-most plots illustrate the spatial distribution of SOC averaged over the reference period 1995-2005; the remaining plots depict the percentage changes relative to this situation for averages of the periods 2045-2050 and 2090-2100 for scenarios A1 and B2.*

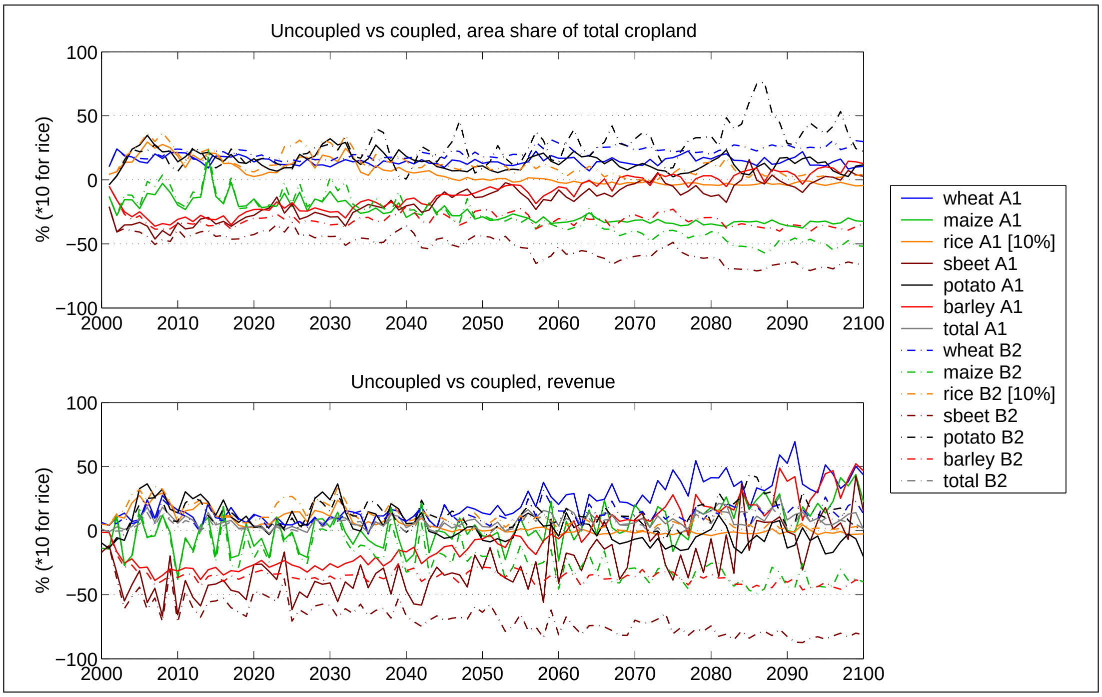

Fig. 5.9. ***The effect of the coupling on area share and revenue.*** *Percentage difference of KLUM standalone versus KLUM@LPJ for European area share (A) and revenue (B). The differences for rice are given in 10% in order to fit in the scheme.*

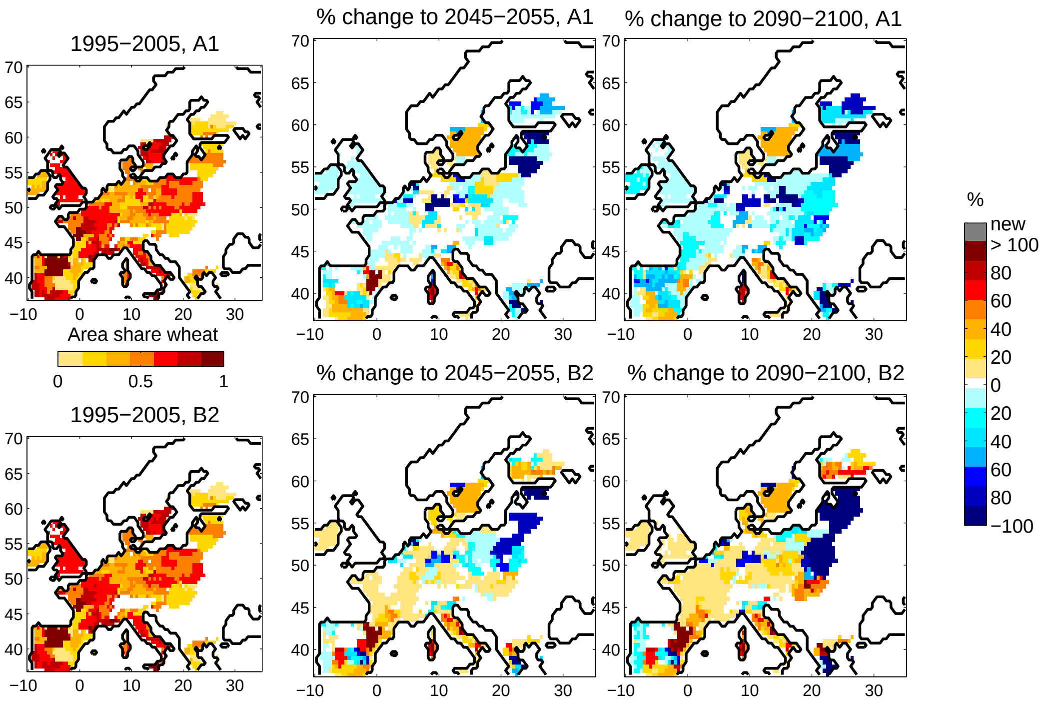

Fig. 5.10. ***Wheat allocation changes according to KLUM standalone.*** *The small left-most plots illustrate the spatial distribution of wheat allocation averaged over the reference period 1995-2005; the remaining plots depict the percentage changes relative to this situation for averages of the periods 2045-2050 and 2090-2100 for scenarios A1 and B2.*

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 caused by underestimations of growing area.

5.6 Discussion and conclusions

This chapter 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.

Since in the current system, management and irrigation are not represented, a certain inconsistency of observed (actual) and simulated (potential) yields has to be

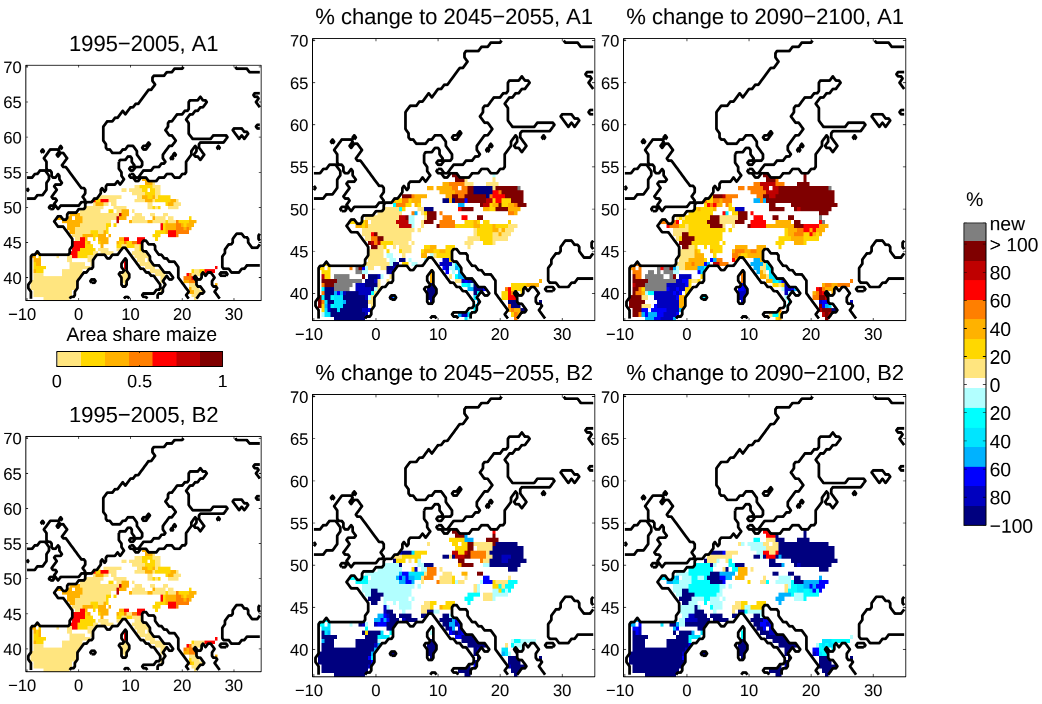

Fig. 5.11. ***Maize allocation changes according to KLUM standalone.*** *The small left-most plots illustrate the spatial distribution of maize allocation averaged over the reference period 1995-2005; the remaining plots depict the percentage changes relative to this situation for averages of the periods 2045-2050 and 2090-2100 for scenarios A1 and B2.*

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 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 overestimation 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 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.

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 factors 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 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 the former chapter; 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 a long way is still ahead. 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.

Yet, 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. But 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. 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, 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.

6. CONCLUDING REMARKS

6.1 Summary

Studying effects of global change and their implications demands a global analysis. Understanding the human impact on the natural environment and resulting consequences for the future of mankind requires an integrated assessment of the different earth system components and their dynamic feedbacks. At the interface between human society and natural environment, land-use decisions are one of the key interactions directly linking antroposhere and biosphere. Thus, in order to couple global models of economy and vegetation a global land-use model – considering the biophysical as well as the economic aspects of land-use decisions – is the ideal tool to link the spatial, temporal and conceptual spheres of the different disciplines.

In this thesis the development of the global agricultural land-use model KLUM and its dynamic coupling to an extended version of the global general equilibrium model GTAP and the global dynamic vegetation model for crops LPJ-C was presented. The developed model is designed as a coupling tool to introduce dynamic feedbacks of biosphere and economy in an integrated framework. Effects and relevance of these feedbacks for computational analysis of climate change impacts are analyzed by means of illustrative future simulations.

In order to capture the economic as well as the biophysical aspects of land-use decisions the developed algorithm is derived from profit maximization, where yield projections enter as a spatially explicit decision factor. The representation of the land-allocation decisions benefits from the comprehensive representation of the respective processes in the specialized models by utilizing their output for the allocation process. The restriction to only the essential parameters as well as the motivationally based approach qualifies the model for long-term predictions, for global analysis and for a dynamic coupling to comprehensive state-of-the-art models of the respective disciplines. The approach is unique in its degree of integration: it delivers a system that dynamically couples a global general equilibrium model and a global dynamic vegetation model within one modeling framework.

The evaluation of KLUM as a stand-alone model in chapter 3 shows that the derived algorithm is capable of reproducing essential dynamics of land-use decisions, theoretically as well as empirically. The mathematical dynamics of the derived algorithm are in line with intuitive logic: the area share allocated to a specific crop increases for a rise in the crop's profitability and decreases for an increase of the crop's riskiness; riskiness is quantified by the variability of profits. Observed global, as well as national allocation patterns can be reproduced by the model with good agreement. False predictions are often a consequence of impacts that do not necessarily show up in price and yield data, such as political changes or local habits. A partly weak temporal agreement between model results and observations indicates that the causal timing of the effects of profitability on land-use changes is not as straight forward as assumed in the model. It seems that the time-lag between a change in price or yield and its effect on the allocation can vary over crop, country and even over time. The good agreement between simulated and observed mean values, however, shows that only the exact timing of the impact is problematic whereas, on average, profitability changes affect on the crop allocation in the suggested way.

The importance of the integrated approach within KLUM could be demonstrated by means of three different future simulations with KLUM as a stand-alone-model. In the first simulation, linearly extrapolated price trends as well as climate induced yield changes are applied to the model; in the two remaining simulations either prices or yields change, and the remaining input is held constant. The results reveal a strong non-linearity in the summed effect of price and yield changes. This emphasizes the importance to include economic as well as biophysical aspects of land-use change decisions in a unifying framework. Especially the representation of competition among similar crops suffers from a separate inclusion of price and yield effects on land allocation.

Above this the results emphasize the importance of a proper inclusion of land-use changes in economic impact estimations. Monetary impacts on the crop production sector can be underestimated by more than 200% and even differ in sign, if land-use changes are ignored. Moreover, the importance of a dynamic representation of the feedbacks among land-use decisions and economic development were highlighted by the results. The extrapolated price trends lead to implausible results, amongst others due to the underestimation of the dynamic adjustment of prices according to a change in supply.

This weakness is addressed in chapter 4 where KLUM is dynamically coupled to the economic trade model GTAP-EFL, an extended version of the established Global Trade Analysis Project model GTAP (Hertel, 1997). The models are linked by replacing the land allocation mechanism of GTAP-EFL with KLUM. Price and management changes, according to GTAP-EFL, and exogenous scenarios of country specific yield values drive KLUM; regionally aggregated changes in area shares of different crops, determined by KLUM are used to update the area shares in GTAP-EFL. This intimate link establishes a dynamic feedback of country-specific land-use decisions and world-regional economic trade and production decisions. The purely economic representation of crop production in GTAP-EFL benefits from the introduction of biophysical aspects of land-use decisions; the impacts of the changing economy can be projected on agricultural land cover on country level enabling a more spatial explicit analysis of biophysical consequences.

GTAP-EFL is a computable general equilibrium model (CGE). CGEs are based on the assumption that a general equilibrium, in which all markets clear over time and space, is the best description of the economic system. Future economic shifts are projected by establishing a new equilibrium under applied changes in key parameters. Consequently, also in the coupled system the equilibrium among the two models is essential to assure consistent and reliable results. Thus, in the coupled framework the data is exchanged in several iterations for each time-step so as to reach a consistent stable equilibrium. The key problem of an ensured convergence of the coupled system is the initial land allocation situation of GTAP in combination with the "rigid structure" of CGEs.

The initial area shares used in the production are given in *value added to the production* in GTAP. 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 area share changes based on observed area shares of FAOSTAT (2004), which differ tremendously from the values used in GTAP. This difference causes a distortion of the introduced changes and can lead to divergence. A plain recalibration of the economic model is not straight forward due to the "rigid structure" of these complex models and might cause problems for model calculations addressing the value of land.

A possible work-around is to lower the responsiveness of the CGE to the introduced area changes. This was established by increasing the sectoral elasticity of substitution for primary factors. By means of a convergence test with the coupled framework a clear improvement of the convergence behavior due to this tactic could be demonstrated. Moreover, the test confirmed the connection of initial land allocation situations and the convergence behavior. The tripled elasticity, which was found to establish convergence for all regions and crops was used in the succeeding simulations, and convergence was audited for the performed experiments. The changes 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, personal communication (2006)). 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.

Projections under climate change for the year 2050 with the coupled system illustrate that plausible and consistent estimations of climate change impacts are nonetheless feasible under the aforementioned uncertainties. An economic baseline scenario was applied to transfer both models to the year 2050; climate induced yield changes were imposed to the established benchmark to assess the impact of climate change on agricultural production and economic development. Changes in GDP, welfare, CO2 emissions and trade balance were studied as indicators of economic development. Changes in the agricultural sector were evaluated by means of crop prices and production as well as country specific crop allocation changes. The general pattern of the predicted results is robust also for a reference scenario in which the climate impacts were directly introduced to the current situation. This illustrates the stability of the coupled framework on the one hand and quantifies the effect of the comparably uncertain economic baseline on the other hand; under the baseline scenario the climate impacts on the economic indicators changed in extent but typically not in sign. Additionally, the simulation point out that the effect of equalizing land values and land quantities in the CGE is enhanced under the (common) assumption that land is becoming more valuable in the future: the analysis reveals an amplifying effect of the baseline scenario on the climate-induced changes in crop prices and production and a mostly dampening impact on the changes in land allocation.

A comparison of uncoupled with the coupled simulation confirms the relevance of the coupling for the impact estimations. With both the uncoupled models the climate impacts were estimated relative to the afore established benchmark of 2050. The general pattern of wins and losses remains more or less unaffected, but a clear effect of the coupling on the relative extent of the changes is evident in both models. The land allocation changes predicted by GTAP-EFL standalone with endogenous land allocation deviate from those of the coupled framework by several hundred percent, demonstrating the relevance of the improved allocation mechanism. Moreover, the deviations are larger for rice and other cereals – the crops with the largest yield changes – indicating that the effect of the coupling will be even more pronounced for greater changes, i.e. more extreme scenarios. Price and production changes in the CGE are affected accordingly, showing deviations of some ten percent up to hundreds of percent and sometimes even have opposite signs.

Also the KLUM standalone simulations end up with area changes which differ from the coupled simulation by some ten to several hundred percent and which even show opposite signs for several countries. All this underpins the relevance of the dynamic feedbacks with the economy for a proper representation of land-use changes.

The feasibility and relevance of the coupling of KLUM to dynamic crop yield predictions is demonstrated in chapter 5 where a C++ version of KLUM is implemented in the dynamic global vegetation model LPJ-C, the Lund Potsdam Jena model for crops (Criscuolo *et al.*, 2005). 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 together with exogenous crop prices to drive the land-use decisions; the allocation coefficients for the different crops are used in LPJ-C to scale the carbon entering the soil litter pool. Like this the effects of a changing economy are projected on the carbon cycle; the environmental changes are projected back on the agricultural sector and can be expressed in economic measures. Thus, the dynamic linkage potentially enables an integrated assessment of the consequences of environmental and economic changes and their mutual interaction on crop growth and agricultural land use.

Also here the different perception of exchanged parameters cause a certain problem for the coupling. The LPJ-C model is a process-based model that simulates the development of plant growth under certain climate conditions. The crop growth is simulated under potential production, i.e. no stress affects the plant, so that the growth is driven only by temperature and light. Accordingly, the projected yields are potential yields differing from the observed yields, which are the relevant input and calibration basis for KLUM. A comparison between modeled and observed area shares was performed to quantify the implications for the simulated land-use changes. A shift of the crop pattern for the benefit of the major crops (wheat, barley, potatoes) was revealed; the general pattern, however, is not dramatically distorted. Thus, the overall performance provides an acceptable basis for a first feasibility study within the mentioned limits of the current system.

A further application of the coupled framework was conducted in order to assess the impacts of climate change within the period 2001-2100 for the European Union; hereby the consistency of the established system was further illustrated. Crop growth, carbon storage and agricultural land use changes were studied for the two IPCC climate scenarios A1 and B2. The results provide a coherent and plausible picture of future changes. The projected land-use changes clearly reflect the yield changes and the extension of the potential growing area, which are driven by CO2 and temperature changes depending on the crop typology. All in all the results demonstrate the sustained functionality and stability of the models in the coupled system, and thus legitimate the coupling procedure.

Again, impact and relevance of the coupling for the results could be clarified by means of reference simulations with the uncoupled models. For this purpose in both model the respectively exchanged variables are kept constant on the level of the initial situation of the coupling. The results demonstrate 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 they emphasize the relevance of spatial analysis of the results. For both models, the spatial pattern as well as the extent of projected changes are impacted by the coupling. Spatial variations of soil organic carbon 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 ones, indicating that a changing crop pattern reduces the carbon stored in the soil.

The results of KLUM standalone simulations suffer from the underestimated growing area and absent 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 naturally results 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 of the factors is stronger. For rice, this leads to a large overestimation of revenue and area share especially in the beginning of the KLUM standalone simulation. A general underestimation of area share is revealed for maize while wheat and potatoes are overestimated; this reflects the underestimated growing area of maize in the uncoupled run.

For all crops the differences of KLUM standalone to KLUM@LPJ simulations are larger for the scenario with higher price changes. This is also reflected in a spatial analysis of differences between coupled and uncoupled runs: Pattern as well as extent of the projected changes are impacted in scenario B2 with large price changes; only the extent differs in scenario A1. This again indicates that the effect of dynamic feedbacks is stronger in more extreme scenarios.

6.2 Conclusion and Outlook

In this thesis a global agricultural land-use model has been developed to establish a dynamic link between comprehensive global state-of-the-art economy and vegetation models. To solve some conceptual differences of the models, compromises and workarounds had to be accepted, which should be revised and eventually resolved in future work. However, the general link to dynamically couple economy and biosphere in a single modeling framework is established; problems of linking the different notions of time, space and key parameters are technically and conceptually addressed and future steps are clearly outlined. The illustrative future simulations with the coupled framework in its different stages suggest that the system is stable and capable of producing a plausible and coherent picture of future pathways.

The expedience and relevance of the included feedbacks for the respective modeling framework and analysis have been demonstrated and assessed for each step of the coupling procedure. Differences in the outcome of coupled and uncoupled models outline the relevance of the introduced feedbacks for the results of the simulation. These differences are even more pronounced with larger changes of exogenous factors, indicating the great relevance for extreme scenarios. All this strongly supports the initial hypothesis that the consideration of the dynamic feedbacks of economy, land use and vegetation are of great importance for climate change analysis; the results clearly motivate a continuation of the present work.

Nonetheless, to really establish a satisfactory modeling framework that allows reliable projections of the joint changes in the natural and economic system a long way is still ahead.

With regard to the coupling the most important next step is to complete the feedback loop by combining the two couplings within one framework. For that a dynamic formulation of GTAP-EFL is an important step. This would also help to simulate future pathways with the coupled framework in small, gradual steps rather than the drastic shocks applied here; the conditions for convergence of KLUM and GTAP-EFL would thus be improved. Yet, the convergence problem and inconsistency in the interpretation of land quantity in the two models need to be resolved in a more fundamental way. One way to address this 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. It would imply, though, that KLUM can no longer be run as a standalone model, hampering model validation. But most importantly it would prevent the coupling to the biophysical model and thus basically obscure the concept and aim of the model. The alternative is an elaborate revision of the land-including mechanisms in the general equilibrium model and - in all likelihood - a recalibration of GTAP-EFL.

The most important issue in the coupling of KLUM and LPJ-C is the re-calibration and spin up of the coupled system as one single model. A proper "translation" of potential into actual yields, in order to make the output of LPJ-C more comparable to the observed yields, would dissolve distortions in the model results in the first years after the spin up. But also the crop harvesting is described with an oversimplified approach in the current framework: storage organs are taken out of the field and the rest of the biomass is moved to the agricultural soil. This misrepresents common harvesting and agronomic techniques, which can be very relevant in the soil carbon balance. In the long run, a feedback of soil dynamics to crop growth in LPJ-C would be desirable in order to close the feedback loop of land use and crop growth.

Concerning the KLUM model itself, the most important expansion is the representation of management and irrigation decisions in the allocation algorithm and the inclusion of other agricultural sectors such as animal or biofuel production; other land intensive sectors such as forestry and finally also recreational and industrial land should follow. Some of these aspects are hard to predict, but they will govern future land-use patterns. To determine e.g. whether food demand in a changing world will be satisfied by the expansion of agricultural area or by the intensification of management and irrigation, a proper description of agricultural practices is just as important as the representation of competition for land among the different sectors.

A first estimate of the impact of management has been introduced by means of the management-induced yield changes exchanged with GTAP. Yet, to assess the environmental impacts and gain a realistic impression of the effect on yields on a local level, a more detailed and spatial representation is required. The most obvious way to express the decision for certain management and irrigation strategies in the allocation algorithm would be via nonlinear cost-functions. This would preserve the current, simple structure of the model and keep the required input data manageable. Additionally, it would add flexibility to the currently fixed cost structure and thus improve the capability of the model to adapt to future changes.

The introduction of further land use types in KLUM is conceptually straight forward for the land-intensive sectors. Biofuels are just another crop and animal production can be treated as a crop in a first instance as well. The "yield" per area of meat and diary production is an issue of the feed conversion factor that determines the fraction of pasture and "fodder-land" used to produce a certain amount of meat or milk; the actual quantity of such a factor could be linked to the associated costs of the different feeding methods.

The main issue concerning forestry is the representation of forward looking behavior; the profit expected in forestry depends on the expected growth and price of timber and should be in line with the predictions of the larger models. Following the present concept of KLUM, the obvious approach would be to base the expectations on past experience. In order to acknowledge the long-term aspect of forest management decisions, not only the average yield of the previous time-steps but also the trend of past observations should be considered in the decision modeling. But to appropriately represent the "entire" value of forests, the recreational and conservational aspects need to be considered as well. Valuation studies could build a first basis to include recreational land-use in the underlying profit function of KLUM. Such studies aim to quantify the current benefit of forest recreation and develop a consistent representation of the implied economic value by transferring this benefit over time and space (Zandersen *et al.*, 2005a; Zandersen *et al.*, 2005b). However, such transfers are subject to high uncertainty (Zandersen, 2005) and it should be critically assessed if the decision of maintaining or protecting recreational and natural land is appropriately represented by a profit maximization. Nonetheless, this is important, as agricultural land in Europe and North America is rapidly converted to areas for nature and recreation.

The inclusion of urban area and industrial land is not so pressing concerning their spatial extent: they account for less than 1% of the land surface (Grübler, 1994). Still, the process of urbanization yields some importance for global land-use change through rural-urban linkage (Clark, 1998; Delgado, 2003); it also governs pollution, infrastructre and run-off. However, the feasibility and relevance of including such level of detail in global models need to be critically assessed. It should be kept in mind that the global level – at least within current state-of-the-art – restricts any analysis to trend analysis. Even though projected on a spatially fine resolved grid, the process representation in the KLUM model is rather coarse, designed for a global model and for trend estimations. To ensure that no fundamental aberrations are accumulated from the local level, also a crosscheck with local studies is important for the further development and evaluation of KLUM.

All in all this work is only a first step of a long way. It should be seen as a feasibility study, pointing out a direction to go.

APPENDIX

A. MODEL SPECIFICATIONS

Tab. A1. ***Regional aggregation of simulated countries in KLUM:*** *Countries in italic letters are used only in the calibration for future scenarios*

Region	Country	Region	Country	Region	Country
ANZ	Australia	SAA	Afghanistan	SSA	Angola
	New Zealand		Bangladesh		Benin
			Bhutan		Botswana
CAM	Belize		India		Burkina Faso
	Costa Rica		Nepal		Burundi
	El Salvador		Pakistan		Cameroon
	Guatemala		Sri Lanka		Cape Verde
	Honduras				Central African Republic
	Mexico	SAM	Argentina		Chad
	Nicaragua		Bolivia		Congo, Dem. Rep. of the
	Panama		Brazil		Congo, Rep. of the
			Chile		Cote d'Ivoire
CAN	Canada		Colombia		Djibouti
			Ecuador		Equatorial Guinea
CEE	Albania		French Guiana		Gabon
	Bosnia and Herzegovina		Guyana		Gambia, The
	Bulgaria		Paraguay		Ghana
	Croatia		Peru		Guinea
	Hungary		Suriname		Guinea-Bissau
	Macedonia, FYR		Uruguay		Kenya
	Poland		Venezuela		Lesotho
	Romania				Liberia
	Slovenia	SEA	Brunei Darussalam		Madagascar
			Cambodia		Malawi
CHI	China		Indonesia		Mali
	Korea, Dem. People's Rep.		Lao People's Dem. Rep.		Mauritania
	Mongolia		Malaysia		Mozambique
			Myanmar (Burma)		Namibia
FSU	*Azerbaijan*		Papua New Guinea		Niger
	Belarus		Philippines		Nigeria
	Estonia		Singapore		Rwanda
	Georgia		Thailand		Samoa
	Kazakhstan		Vietnam		Senegal
	Kyrgyzstan				Sierra Leone
	Latvia	SIS	Antigua and Barbuda		Somalia
	Lithuania		Bahamas		South Africa
	Moldova		Barbados		Sudan
	Russian Federation		Bermuda		Swaziland
	Tajikistan		Comoros		Tanzania, United Rep.
	Turkmenistan		Cuba		Togo
	Ukraine		Dominica		Uganda
	Uzbekistan		Dominican Republic		Zambia
			Fiji		Zimbabwe
JPK	Japan		French Polynesia		
	Korea, Rep.		Grenada	USA	United States
			Guadeloupe		
MAF	Algeria		Haiti	WEU	Austria
	Egypt		Jamaica		Belgium
	Libyan Arab Jamahiriya		Maldives		Cyprus
	Morocco		Martinique		Denmark
	Tunisia		Mauritius		Finland
			New Caledonia		France
MDE	Iran, Islamic Rep.		Puerto Rico		Germany
	Iraq		Reunion		Greece
	Israel		Sao Tome and Principe		Iceland
	Jordan		Seychelles		Ireland
	Kuwait		Solomon Islands		Italy
	Lebanon		St. Kitts and Nevis		Malta
	Oman		St. Lucia		Netherlands
	Qatar		St. Vincent & Grenadines		Norway
	Saudi Arabia		Tonga		Portugal
	Syrian Arab Rep.		Trinidad and Tobago		Spain
	Turkey		Vanuatu		Sweden
	United Arab Emirates				Switzerland
	West Bank and Gaza				United Kingdom
	Yemen				

Tab. A2. ***Parameterization in KLUM:*** *The risk aversion parameter γ as calculated in the full calibration run with restricted γ*

Country	γ	Country	γ	Country	γ
Australia	9.87E-06	Bhutan	2.25E-14	Botswana	0.00141
New Zealand	2.54E-05	India	5.40E-05	Burkina Faso	3.79E-05
Belize	4.83E-05	Nepal	2.22E-14	Burundi	2.22E-14
Costa Rica	2.22E-14	Pakistan	5.85E-05	Cameroon	3.56E-14
El Salvador	2.23E-14	Sri Lanka	2.22E-14	Cape Verde	2.22E-14
Guatemala	0.000127	Argentina	2.94E-05	Central African Republic	2.34E-14
Honduras	2.22E-14	Bolivia	2.43E-14	Chad	0.000266
Mexico	1.12E-11	Brazil	3.07E-05	Congo, Dem. Rep. of the	3.01E-14
Nicaragua	2.22E-14	Chile	2.22E-14	Congo, Rep. of the	2.23E-14
Panama	3.55E-06	Colombia	2.73E-14	Cote d'Ivoire	2.22E-14
Canada	5.15E-05	Ecuador	3.29E-14	Djibouti	3.00E-07
Albania	9.51E-08	French Guiana	2.22E-14	Equatorial Guinea	1.39E-09
Bosnia and Herzegovina	6.68E-07	Guyana	4.02E-05	Gabon	2.22E-14
Bulgaria	2.23E-14	Paraguay	2.30E-14	Gambia, The	2.73E-14
Croatia	5.19E-07	Peru	2.22E-14	Ghana	2.22E-14
Hungary	2.22E-14	Suriname	2.38E-14	Guinea	0.00136
Macedonia, FYR	6.19E-07	Uruguay	2.22E-14	Guinea-Bissau	3.63E-06
Poland	2.15E-07	Venezuela	2.22E-14	Kenya	3.62E-06
Romania	1.54E-07	Brunei Darussalam	1.13E-05	Lesotho	2.22E-14
Slovenia	5.95E-07	Cambodia	2.22E-14	Liberia	2.23E-14
China	1.88E-13	Indonesia	2.26E-14	Madagascar	3.96E-14
Korea, Dem. People's Rep.	1.75E-05	Lao People's Dem. Rep.	7.38E-11	Malawi	4.02E-05
Mongolia	2.22E-14	Malaysia	2.22E-14	Mali	2.22E-14
Azerbaijan	2.68E-09	Myanmar (Burma)	2.23E-14	Mauritania	0.00018
Belarus	1	Papua New Guinea	1.14E-06	Mozambique	0.00122
Estonia	1.38E-05	Philippines	2.62E-14	Namibia	2.39E-14
Georgia	6.34E-10	Singapore	1.63E-05	Niger	2.42E-08
Kazakhstan	1.51E-07	Thailand	1.95E-05	Nigeria	9.65E-07
Kyrgyzstan	9.61E-10	Vietnam	2.71E-14	Rwanda	2.39E-14
Latvia	2.53E-08	Antigua and Barbuda	0.0383	Samoa	5.82E-14
Lithuania	3.91E-08	Bahamas	2.22E-14	Senegal	2.43E-14
Moldova	0.999	Barbados	2.23E-14	Sierra Leone	2.23E-14
Russian Federation	6.50E-08	Bermuda	0.1	Somalia	3.52E-14
Tajikistan	0.1	Comoros	2.33E-06	South Africa	3.05E-14
Turkmenistan	0.999	Cuba	3.23E-06	Sudan	2.54E-12
Ukraine	0.992	Dominica	0.121	Swaziland	2.22E-14
Uzbekistan	7.05E-05	Dominican Republic	2.22E-14	Tanzania, United Rep.	2.22E-14
Japan	2.22E-14	Fiji	3.03E-05	Togo	7.51E-05
Korea, Rep.	5.55E-07	French Polynesia	1	Uganda	7.84E-06
Algeria	2.78E-05	Grenada	2.22E-14	Zambia	1.68E-08
Egypt	4.00E-06	Guadeloupe	7.23E-06	Zimbabwe	4.22E-14
Libyan Arab Jamahiriya	1.18E-05	Haiti	2.22E-14	United States	0.000591
Morocco	8.66E-06	Jamaica	2.00E-07	Austria	2.23E-14
Tunisia	2.22E-14	Maldives	2.56E-06	Belgium	6.20E-06
Iran, Islamic Rep.	2.61E-14	Martinique	3.57E-05	Cyprus	2.22E-14
Iraq	5.71E-06	Mauritius	2.25E-14	Denmark	4.27E-14
Israel	2.22E-14	New Caledonia	9.58E-07	Finland	1.34E-05
Jordan	2.22E-14	Puerto Rico	0.0916	France	2.22E-14
Kuwait	2.22E-14	Reunion	6.08E-07	Germany	4.14E-14
Lebanon	2.47E-14	Sao Tome and Principe	2.24E-14	Greece	2.60E-14
Oman	2.22E-14	Seychelles	6.50E-06	Iceland	0.1
Qatar	3.55E-14	Solomon Islands	2.22E-14	Ireland	2.46E-14
Saudi Arabia	6.05E-06	St. Kitts and Nevis	4.46E-06	Italy	0.00221
Syrian Arab Rep.	0.00106	St. Lucia	4.55E-06	Malta	4.08E-08
Turkey	2.29E-14	St. Vincent & Grenadines	2.22E-14	Netherlands	1.01E-06
United Arab Emirates	7.05E-06	Tonga	2.22E-14	Norway	3.50E-14
West Bank and Gaza	4.98E-07	Trinidad and Tobago	4.14E-06	Portugal	0.00145
Yemen	8.89E-06	Vanuatu	2.24E-14	Spain	4.32E-14
Afghanistan	2.51E-13	Angola	2.22E-14	Sweden	2.22E-14
Bangladesh	2.22E-14	Benin	2.55E-14	Switzerland	1.41E-07
				United Kingdom	2.22E-14

Tab. A3. ***Sectoral aggregation of GTAP-EFL***

Sector	Description
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

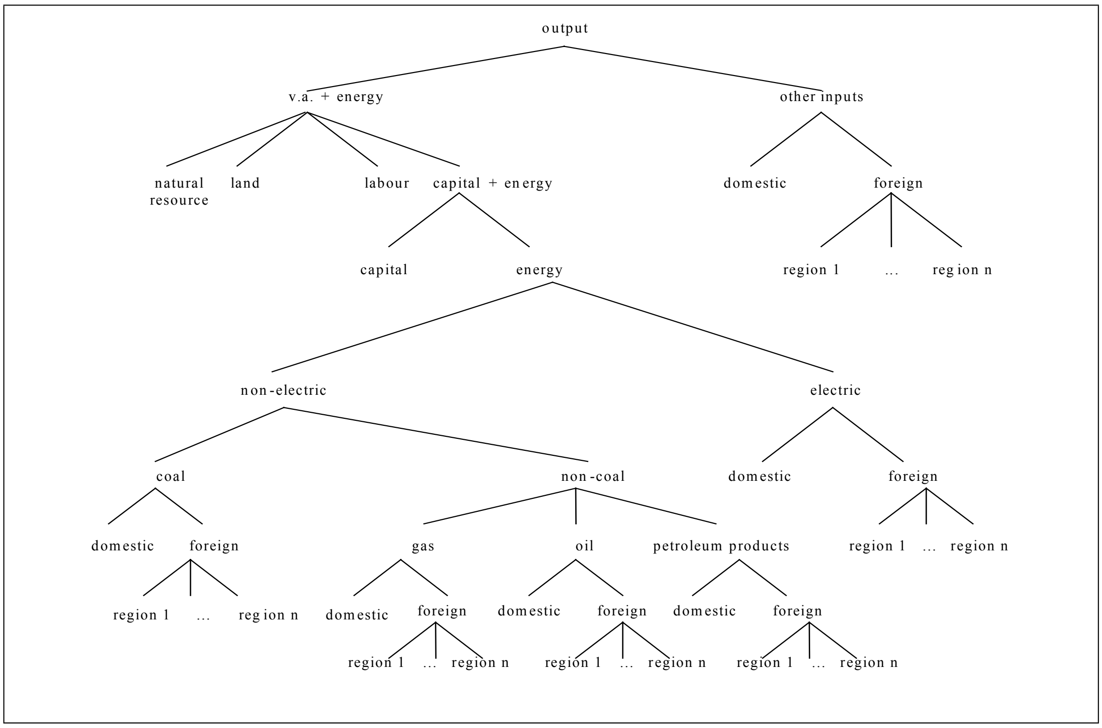

Fig. A1. ***Industrial Production in GTAP-EFL:*** *Nested tree structure for industrial production processes in GTAP-EFL*

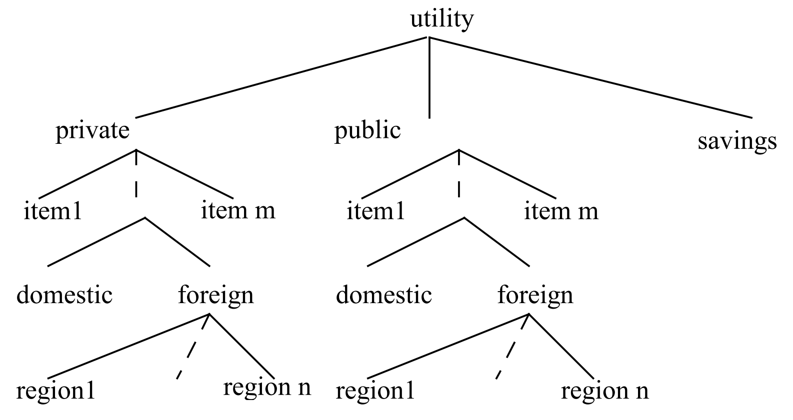

Fig. A2. ***Final demand in GTAP-EFL:*** *Nested tree structure for final demand in GTAP-EFL*

B. SCENARIO ASSUMPTIONS

Tab. B1. ***Baseline scenario:*** *Exogenous changes in key macroeconomic variables applied in the 2050 baseline. Values are expressed as percentage changes relative to 1997 quantities. With LUS we refer 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 land productivity**
	population	capital	labor	LUS, Forestry, Fishing, En_Int_ind	Energy	Electricity	Water, Oth_ind, MServ, NMServ	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

KLUM@GTAP

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 *naturally exogenous* in CGE models. For example, the national labor force is usually taken as given. In the baseline scenario, we shock the exogenous variable

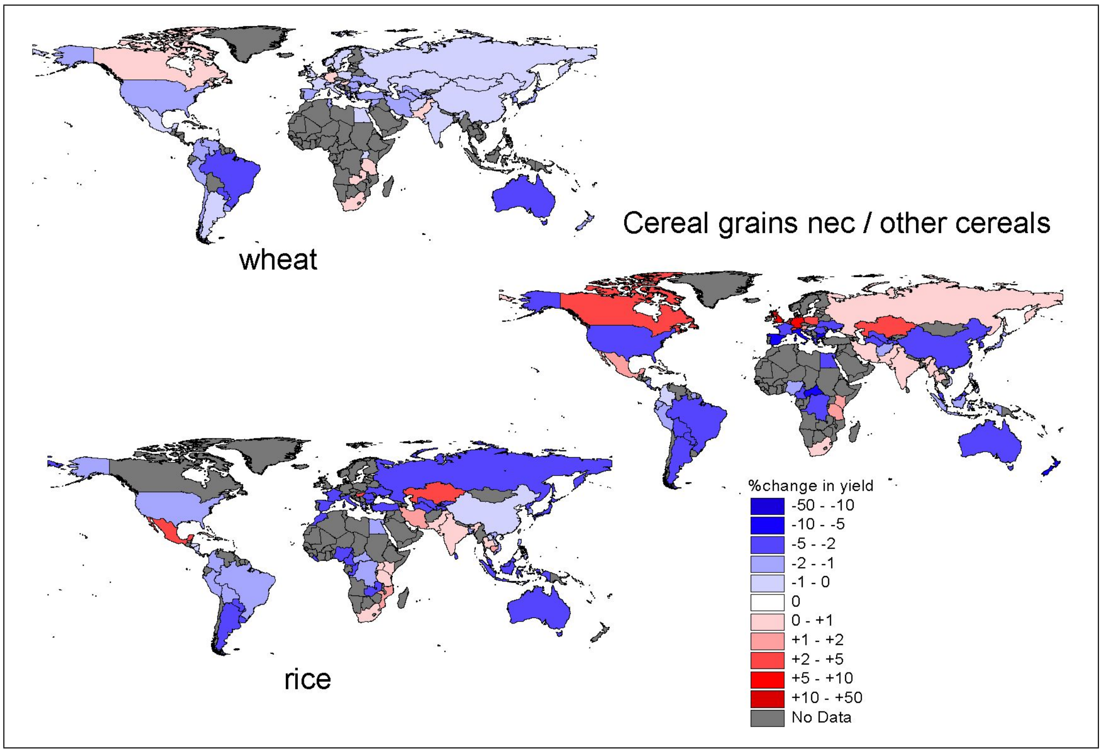

Fig. B1. ***Climate change scenario:*** *Yield changes assumed in the climate change scenarios. Values are adopted from (Tan & Shibasaki, 2003).*

labor 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. We use the same data as in the KLUM standalone simulation described in Section 3.4. The yield changes are depicted in Figure (see Figure B1). The yields of the vegetables & fruits aggregates are assumed to stay on the level of 1997.

In all simulations the variances σ^2 (compare equation 3.2.2), reflecting the riskiness of a certain crop in KLUM, 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 to be

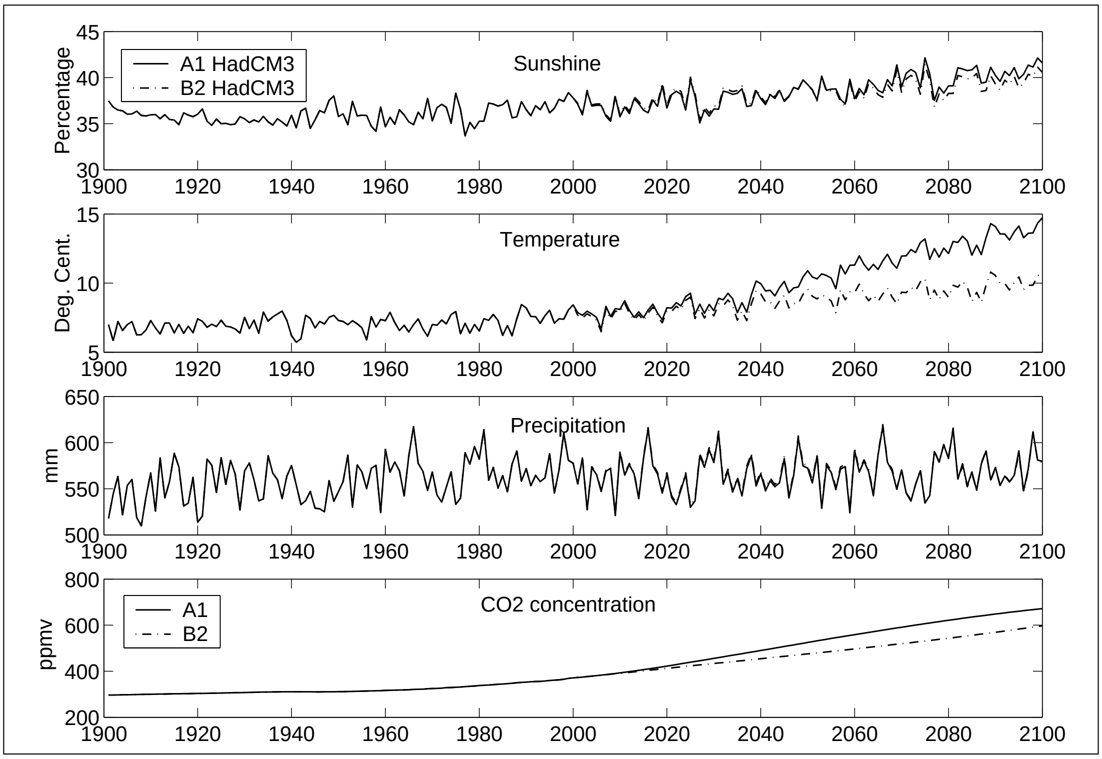

Fig. B2. ***Climate change scenarios for KLUM@LPJ:*** *Climate forcing for the different scenarios averaged over the simulation grid.*

$ESBV \approx 0.711$, which is the triple of the original value.

KLUM@LPJ

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 B2). 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 B3). Total available cropland is assumed to stay on current level (see Figure B4) for the entire simulation.

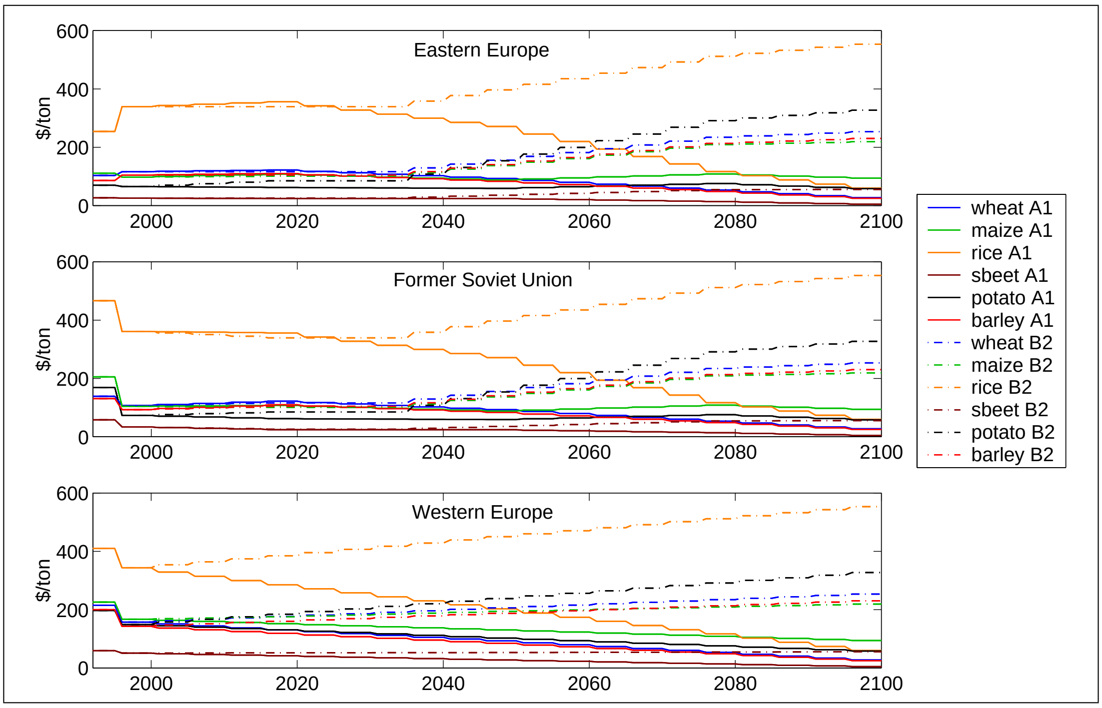

Fig. B3. ***Price scenarios for KLUM@LPJ:*** *future price changes for the different economic regions.*

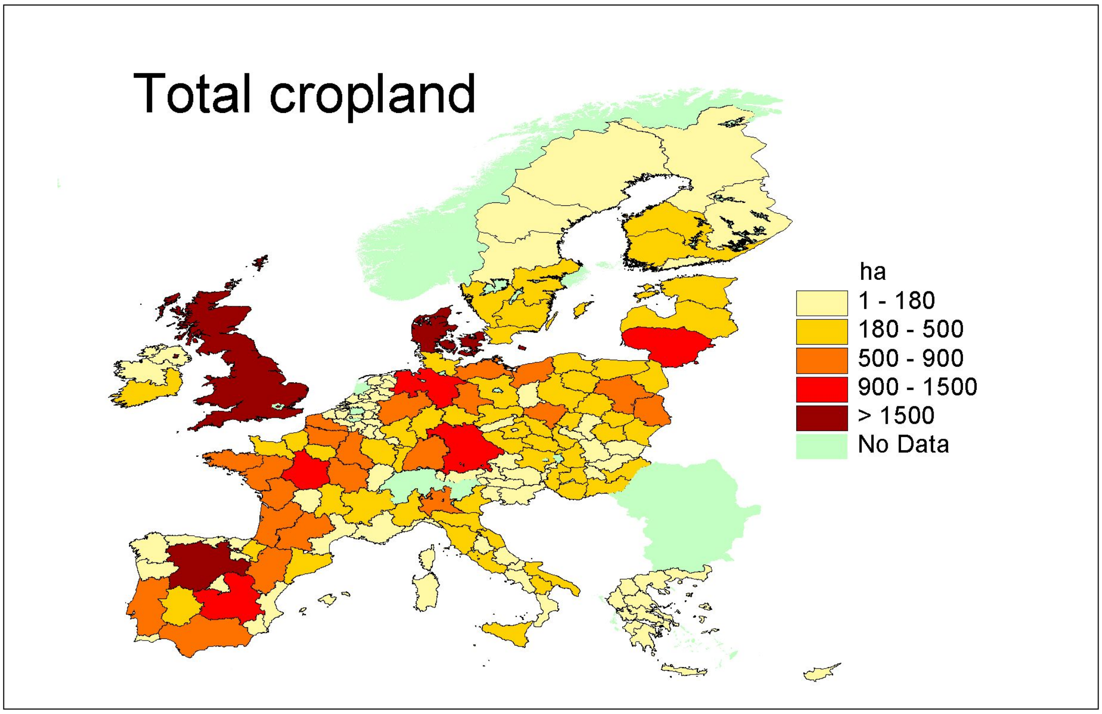

Fig. B4. ***Total available cropland in KLUM@LPJ:*** *Total cropland in ha for the different NUTS2 regions.(adopted from (Eurostat New Cronos, 2005))*

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