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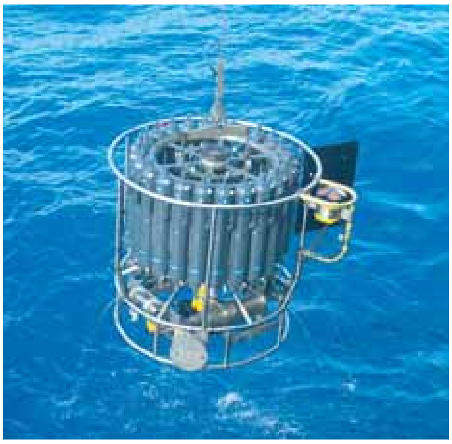
Climate Change and Global Land-Use Patterns — Quantifying the Human Impact on the Terrestrial Biosphere

Christoph Müller



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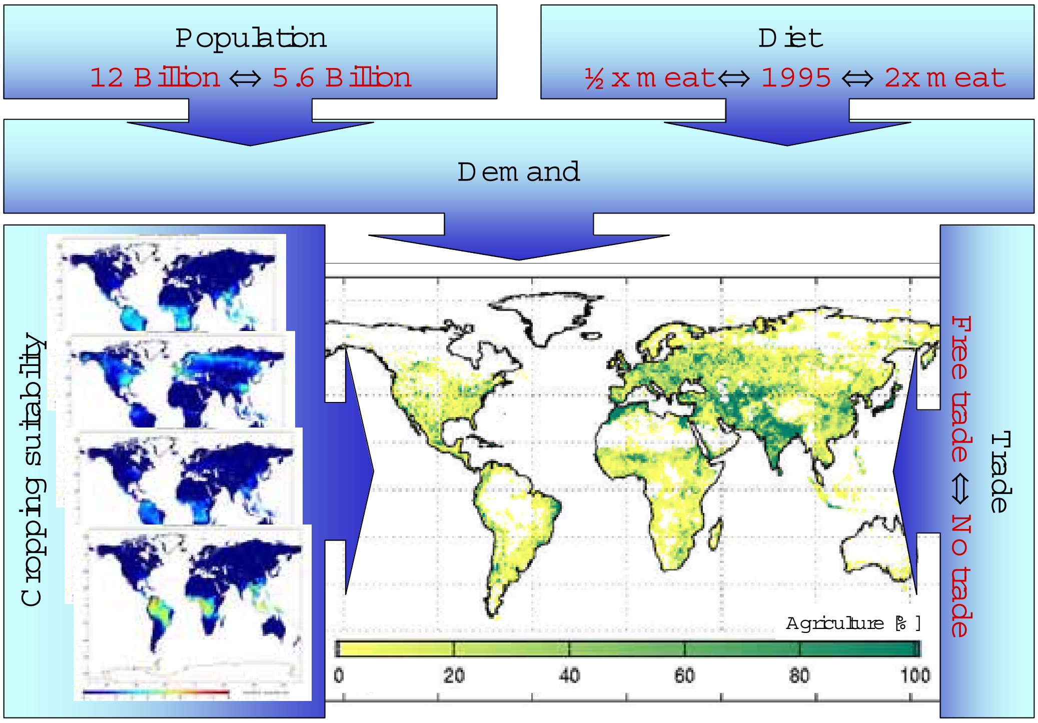

Christoph Müller

Potsdam 2007

The intellectual is constantly betrayed by his vanity. Godlike he blandly assumes that he can express everything in words; whereas the things one loves, lives, and dies for are not, in the last analysis, completely expressible in words.

Anne Murrow Lindbergh

This thesis was printed on paper that was produced with elemental chlorine free bleaching process, using wood from sustainable forestry.

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> *A human being should be able to change a diaper, plan an invasion, butcher a hog, conn a ship, design a building, write a sonnet, balance accounts, build a wall, set a bone, comfort the dying, take orders, give orders, cooperate, act alone, solve equations, analyze a new problem, pitch manure, program a computer, cook a tasty meal, fight efficiently, die gallantly.*
> *Specialization is for insects.*
>
> Robert Heinlein, Time Enough for Love

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Abstract

Humans actively shape the terrestrial biosphere in order to produce essential resources such as food, fiber, and wood as well as for settlements, industries, and infrastructure. Their activities also affect climate, oceans, and the functioning of the Earth System and, thus, change the terrestrial biosphere also indirectly. It is important to understand the processes, dynamics, and interactions of the Earth System in order to assess the consequences of human activity, such as large-scale fossil fuel combustion or tropical deforestation. With the help of computer models, the future development of the Earth System can be projected into the future under different scenarios of societal development.

This study focuses on the effects of human land use and climate change on the global terrestrial biosphere. I demonstrate the importance of land use and land-use change for the global terrestrial carbon and water cycles in two different analyses: In a static-comparative setting, investigating the effects of three different socio-economic drivers of land-use change (demography, diet, market structure) and in consistent future projections of the 21st century, analyzing the effects of land-use change and climate change. For the first study, I generated stylized spatially explicit land-use data. In the second, I used the consistent land-use and climate data sets generated by the Integrated Model to Assess the Global Environment (IMAGE 2.2) for the Special Report on Emission Scenarios (SRES) A2, B1, and B2. Both analyses show that the effects of land use and land-use change on the global terrestrial carbon cycle are equally important to the effects of CO_2 fertilization and climate change, causing terrestrial carbon losses of up to 450 PgC under the A2 scenario. For the terrestrial water cycle, land use and land-use change mainly result in reduced transpiration and increased evaporation fluxes, with little effects on runoff at the global scale.

The rate of land-use change and the spatial localization of agricultural production are of major importance for the effects of land use and land-use change on the terrestrial biosphere. However, reliable, spatially explicit data on global land-use change for future projections are hardly available. To overcome this imbalance between importance and availability of land-use data, a globally applicable, spatially explicit land-use model is needed. In a review of the state-of-the-art of large-scale land-use modeling, I provide an overview of existing models and approaches. Geographic approaches focus on land suitability, spatial interaction and constraints on the supply side, while economic approaches focus on the demand side, employing preferences, motivations, as well as market and population structures to explain changes in the production of land-intensive goods. Integrated approaches exist that combine economic and geographic methodologies. However, they do not exploit the entire potential of this integration yet. A major obstacle in integrating economic and geographic approaches is the difference in spatial scales. Economic models typically operate at regional or national scales, while geographic models mainly operate on spatially explicit grids. To bridge the gap between these spatial scales, I explore the robustness of Dynamic Global Vegetation Model (DGVM) simulations against reductions in spatial resolution. Coarser spatial resolutions do not differ qualitatively from finer spatial grids, as the deviation from the typically used 0.5° grid increases linearly with grid coarseness with a small slope (less than 1.5 percent deviation per degree).

As an outlook, I introduce a newly developed globally applicable land-use model, MAgPIE (Model of Agricultural Production and its Impact on the Environment), an economic optimization model, which generates spatially explicit land-use patterns at a spatial resolution of 3.0° x 3.0°. Essential inputs are spatially explicit data on yield levels and freshwater availability, which are provided by the Lund-Potsdam-Jena DGVM for managed Lands (LPJ/mL), and regional data on population, production costs, and Gross Domestic Product (GDP) only. MAgPIE internally computes changes in diets, and thus demand, based on empirical relations to GDP if no suitable input data are available. Besides generating spatially explicit land-use patterns, MAgPIE allows for exploring the effects of technology change and trade liberalization, and for valuating the competition for land and water.

Zusammenfassung

Die terrestrische Biosphäre wird durch Landnutzung, Klimawandel und erhöhte Kohlenstoffdioxidkonzentrationen in der Atmosphäre stark vom Menschen beeinflusst. Da sie die Grundlage der land- und holzwirtschaftlichen Produktion ist, ist es von besonderer Wichtigkeit, die Prozesse und Rückkopplungen zwischen der Biosphäre und der menschlichen Gesellschaft zu untersuchen, um die Auswirkungen der menschlichen Einflussnahme, wie z.B. die der tropischen Abholzung oder von großskaliger Verbrennung von fossilen Brennstoffen, abschätzen zu können.

In zwei unterschiedlichen Studien wird die Bedeutung der Landnutzung und des Landnutzungswandels für die terrestrischen Kohlenstoff- und Wasserkreisläufe demonstriert: die Bedeutung von drei verschiedenen sozio-ökonomischen Triebkräften (Demographie, Ernährungsgewohnheiten, Handelsstrukturen) des globalen Landnutzungswandels wird in vergleichenden Szenarien untersucht, und das Zusammenwirken von Klima- und Landnutzungswandel wird in konsistenten Zukunftsprojektionen des 21. Jahrhunderts ergründet. Beide Analysen zeigen, dass die Auswirkungen von Landnutzung und Landnutzungswandel auf den terrestrischen Kohlenstoffkreislauf vergleichbar sind mit denen des Klimawandels und der erhöhten atmosphärischen Kohlenstoffdioxidkonzentration. Durch Landnutzungswandel werden bis zum Jahre 2100 bis zu 450 Pg terrestrischen Kohlenstoffs freigesetzt. Beim terrestrischen Wasserkreislauf ist vor allem eine Verschiebung von Transpirations- zu Evaporationsflüssen zu beobachten mit — auf globaler Ebene — geringen (<4 %) Auswirkungen auf den Abfluss.

Es wird gezeigt, dass die räumliche und zeitliche Dynamik des Landnutzungswandel von besonderer Wichtigkeit für das Ausmaß der Beeinflussung der globalen Kohenstoff- und Wasserkreisläufe ist. Räumlich explizite Daten zu möglichen zukünftigen globalen Landnutzungsmustern sind jedoch bis auf wenige Ausnahmen nicht verfügbar. In einem Review zum Stand der wissenschaftlichen Landnutzungsmodellierung auf der kontinentalen bis globalen Skala wird ein Überblick über bestehende Ansätze gegeben: Disziplinäre Ansätze sind geographisch oder ökonomisch orientiert und konzentrieren sich entweder auf die räumlichen Einschränkunger der Produktion oder auf das ökonomische Zusammenspiel von Angebot, Produktion und Nachfrage. Integrierte Ansätze versuchen die Stärken dieser disziplinären Methoden zu kombinieren, schöpfen bisher aber nicht das volle Potential dieser interdisziplinären Integration aus.

Ein Haupthindernis für die Integration von geographischen und ökonomischen Methoden sind ihre unterschiedlichen räumlichen Skalen. Um ihre Passfähigkeit zu erhöhen, wird die Beständigkeit der Simulationsergebnisse von globalen Ökosystemmodellen unter reduzierten räumlichen Auflösungen untersucht. Gröbere räumliche Auflösungen unterscheiden sich qualitativ nicht von feineren; die prozentuale Abweichung von den validierten globalen Ergebnissen des Halbgradrasters nimmt linear und mit einer flachen Steigung zu (<1,5 % pro Grad).

Als Ausblick wird ein neues, global anwendbares Landnutzungsmodell vorgestellt. Dieses generiert räumlich explizite Landnutzungsmuster auf einem 3,0° x 3,0° Raster unter Berücksichtigung geographischer Muster der Landnutzungseignung und ökonomischer Strukturen. Das Modell wird validiert und Erweiterungspotentiale und Limitationen werden aufgezeigt.

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Chapter 1

General Introduction

> *Destiny came down to an island, centuries ago, and summoned three of the inhabitants before him. "What would you do," asked Destiny, "if I told you that tomorrow this island will be completely inundated by an immense tidal wave?" The first man, who was a cynic, said, "Why, I would eat, drink, carouse and make love all night long!" The second man, who was a mystic, said, "I would go to the sacred grove with my loved ones and make sacrifices to the gods and pray without ceasing." And the third man, who loved reason, thought for a while, confused and troubled, and said, "Why, I would assemble our wisest men and begin at once to study how to live under water."*
>
> Leo Rosten, Captain Newman, M.D.

1.1 Background and Motivation

Human existence is closely linked to the environmental conditions on earth, which enabled human civilizations to develop and flourish. For most of their existence, human beings utilized and shaped their natural environment at the local or — at most — regional level. This, however, has changed. During the Industrial Age, human interaction with the natural environment has increased in intensity and expanded in space. The effects are no longer limited to the locality of interaction but sum up to impacts that are perceivable at the global scale, as e.g. climate change. Main drivers of this growing impact are population and economic growth, increasing the number of consumers and per-capita consumption of resources. Fossil fuels, such as oil and coal, are exploited at ever increasing rates [IPCC, 2001] to satisfy the increasing demand for energy. The growing demand for food, fibers, and wood shapes the earth's surface. Additional land is being cultivated or intensified to supply these resources in increasing quantities [FAO, 2002], but land is also abandoned after overexploitation or for economic reasons. Impacts are numerous and affect various compartments of the Earth System as well as their interactions with each other: Fossil fuel emissions transfer additional carbon to the atmosphere, biosphere, and oceans, affecting climate [IPCC, 2001], oceanic chemistry [Andersson et al., 2006], and vegetation dynamics [Woodward and Lomas, 2004]. Changes in land use contribute to and modulate these processes but also affect freshwater availability [Wallace, 2000], soil fertility [McNeill and Winiwarter, 2004], and species diversity [Sala et al., 2000], which are also affected by climate change.

Being globally perceivable, environmental change has also become a matter of global public concern, which is manifested in various political instruments, as e.g. the Rio Declaration on Environment and Development [United Nations, 1992] and the Kyoto Protocol to the United Nations Framework Convention on Climate Change [UNFCCC, 1997]. Climate change is the predominant topic within the Global Change debate: causes and consequences are complex and concern both natural systems and human societies. Climate change abatement and adaptation measures are heavily debated, as some fear that mitigation costs may not be balanced by avoided climate change damages, while others fear that mitigation measures as planned will not suffice to limit climate change damages to acceptable bounds [Tol, 2005]. A thorough understanding of the Earth System is needed in order to derive adequate solution strategies and to reduce the uncertainty of climate change and climate change impact projections.

With our current understanding of the Earth System and the computer models derived from this knowledge, we are able to project some significant aspects of its future development. These projections are uncertain, given that many processes and interactions are not completely understood or quantified.

However, model-based projections allow for an early assessment of possible future developments and — provided that adequate measures can be identified and implemented — for early interventions, if the projected development seems unfavorable. In order to reduce the uncertainty of future projections, it is of crucial importance to understand the most important processes in the Earth System and to quantify them.

Within this thesis, I concentrate on the terrestrial carbon cycle, which constitutes an important linkage between human activities, the atmosphere, oceans, and the terrestrial biosphere. In the next section, I introduce the relevant processes of the terrestrial carbon cycle that interacts with the terrestrial water cycle, climate, and land-use changes and identify gaps of knowledge that need to be addressed in order to better understand the role of the terrestrial carbon cycle within the Earth System. Based on this overview, I introduce the objectives of this thesis in Section 1.3 and summarize the results in Section 1.4, concluding with a discussion of my findings in Section 1.5. Section 1.6 provides an overview of my personal contributions to the individual papers of this thesis.

1.2 Terrestrial carbon cycle, climate, and land use

The global carbon cycle is most important within the Earth System, because carbon dioxide (CO_2) is — followed by methane (CH_4), nitrous oxide (N_2O) and several other radiatively active carbon compounds — the most prominent and most important anthropogenic greenhouse gas, and largely responsible for climate change [IPCC, 2001]. The carbon exchange between the atmosphere, oceans, and the terrestrial biosphere largely constitutes the global carbon balance[1]. In the 1990s, the carbon uptake by oceans and the terrestrial biosphere was 1.7(±0.5) and 1.4(±0.7) PgC per year respectively, dampening the carbon emissions of 6.3(±0.4) PgC per year to an atmospheric increase of 3.2(±0.1) PgC per year [IPCC, 2001].

Under natural vegetation, two opposed processes basically determine the land-atmosphere carbon exchange: Plants accumulate atmospheric carbon through net primary production (NPP) and transfer it through litterfall to the soil, from where it is returned to the atmosphere by heterotrophic respiration (R_h). In case of fire, the carbon stored in biomass and litter is directly returned to the atmosphere. Under stable climatic and management conditions, NPP and R_h are in equilibrium, with steady carbon pools in vegetation and soil. Changing climate and increasing atmospheric CO_2 concentrations, which enhance plant growth via CO_2 fertilization[2], destabilize the terrestrial carbon balance. Thus, the terrestrial biosphere currently acts as a net carbon sink [House et al., 2003; Malhi, 2002; Prentice et al., 2001], dampening the accumulation of CO_2 in the atmosphere from fossil fuel combustion and cement production. Model results show, however, that during the course of the 21st century the terrestrial biosphere may become a net source of carbon and lead to additional carbon emissions [e.g. Cox et al., 2000; Schaphoff et al., 2006], accelerating and amplifying climate change.

Size and direction of this land-atmosphere carbon exchange flux are strongly affected by water availability. On the one hand, plants transpire water in exchange for carbon uptake and need to reduce their stomatal conductance under water stress, reducing their growth and, thus, less carbon is being accumulated. Under severe water stress, plants cannot exist and no carbon is stored in the soil, as in many deserts. Climate change and especially changes in precipitation patterns thus affect the vegetation cover. This is demonstrated for example by Cox et al. [2004], who project a dieback of the Amazon rainforest due to decreasing precipitation in this area and by de Noblet-Ducoudre et al. [2000], who show that the vegetation cover in the Sahara region 6000 years ago was strongly determined by precipitation patterns. On the other hand, soil moisture determines, in combination with temperature, the rate of soil respiration [Gerten et al., 2004]. Water availability affects both carbon uptake (NPP) and carbon emissions (R_h) of the terrestrial biosphere and, thus, plays a pivotal role in the global carbon cycle.

This natural interaction between climate, vegetation and the coupled carbon and water cycles is largely affected by human modifications of the earth's surface. Humans transform earth's soil and vegetation cover in order to produce land-intensive commodities, such as food, fiber, and wood. These land-use changes are basically determined by the demand for these commodities and the land's suitability to

---

[1] Geological processes, such as rock weathering, volcanism, and plate tectonics also affect the global carbon balance. However, they are much slower processes with annual carbon exchange rates that are 3 orders of magnitude (10^3) smaller than the exchange rates between the atmosphere, oceans, and terrestrial biosphere [Kerrick, 2001] and can thus be ignored here.

[2] CO_2 fertilization has been shown to enhance C_3 plant photosynthesis and carbon uptake in laboratory and field experiments [Curtis and Wang, 1998]. However, the response varies greatly between species and age-classes, is affected by nutrient availability, and often decreases over time [Derner et al., 2003; Ellsworth et al., 2004; Körner et al., 2005; Lee et al., 2001]. Model results show that the effects of photosynthetic downregulation under elevated atmospheric CO_2 concentrations are small at the global scale, although it reduces overall NPP in the mid- and high latitudes [El Mayaar et al., 2006].

supply these. However, this basic interaction is modulated by a multitude of processes and conditions: Land suitability is largely determined by local environmental conditions, such as climate and soil fertility, but it is also affected by societal context, such as land management, land tenure, and market access [Geist and Lambin, 2001]. Demand for land-intensive commodities, on the contrary, is chiefly determined by economic processes: With economic growth, people become wealthier and tend to consume more [Delgado, 2003]. Total demand increases with rising per-capita consumption and growing population, but is also affected by supply, trade [Dore et al., 1997], lifestyle [Delgado, 2003], substitutability with other commodities, and cultural background [Rockwell, 1994]. Changes in demand or in land suitability, which may be caused by climate change for example, induce land-use changes, such as deforestation, agricultural intensification, or abandonment.

Land-use changes affect the terrestrial carbon storage capacity, water flows, nutrient cycles, and exchange fluxes of carbon, water, and energy between the terrestrial biosphere and the atmosphere [Brovkin et al., 2006; Farley et al., 2005; Gitz and Ciais, 2004; Houghton, 2003a; McGuire et al., 2001]. Generally, agricultural land use significantly reduces the carbon pools of vegetation and — except under some types of grassland — of soil [Caspersen et al., 2000; Fearnside, 2000; Guo and Gifford, 2002], releasing carbon to the atmosphere under agricultural expansion. Agricultural land use also reduces the land's capacity to sequester carbon, via the so-called *land-use amplifier* effect: large fractions of NPP are removed at harvest and are quickly consumed (i.e. respired and returned to the atmosphere), reducing turnover times and inhibiting larger soil carbon pools to build up [Gitz and Ciais, 2003]. Water runoff increases with deforestation [Farley et al., 2005], as the decrease in transpiration and interception is not counterbalanced by the increase in evaporation, enhancing the risk of flooding and soil erosion [Rosegrant et al., 2002b]. Different vegetation types and even differences in plant performance affect the reflection of incoming radiation (albedo) and the water transfer to the atmosphere (evapotranspiration). Hence, land-cover and land-use changes affect the latent and sensible heat exchanges between the terrestrial biosphere and the atmosphere, affecting the climate system: Brovkin et al. [2004] show that historical deforestation has caused a biogeophysical cooling effect that is comparable to the biogeochemical warming due to the CO_2 released during that period.

Giving credit to the complexity, global climate, economy, and carbon and water cycles are being studied with computer models. These models reduce the problems to the most relevant processes and therefore allow for a better understanding of their dynamics and role in the Earth System [Dürr, 1998] and also for future projections. Computer assisted modeling of the general atmospheric circulation [Phillips, 1956] and of elementary economic systems [Leontief, 1951] started in the mid 20th century, while modeling of the terrestrial biosphere started about 30 years later [Box, 1981]. With time and growing knowledge about the systems' characteristics and behaviors, the models became more complex and integrative, while new questions arose from the insights gained and from observations. Models of the terrestrial biosphere evolved from static biome distribution models [Box, 1981; Prentice et al., 1992; Woodward, 1978] to Dynamic Global Vegetation Models (DGVMs) of potential natural vegetation that incorporate the global carbon and water cycles and simulate the dynamics under changes in climate and atmospheric CO_2 concentrations. With DGVMs, the role of the terrestrial biosphere for the Earth System was elucidated and several processes were quantified, including the carbon exchange with the atmosphere, modifications of the energy exchange fluxes via changes in albedo, and the dynamic development of biome distributions [e.g. Berthelot et al., 2005; Brovkin et al., 2004; Cramer et al., 2001; Delire et al., 2003; Kucharik et al., 2000; Schimel et al., 2001].

Despite these achievements, the role of human activities for the terrestrial carbon cycle beyond fossil fuel combustion has not been sufficiently explored so far. Current research increasingly focuses on the role of land use and land-use change for the land-atmosphere carbon exchange. Historic land-use change has been significantly affecting the terrestrial carbon balance [Bondeau et al., 2007; Houghton, 2003a; McGuire et al., 2001]; the additional carbon emissions are comparable in size to historic emissions from fossil-fuel combustion [House et al., 2002]. Given this importance in the past, land-use change can be expected to significantly affect the terrestrial carbon balance in the future, too. Future changes in land-use, however, are rarely addressed explicitly in carbon cycle studies at the global scale. Reasons for this are the large uncertainties connected with the drivers of land-use change [Gitz and Ciais, 2004], and the absence of numerical modules for carbon dynamics under cultivation in most global process-based models. First approaches to study the effects of future land-use changes on the carbon cycle at the global scale include bookkeeping models [e.g. Houghton, 2003a], light-use efficiency models [e.g. DeFries, 2002] and adapted DGVMs [e.g. Cramer et al., 2004; Levy et al., 2004a; McGuire et al., 2001], driven by hypothetical data, trend extrapolations or land-use data derived from the Special Report on Emission Scenarios (SRES) story lines [Nakicenovic and

Swart, 2000]. However, these studies differ in their assumptions and findings and do not allow for a general assessment of the role of land-use change within the terrestrial carbon balance yet: Levy et al. [2004a], who concentrate on re- and afforestation scenarios find the role of land-use change to be of minor importance for the 21st century if compared to the role of CO_2 fertilization and climate change, while Gitz and Ciais [2004] studying deforestation scenarios attribute a strong amplifying effect on the carbon budget to land-use change, supported by Cramer et al. [2004] for the tropics. Additional differences in methods, tools, and data used demand for a thorough analysis of potential land-use change effects on the terrestrial carbon balance.

Reflecting the increasing recognition of the importance of land use and land-use change [Foley et al., 2005], DGVMs, as state-of-the-art models of the terrestrial biosphere, are currently being advanced to represent cultivated land. Early approaches include the representation of agricultural land use by prescribing natural grassland [Cramer et al., 2004] and the assignment of specific carbon allocation rules to the simulated natural vegetation in order to mimic the carbon dynamics under cultivation [Levy et al., 2004a; McGuire et al., 2001]. More recently, DGVMs have been coupled to crop models [de Noblet-Ducoudre et al., 2004; Gervois et al., 2004] or are expanded by crop functional types (CFTs) [Bondeau et al., 2007], to better represent the carbon and water cycles under cultivation.

1.3 Objectives

Within this thesis, I address two different but related questions that emerge from the discussion on the role of land use and land-use change for the terrestrial biosphere: How important is potential future land-use change for the terrestrial carbon and water cycles and, second, how can we acquire spatially explicit data on possible future land-use patterns?

The first question is addressed in Chapters 2 and 3, analyzing the effects of land use and land-use change on the terrestrial biosphere. In Chapter 2, I explore the importance of addressing land use and land-use change in studies on the future development of the terrestrial biosphere with the following questions:

- What is the range of possible land-use patterns, considering changes in population, diet and trade?
- How important are these socio-economic drivers of land-use change compared to each other?
- What are the effects of these land-use patterns on the terrestrial carbon pools and the terrestrial water cycle?
- How do these effects on the terrestrial carbon cycle compare to the effects of climate change?

In Chapter 3, I seek to verify my findings of Chapter 2 under consistent future projections of climate and land-use patterns for the 21st century by addressing the following questions:

- Under consistent assumptions on population growth, economic development and climate change, how do global land-use change and climate change affect the terrestrial carbon balance?
- What are the effects of land use and land-use change on the global land-atmosphere carbon exchange over the 21_{st} century?

In Chapters 4–6, I concentrate on the second question raised above: How can we acquire spatially explicit data on possible future land-use patterns? I review the state-of-the-art of current land-use modeling approaches in Chapter 4, posing the questions:

- What data and methodologies are used to explore and project land-use change at the continental to global scale?
- What are the achievements and deficits of these approaches?
- What are the potentials of combining different methodologies to project land-use patterns under changing environmental and socio-economic conditions?

Such integrated approaches need to bridge the gaps between these disciplines with respect to thematic, temporal and spatial scales. Land suitability varies greatly over space. If it is represented as a regional average, total area demand cannot be determined adequately (Chapter 2), while the interaction of production, consumption and trade can only be represented at a regional resolution at the global scale. In order to harmonize these differences in spatial scales, I ask in Chapter 5:

- How robust are DGVM simulations against reductions in spatial resolution?

As an outlook, I introduce a new approach to project future land-use patterns that accounts for spatially explicit variations in land suitability in an economic optimization of agricultural production in

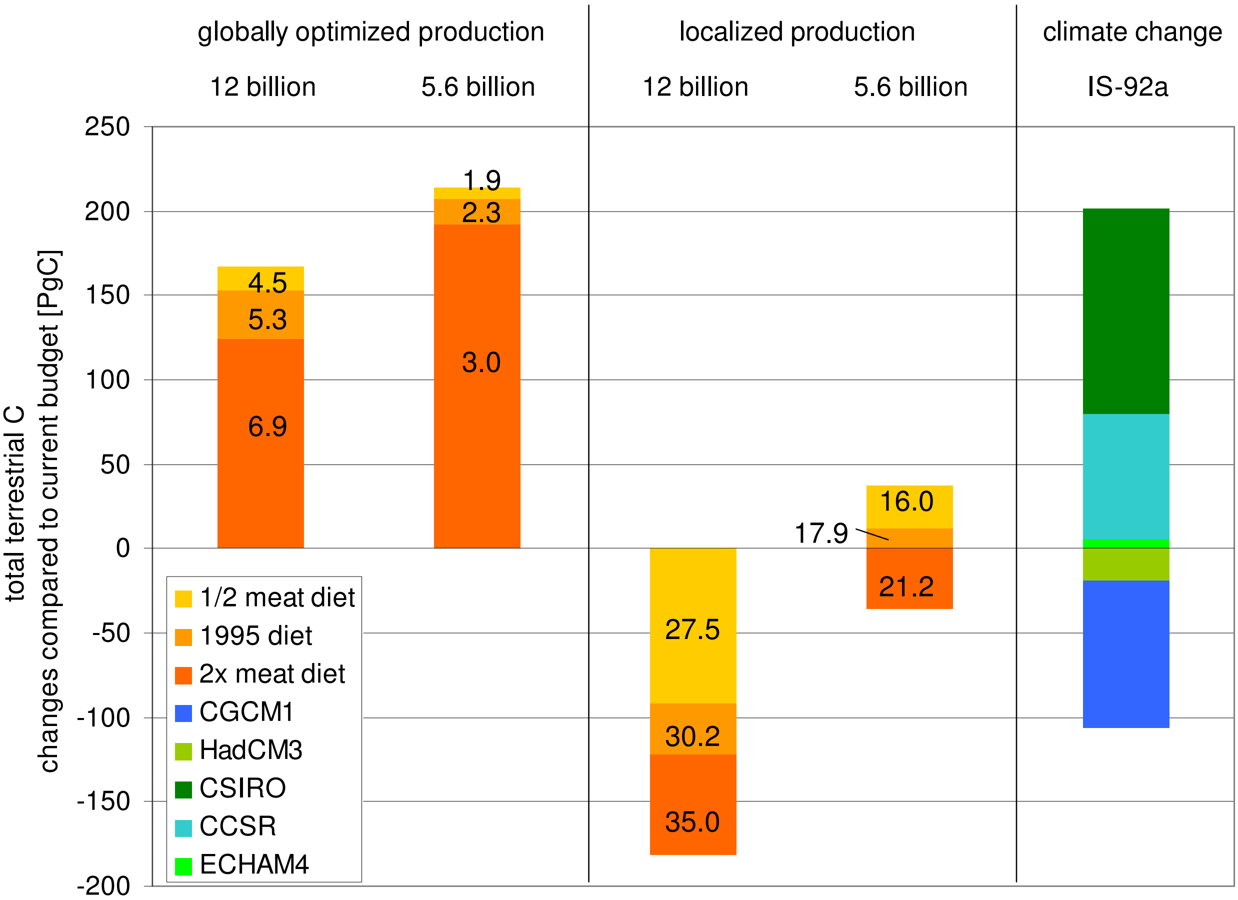

Figure 1.1: Changes in total terrestrial carbon pools under different stylized land-use patterns, represented as differences with baseline run. Numbers show the total agricultural area of each scenario in million km^2. Carbon pool changes from climate change and CO_2 fertilization as computed by 5 general circulation models (GCM) under the IS92a emission scenarios are shown as difference between the 30-year averages of 1971-2000 and 2071-2100 [Schaphoff et al., 2006].

Chapter 6. Besides projecting spatially explicit land-use patterns, this integration of geographic and economic drivers of land-use change allows for a better understanding of the effects of resource scarcity (land, water), trade, management, and changes in demand for agricultural products.

1.4 Overview of Results

Making use of the DGVM LPJ/mL (Lund-Potsdam-Jena DGVM for managed Lands) [Bondeau et al., 2007], I here demonstrate the importance of land use and land-use change for the terrestrial carbon and water budgets. In Chapter 2, I analyze the potential of three socio-economic drivers of land-use change (population, diet, trade) to alter the terrestrial carbon and water cycles in a comparative static setting. For the required land-use data, I generate stylized land-use patterns based on assumptions that are strong but nonetheless within the range of projected developments, in order to cover the range of possible land-use patterns. The different assumptions on demand (doubling of population and/or doubling or halving of meat consumption) and trade, represented as constraints on the spatial localization of agricultural production, (globalized vs. localized agricultural production) are combined with spatially explicit yield data supplied by LPJ/mL, which are used to determine land suitability, in order to generate spatially explicit land-use patterns. Results show, that the constraints on the spatial localization of agricultural production largely determine total area demand and, thus, the magnitude of land use and land-use change effects on the global carbon and water budgets. Population and diet also affect the terrestrial carbon and water cycles, although diet is of lesser importance under the globalized production scenarios. Potential changes in land-use patterns largely affect the terrestrial carbon and water cycles: Under localized agricultural production, total terrestrial carbon decreases by up to

181 PgC, while it increases by up to 214 PgC under globalized production. Global runoff and evaporation rates increase under localized production by up to 1.600 km^3/a and 4.100 km^3/a respectively, while they decrease under globalized production by up to 1.100 km^3/a and 2.200 km^3/a respectively. Global transpiration, on the contrary, decreases under localized production by 4.300 km^3/a and increases under globalized production by up to 1.200 km^3/a. Figure 1.1 shows, that the effects of possible land-use changes on the terrestrial carbon pools are comparable in size to the effects of CO_2 fertilization and climate change under a high emission scenario (IS92a).

This assessment of first-order effects calls for a more direct comparison of climate and CO_2 fertilization versus land-use change and for studying more sophisticated land-use patterns. Consequently, I study the effects of CO_2 fertilization, climate, and land-use change under three different SRES scenarios (A2, B1, and B2) in Chapter 3, using consistent input data that are supplied by the Integrated Model to Assess the Global Environment (IMAGE 2.2, [IMAGE team, 2001]). I confirm the general findings of Chapter 2, by demonstrating that the importance of land-use change for the global carbon cycle is also equal to that of CO_2 fertilization and climate change under consistent scenarios of changes in atmospheric CO_2 concentrations, climate, and land-use patterns. Here, land-use change significantly affects the terrestrial carbon balance, offsetting the effects of climate change and CO_2 fertilization under the regionalized (A2 and B2) SRES scenarios. While climate change and CO_2 fertilization cause additional carbon uptakes of up to 220 PgC, land-use change releases up to 450 Pg of terrestrial carbon to the atmosphere over the 21st century. Figure 1.2 gives an overview of the A2 (regionalized, intensive) and B1 (globalized, extensive) scenario settings and their effects on the terrestrial carbon balance over the 21st century. A switching of the terrestrial biosphere from being a carbon sink to being a carbon source around the year 2050 as projected by Cox et al. [2000] and Schaphoff et al. [2006] could not be reproduced: Under the assumption of static land-use patterns from 1970 to 2100, the terrestrial biosphere remains a stable carbon sink over the 21st century under all scenarios studied here, while it is a stable carbon source over this period if land-use changes are considered. The overestimation of deforestation rates in the late 20th century are a major reason for the failure to reproduce the observed terrestrial carbon sink during this period. This emphasizes the importance of the rate of land-use change for quantifying the effects of land-use change, supporting the findings of Jain and Yang [2005].

The importance of both spatially explicit land-use patterns (Chapter 2) and the rate of land-use change (Chapter 3) expresses the need for reliable, temporally and spatially explicit data on land-use change. While such data are available for the historic period — although in limited quality only [Jain and Yang, 2005] — there are hardly any global future projections available besides the implementation of the SRES scenarios by the IMAGE 2.2 model [IMAGE team, 2001]. This imbalance between importance and availability of data demands new means of generating temporally and spatially explicit data of land-use change. In a review of the different approaches to model land-use changes at the continental to global scale, I analyze the achievements, deficits and potentials of large-scale land-use modeling approaches (Chapter 4). Land use and land-use changes are mainly addressed with geographic and economic methodologies at the continental to global scale. Disciplinary approaches largely focus on either the supply or the demand side but do not include their mutual interactions: Geographic approaches focus on land suitability, spatial interaction and constraints on the supply side in order to generate spatially explicit land-use patterns for an externally given demand. Economic approaches, on the contrary, focus on the demand side, employing preferences and motivations of producers and consumers, as well as market and population structures to explain changes in the production of land-intensive goods, but are limited in accounting for resource constraints. In order to overcome the disciplinary shortcomings, integrated approaches combine economic and geographic methodologies. However, approaches that link economic and geographic models in order to combine their strengths yield the risk of inconsistencies and redundancies. Furthermore, they do not exploit the entire potential of this integration yet: Several processes that drive and affect land-use changes, as e.g. the trade-off between spatial expansion and intensification, are not addressed sufficiently in globally applicable land-use models and the role of water availability for land-use decisions is largely neglected so far.

A major obstacle in integrating economic and geographic approaches is their mismatch in spatial scales. Exploring the robustness of DGVM simulations against reductions in spatial resolution in Chapter 5, I find that coarser spatial resolutions do not differ qualitatively from finer spatial grids. The deviation from the typical 0.5° grid increases linearly with grid coarseness, but with a small slope (less than 1.5 percent deviation per degree). However, information on spatial heterogeneity is lost, when grid coarseness increases. Figure 1.3 shows the difference in NPP simulations at spatial resolutions of 1.0° x 1.0°, 2.5° x 2.5°, 5.0° x 5.0°, and 10.0° x 10.0° with the benchmark run at the spatial resolution of

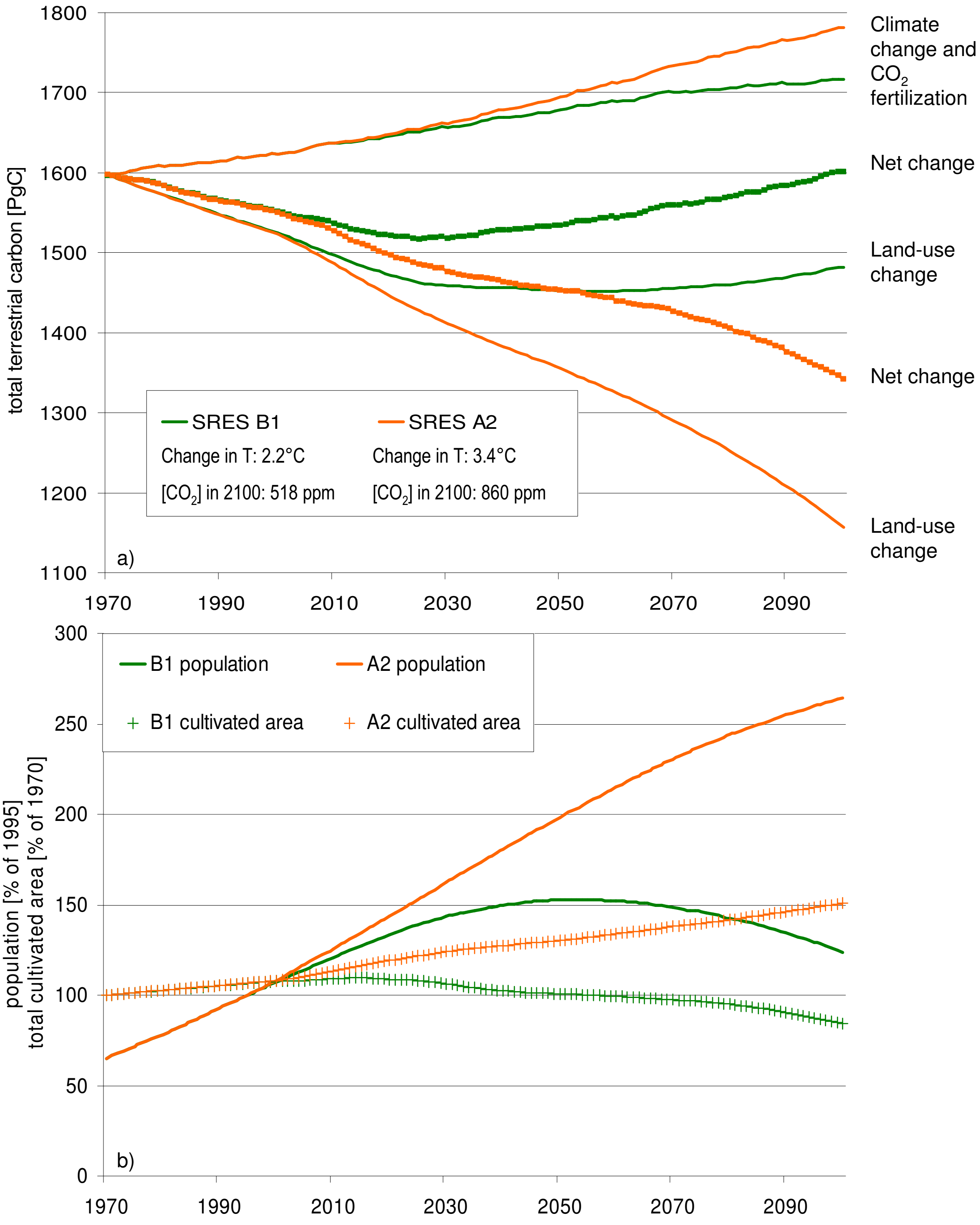

Figure 1.2: Development of the terrestrial carbon budget (a) under the A2 and B1 SRES scenarios (for scenario settings see legend and panel (b)) from 1970 to 2100. The net change in total terrestrial carbon is determined by the effects of climate change and CO_2 fertilization as well as by land-use changes, which are shown separately here.

0.5° x 0.5°.

As an outlook, I describe a newly developed land-use model, the *Model of Agricultural Production and its Impact on the Environment* (MAgPIE) in Chapter 6. It is a linear optimization model that generates spatially explicit land-use patterns at a spatial resolution of 3.0° x 3.0°. The model is driven by economic demand for agricultural products and spatially ex-

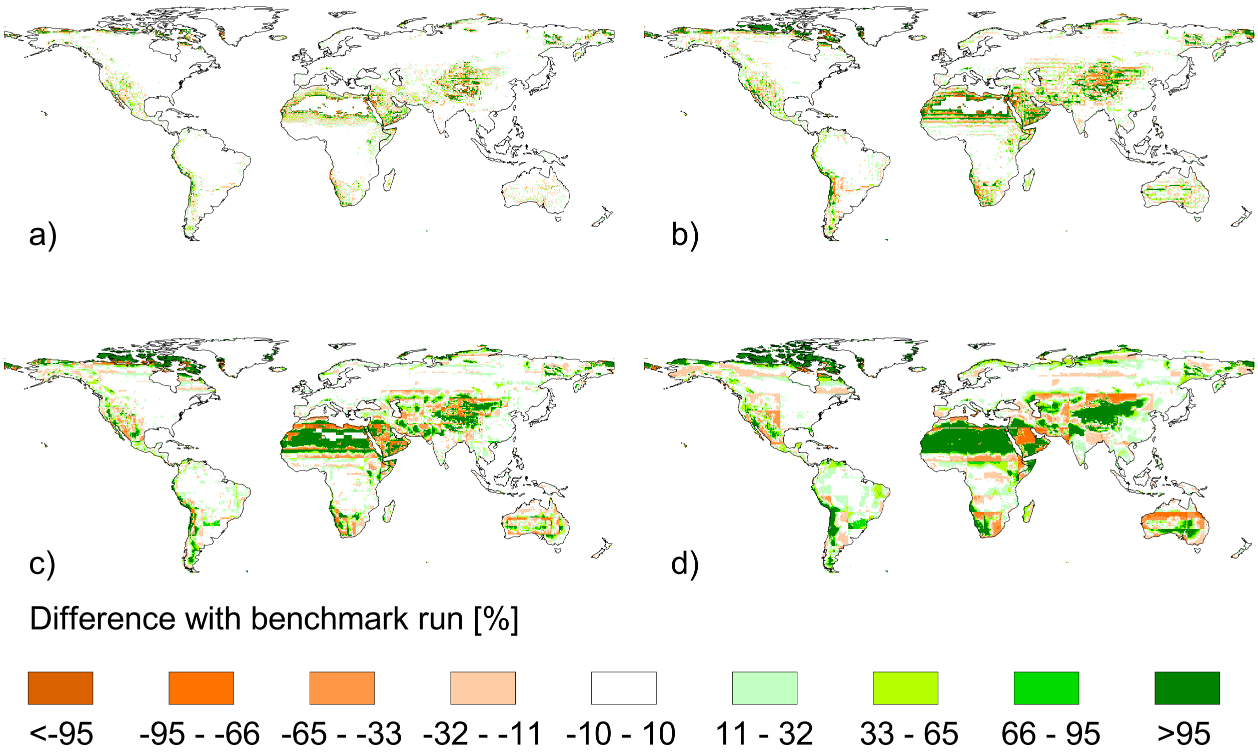

Figure 1.3: Difference of NPP at spatial resolutions of (a) 1.0°x1.0°, (b) 2.5°x2.5°, (c) 5.0°x5.0°, and (d) 10.0°x10.0° with benchmark run at 0.5°x0.5°. Note that large increases (dark green) in regions with low NPP in the benchmark run (e.g. deserts) may be low increases in absolute numbers.

plicit data on land suitability that constrains the supply side. Regional agricultural demand is computed by regional data on population and Gross Domestic Product (GDP) via an empirical relationship between demand patterns and income and by minimal self-sufficiency ratios. Land suitability is determined by spatially explicit data on yield levels and water availability for irrigation as well as regional data on production costs and by crop rotational constraints. MAgPIE's capability to simulate realistic land-use patterns is demonstrated by reproducing historical land-use patterns. This validation demonstrates the suitability of the approach to generate spatially explicit land-use data: GDP-driven changes in demand, total cropland area, and crop mixes are reproduced reasonably well by the model. However, it also shows that the interregional distribution of cropland and also total cropland area respond sensitively to prescribed trade patterns. MAgPIE allows for future projections of spatially explicit land-use patterns, for exploring the effects of technology change and trade liberalization, and for valuating the competition for land and water (see figure 1.4). It can serve as an interface to couple spatially explicit models of the terrestrial biosphere and macro-economic models in order to establish the feedback of land scarcity on production patterns and demand.

1.5 Discussion and Conclusions

Land use and land-use change strongly affect the terrestrial carbon budget, which I demonstrated under stylized comparative static scenarios as well as under consistent, dynamic projections of atmospheric CO_2 concentrations, climate, and land use of the 21st century. In both cases, land-use change is equally important to climate change for the terrestrial carbon balance, although the processes are different: Climate change and CO_2 fertilization strongly increase NPP, which leads to larger carbon pools in vegetation and soil. Higher temperatures also cause higher soil respiration rates (R_h), reducing soil carbon stocks, especially in the high latitudes [Schaphoff et al., 2006]. Changes in land-use, on the contrary, hardly affect NPP at the global scale, although there may be also strong effects on NPP at the local scale, especially under irrigated agriculture. However, carbon stocks decline strongly under agricultural expansion because large portions of the accumulated carbon are removed at harvest and respired quickly. This increase in turnover rates is also referred to as the *land-use am-*

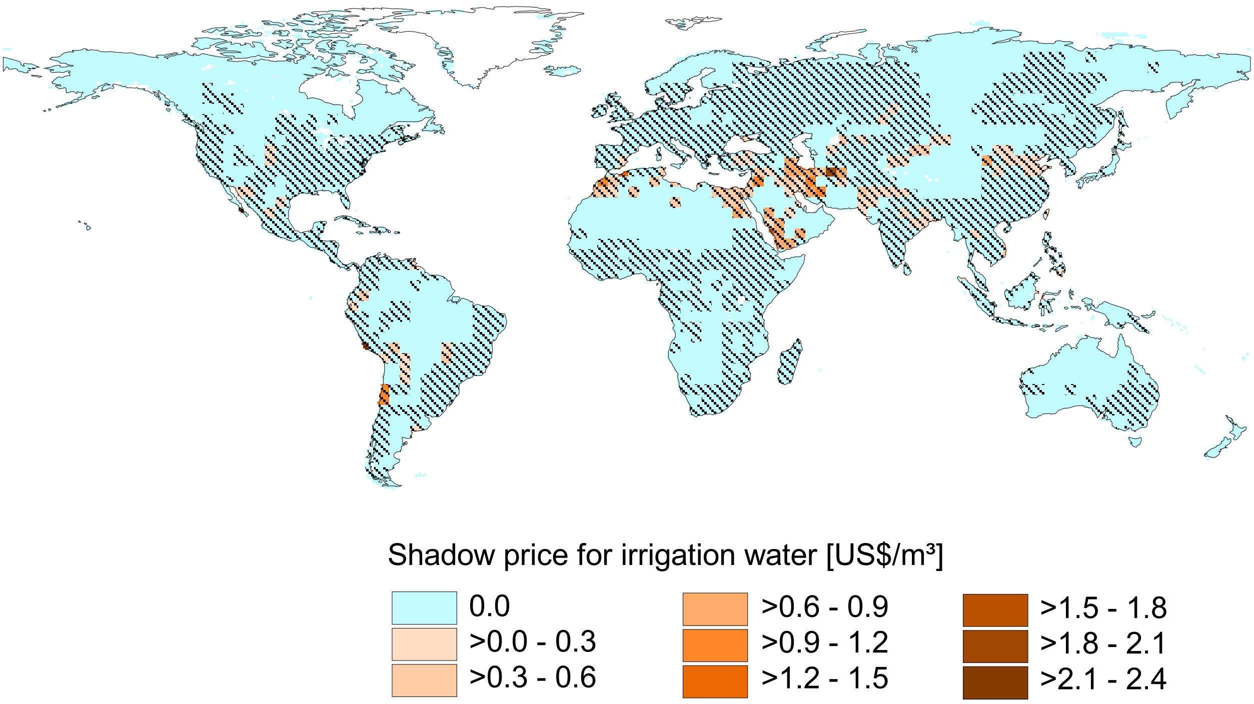

Figure 1.4: Shadow price for irrigation water [US$/m^3] in 1995 as simulated by MAgPIE. Shadow prices are shown only in grid cells where irrigation water is available but in limited amounts only. If sufficient irrigation water is available, the shadow price is zero by definition. Hatched areas are simulated as fractionally used for cropland.

plifier effect [Gitz and Ciais, 2003].

My results challenge earlier study results on the future terrestrial carbon balance that project the terrestrial biosphere to switch from being a carbon sink to being a carbon source around the year 2050. These studies are conducted for potential natural vegetation and disregard the effects of land use and land-use change. I could show that agricultural land use significantly reduces carbon stocks. Consequently, the impact of higher temperatures and changed soil moisture regimes on soil respiration is also smaller, if land-use patterns are considered, since soil respiration rates are largely determined by soil carbon stocks. With static land-use patterns as in the year 1970 throughout the 21st century, the terrestrial biosphere remained a stable carbon sink in all 12 SRES scenarios studied here. However, the climate scenarios used here, which have been generated by the IMAGE 2.2 model, are more moderate than the climate scenarios used by Cox et al. [2000] and Schaphoff et al. [2006]. My results therefore cannot be compared directly to results of their studies. Land-use change, on the contrary, may cause the terrestrial biosphere to become a net carbon source much earlier in the case of net deforestation, or reinforce the stable carbon sink under afforestation. Carbon fluxes from land-use change are in the same order of magnitude as carbon fluxes from CO$_2$ferilization and climate change and, thus, may counterbalance or outweigh the effects of climate change.

Jain and Yang [2005] observe that the effects of land-use change are strongly determined by the rate of land-use change, while the exact localization of land-use changes is of minor importance. These findings are supported by the analyzes conducted here; however, I find that the exact localization of land-use changes is of major importance for the terrestrial carbon and water budgets in an indirect way: Land suitability varies strongly in space. Consequently, land-use efficiency, or the area requirements to produce a defined amount of agricultural goods, is strongly determined by the exact location of agricultural production. Total agricultural area and, thus, the effects of land-use change are therefore largely determined by the localization of land use, as demonstrated in Chapter 2.

The effects of land use and land-use change on the terrestrial water cycle deserve to be studied in more detail. Generally, agricultural land use reduces the length of the vegetation period and thus increases evaporation and runoff at the cost of reduced transpiration and interception rates. Interception, evaporation, and transpiration jointly constitute the water flux from the terrestrial biosphere to the atmosphere, transferring latent heat. Runoff increases under cultivated land because the decrease in interception and transpiration is not completely counterbalanced by increased evaporation rates. Globally, the transfer of water vapor and latent heat to the atmosphere is not sensitive to land-use changes: global runoff, as the balancing water flow, changes only by less than 4 %. Nonetheless, land-use change is an important factor in the terrestrial water cycle. Although not studied here, it can be assumed that changes in local water balance are more pronounced and even changes in the temporal distribution of latent heat transfer to the atmosphere may affect regional climate [Pielke et al., 2002], together with the differences in albedo. The effects of land-use change on the terrestrial water cycle need to be addressed at smaller scales, also considering regional and local conditions of water management, which also modulate the impacts of changes in the terrestrial water cycle.

The effects of land use and land-use change significantly affect the Earth System, as demonstrated here for the terrestrial carbon and water cycles. High-quality data on the spatial patterns and temporal dynamics of land use are essential inputs needed to quantify these. However, such data sets with global coverage rarely exist. For the historic period, data sets are available, but of limited quality only Jain and Yang [2005]. For future projections, hardly any land-use data sets with global coverage are available besides the IMAGE 2.2 implementations of the SRES scenarios [IMAGE team, 2001]. On the one hand, important data to generate these are also not available: For example, most economic information is not projected further into the future than one or two decades. Globally applicable land-use models that are capable of generating such data exist, but have not satisfactorily resolved some important aspects of land-use change yet. Disciplinary approaches suffer from under-representation of either the demand or supply side, while integrated economic-geographic approaches risk inconsistencies and redundancies in order to account for a larger set of drivers of land-use change. Beyond, several important feedbacks as, for example, the trade-off between intensification and spatial expansion of agricultural production have not been addressed sufficiently yet and important aspects of land suitability, like freshwater availability, are largely ignored.

An important issue hampering the integration of economic and biogeochemical models is their mismatch in spatial resolutions. I found DGVM simulations of the global carbon and water cycles to be amazingly robust against reductions in spatial resolution as shown in Chapter 5. However, a most suitable spatial resolution or a range of suitable resolutions cannot be determined in general. Regular grids in the range of 1.0° to 10.0° do not differ qualitatively from the 0.5° grid, although the deviation of global results from the 0.5° grid increases with grid coarseness. It is therefore necessary to determine the most suitable spatial resolution under careful consideration of the application-specific requirements. Reductions in spatial resolution necessarily lead to information losses on spatial heterogeneity — a crucial factor in determining total agricultural area demand as shown in Chapter 2. The spatial resolution of land-use models should therefore be as detailed as computationally feasible. If the implementation of economic processes prohibits sub-regional or sub-country spatial resolutions, alternative means of representing spatial heterogeneity have to be considered, as e.g. the hyperbolic *land-supply curves* used in the coupling of the GTAP and IMAGE models [van Meijl et al., 2006].

For the new land-use model MAgPIE, a spatial resolution of 3.0° x 3.0° is appropriate because it permits to simultaneously account for sub-regional spatial heterogeneity in land suitability and for economic trade, demand, and production structures in the computation of spatially explicit production patterns. The satisfactory ”backcast” simulation of the agricultural land-use pattern of 1970, strictly using data on GDP-, population- and yield development only, demonstrates the possibility to project future land-use patterns, even though detailed economic data may not be available. Simulations have shown that the inter-regional distribution and also the size of total agricultural land react sensitively to trade structures, which are prescribed in form of self-sufficiency ratios. This allows for detailed studies on the effects of trade on global land-use patterns and the terrestrial carbon and water cycles. However, this also yields the risk of systematically biased projections if trade patterns are not parameterized adequately.

The model structure allows for implementing different management regimes and MAgPIE can, thus, represent the trade-off between changes in management and spatial expansion endogenously. However, these have not been implemented so far and require a separation of production costs that are available in aggregated form only. This also requires yield data for different management types, which can be simulated by LPJ/mL [Bondeau et al., 2007] in principle. However, the calibration of yield levels under different types of management is difficult as well, since observed data are, except for some site specific data sets, also available in aggregated from only. Technology development is not endogenously modeled but needs to be specified for each scenario. The effects of climate change on yield levels and spatial patterns, however, are captured by the yield data supplied by LPJ/mL.

Land use and land-use change need to be accounted for in carbon- and water cycle studies as they yield the potential to offset or amplify the effects of climate change. However, the impact of land use is not limited to these but affects also several other biogeochemical cycles, such as of different nutrients (nitrogen, phosphorus, sulfur etc.), and ecosystem services (conservation of biodiversity, freshwater availability, protection against erosion and flooding etc.), which have not been studied here. The simulation of management will need additional attention in the subsequent steps: Differences in management largely affect the size of area under cultivation but also directly affect biogeochemical cycles. However, DGVMs such as LPJ/mL do not sufficiently include management options yet that directly affect the carbon-, water- and nutrient cycles, as e.g. different types of tillage. This deficiency is also due to the lack of suitable global data sets for the historic period.

Within this thesis, I was able to demonstrate the importance of global land-use change for the Earth System by quantifying the effects of potential land-use change on the terrestrial carbon and water cycles. In spite of the findings presented here, land use and land-use change remain major scientific challenges in both projecting realistic future developments as well as in quantifying their impacts on the terrestrial biosphere. The implementation of land-use changes as measures to mitigate climate change in political instruments [see e.g. Jung, 2005; UNFCCC, 1997] underscores the importance of a thorough understanding of the interaction of land use and land-use change with the Earth System.

1.6 Author's contribution to the individual papers of this thesis

Paper 1 (Chapter 2): Based on discussions with Alberte Bondeau and Wolfgang Lucht, I developed the idea to this study, prepared the literature review, collected, prepared, and generated the input data, performed the simulations, interpreted the results and wrote the manuscript with helpful comments from my co-authors Alberte Bondeau, Hermann Lotze-Campen, Wolfgang Cramer, and Wolfgang Lucht and also from Dieter Gerten.

Paper 2 (Chapter 3): Based on the cooperation between MNP (RIVM at that time) and PIK, I used the IMAGE implementations of the SRES scenarios to study the effects of changes in CO_2, climate and land use on the terrestrial carbon budget over the 21st century. Together with Bas Eickhout, I developed the modeling strategy, selected the scenarios and interpreted the results. I prepared the input data and the relevant literature review, performed the simulations, post-processed the results and wrote the paper, again with helpful comments from my co-authors Bas Eickhout, Alberte Bondeau, Sönke Zaehle, Wolfgang Cramer, and Wolfgang Lucht.

Paper 3 (Chapter 4): Kerstin Ronneberger, Maik Heistermann and I jointly wrote this review paper on the state-of-the-art of large-scale land-use modeling, based on a suggestion by Richard Tol. All three of us contributed equally to all parts of preparing and writing the paper, impeding a strict separation of individual contributions.

Paper 4 (Chapter 5): Wolfgang Lucht had the idea to systematically analyze the suitability of coarser spatial resolutions in DGVM simulations; I reviewed the literature, developed the modeling strategy, compiled the input data, performed the simulations, analyzed the results, and drafted the manuscript. Dieter Gerten and Wolfgang Lucht contributed to it in valuable discussions.

Paper 5 (Chapter 6): Hermann Lotze-Campen had started to develop a global land-use model based on linear optimization when I started my PhD studies at PIK. Ever since that time I closely discussed the model design with him, prepared the climatic and geographic input data, performed preliminary LPJ/mL simulations with MAgPIE results, interpreted results, and wrote most of the paper presented here.

Chapter 2

Comparative impact of climatic and nonclimatic factors on global terrestrial carbon and water cycles[1]

> *Every attempt to employ mathematical methods in the study of chemical questions must be considered profoundly irrational and contrary to the spirit of chemistry... If mathematical analysis should ever had prominent place in chemistry — an aberration, which is happily almost impossible — it would be a rapid and widespread degeneration of that science.*
>
> Auguste Comte, Philosophie Positive (1830)

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Abstract

The coupled global carbon and water cycles are influenced by multiple factors of human activity such as fossil-fuel emissions and land-use change. We used the LPJ/mL Dynamic Global Vegetation Model (DGVM) to quantify the potential influences of human demography, diet, and land allocation, and compare these to the effects of fossil-fuel emissions and corresponding climate change. For this purpose, we generate 12 land-use patterns in which these factors are analyzed in a comparative static setting, providing information on their relative importance and the range of potential impacts on the terrestrial carbon and water balance. We show that these aspects of human interference are equally important to climate change and historic fossil-fuel emissions for global carbon stocks but less important for net primary production (NPP). Demand for agricultural area and, thus, the magnitude of impacts on the carbon and water cycles are mainly determined by constraints on localizing agricultural production and modulated by total demand for agricultural products.

2.1 Introduction

Currently, the terrestrial biosphere acts as a net sink of carbon, removing anthropogenic carbon dioxide from the atmosphere [House et al., 2003]. Several studies show, however, that in the future a positive feedback between the biospheric carbon cycle and climate change may establish [Cox et al., 2000; Friedlingstein et al., 2003; Berthelot et al., 2005; Schaphoff et al., 2006] so that the terrestrial biosphere

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[1] An edited version of this chapter was published in *Global Biogeochemical Cycles*, Copyright (2006) American Geophysical Union.
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might turn into a net source of carbon dioxide later this century, accelerating climate change.

These results have been obtained by models reflecting the response of potential natural vegetation to climate change. However, global change consists of a much wider range of processes than just climate change [Steffen et al., 2004]. Global agricultural production patterns are likely to change [Pinstrup-Andersen, 2002] — given pressures from conservation, increasing food demand, and new land-intensive commodities such as biofuels [Hoogwijk et al., 2003] entering the competition for fertile land as well as changes in demography and diet. Human alterations of the global land surface have a major impact on the exchange fluxes within the biosphere and between the biosphere and the atmosphere [Brovkin et al., 2004; Houghton, 2003a; House et al., 2002; McGuire et al., 2001], an impact that is likely to increase [Millennium Ecosystem Assessment, 2005]. These land-use and land-cover changes also affect the water cycle that is intrinsically coupled to vegetation and the carbon cycle [Gerten et al., 2004; Kucharik et al., 2000]. Even in the complete absence of climate change, large-scale changes in global biogeochemistry would have to be expected in this century as a consequence.

Land use is increasingly recognized as a force of global importance [Foley et al., 2005]. However, the development of land-use patterns is rarely addressed explicitly in studies on global change — regardless of its close entanglement with the natural environment and society [Heistermann et al., 2006, see Chapter 4]. The impact of land use on the global carbon cycle has been addressed in various studies [e.g. Brovkin et al., 2004; Dale, 1997; Fearnside, 2000; Houghton, 2003a; McGuire et al., 2001] but these are mostly concentrated on historical deforestation, cultivation, and forest regrowth. Potential (future) land-use changes are rarely addressed explicitly and are often included in terms of CO_2 emissions only [Berthelot et al., 2005; Cox et al., 2000; Dufresne et al., 2002; Friedlingstein et al., 2003]. Besides transfering biospheric carbon to the atmosphere, which can be represented as additional carbon emissions, expansion of cultivated land also reduces the biospheric capacity to accumulate carbon due to higher turnover rates under cultivation (”land use amplifier”) [Gitz and Ciais, 2003; Sitch et al., 2005]. DeFries [2002] studies the effects of possible future land-use changes on net primary production (NPP); House et al. [2002] assess the effects of total de- and afforestation; Cramer et al. [2004] extrapolate different deforestation trends in the tropics; and Levy et al. [2004a] study regionally differentiated trends of land-use change supplied by the SRES-scenarios [Nakicenovic and Swart, 2000]. The latter two studies apply the same trends to all grid cells, neglecting the spatial arrangements of land use. Spatially explicit land-use patterns for the SRES-scenarios as supplied by the IMAGE 2.2 model [IMAGE team, 2001] are used by Gitz and Ciais [2004] and by Sitch et al. [2005] to study the effects on the global carbon cycle in a carbon-cycle model and in a coupled DGVM-climate model (LPJ-CLIMBER2), respectively. Although land use is included in their studies, they do not supply information on the importance of different aspects of land-use change (e.g. total demand, changes in productivity, spatial heterogeneity). These are included in the most comprehensive integrated Earth System projections available, such as the IMAGE SRES implementations [IMAGE team, 2001], but their importance for the Earth System is neither addressed explicitly nor quantified. Moreover, most of these studies do not simulate crop- and grasslands explicitly. Sitch et al. [2005] (based on McGuire et al. [2001]) and Levy et al. [2004a] prescribe special carbon allocation schemes for the NPP of natural vegetation to simulate harvest and land-management, Gitz and Ciais [2004] account for land-use transitions but assign a single global average value to determine NPP of crops in their bookkeeping approach [Gitz and Ciais, 2003].

The future developments of land use and of human population [Lutz et al., 2001], diet [Lang, 1999], and agricultural market structure [Pinstrup-Andersen, 2002] as drivers of land-use change are highly uncertain [Gregory and Ingram, 2000]. The objective of this paper is to consider first-order effects of three fundamentally different global change processes upon the global carbon and water cycles: (i) demography; (ii) human diet; and (iii) market structure, constraining the spatial distribution of global agricultural production. In our static comparative setting, we concentrate on these processes in order to provide a first-order assessment of the range of impacts and relative importance of the three listed factors, which to our knowledge has not been quantified at the global scale before. With this selection of global change processes, we directly or indirectly cover all important drivers of agricultural area demand [Alcamo et al., 2005], except those that influence local productivity: technology development and climate change. The impact of the latter two on future land-use patterns is strong [e.g. Rounsevell et al., 2005; Wang, 2005], but their development highly uncertain [e.g. Ewert et al., 2005; Murphy et al., 2004; Stainforth et al., 2005] and deserves a separate in-depth analysis, which is beyond the scope of this study. Our scenarios are designed to outline the range of potential impacts of land use under the assumption of static local productivity levels and do not provide realistic future trajectories or scenarios. To supply a measure of relative importance, we compare the effects of demography, human diet and market structure on the terrestrial carbon cycle with the effects of different climate projections for the 21st century under a high emission scenario (IS92a) as reported by Schaphoff et al. [2006].

We study their relative importance using the LPJ/mL model (LPJ for managed Lands), which is an extended version of the LPJ-DGVM [Gerten et al., 2004; Sitch et al., 2003], a state-of-the-art global biogeochemical carbon-water model of terrestrial vegetation and soil. LPJ/mL has been extended to simulate global crop yields and the carbon and water cycles under agricultural cultivation [Bondeau et al., 2007].

2.2 Methods

2.2.1 Modeling Strategy

We study three different dimensions of human activity (population, diet, market structure), which are determinants of spatially explicit land-use patterns. In order to outline the range of possible changes, accounting for the inherent uncertainties, we choose a straightforward approach: We generated 12 different spatially explicit land-use patterns based on different demand patterns and production schemes. We derived 6 different demand patterns by doubling and/or halving the present-day values of population and consumption of animal products. These assumptions allow for characterizing the possible range of impacts since they are extreme but well inside the spectrum of potential changes [Lutz et al., 2001; Rosegrant et al., 1999]. Agricultural production to satisfy these demand patterns was located in 2 different ways: i) production was assumed to be located in the most productive areas only (globalized production); and ii) local production was assumed to satisfy local demand (localized production). Although both production schemes are not realistic, a comparison of these approaches clearly outlines the potential impact of different global land-use patterns as they may result from globalized or regionalized world economies.

As reference land-use pattern, we use the observed crop area based on Ramankutty and Foley [1999] and Leff et al. [2004] (figure 2.1). Although we consider all major crops[2], these account for 9.5 million km^2 (75% of the total arable land) only. The land-use mask as supplied by Ramankutty and Foley [1999] and Leff et al. [2004] on the contrary covers the total agricultural area of 15.8 million km^2, which includes forage crops but does not include managed grasslands. Since this area is considerably larger than the 9.5 million km^2 that are currently (i.e. 1995) needed to produce the agricultural commodities considered in this study, we scaled the cropland area of each grid cell accordingly. We assume the remainder to be managed grassland as this is not included in the land-use datasets used. All grassland simulated in our scenarios is highly productive grassland and is thus not comparable to the much larger area classified as grassland by FAO [2005a] or the HYDE data base [Klein Goldewijk, 2001]. These datasets include natural grassland as well and are not well differentiated from shrub-land and forests [FAO, 2005a].

We do not assign any likelihood to these scenarios. They are intended for a study of the comparative order-of magnitude of effects that play a role in global change, not for an assessment of potential future developments.

Table 2.1: Crop functional types implemented in LPJ/mL.

Crop functional type (CFT)	Main representative
Temperate Cereals	Summer/winter wheat
Tropical Cereals	Millet
Temperate Corn	Corn
Tropical Rice	Rice
Temperate Pulses	Lentil
Temperate Roots and Tubers	Sugar beet
Tropical Roots and Tubers	Manioc
Temperate Soybean	Soybean
Temperate Sunflower	Sunflower
Tropical Peanuts	Peanut
Temperate Rapeseed	Rapeseed
Managed C_3-grassland	C_3 pasture
Managed C_4-grassland	C_4 pasture

2.2.2 LPJ/mL Dynamic Global Vegetation Model

The LPJ/mL model is based on the LPJ-DGVM [Sitch et al., 2003], a biogeochemical process model that simulates global terrestrial vegetation and soil dynamics and the associated carbon and water cycles. For this, the processes of photosynthesis, evapotranspiration, autotrophic and heterotrophic respiration, including the effects of soil moisture and drought stress, as well as functional and allometric rules are implemented [Gerten et al., 2004; Sitch et al., 2003]. NPP (gross primary production less autotrophic res-

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[2] Except cotton seed (2.8%) and 3 forage categories (1.0–1.5%) all crops with an area larger 1% of the total arable land according to FAO [2005a] have been considered.

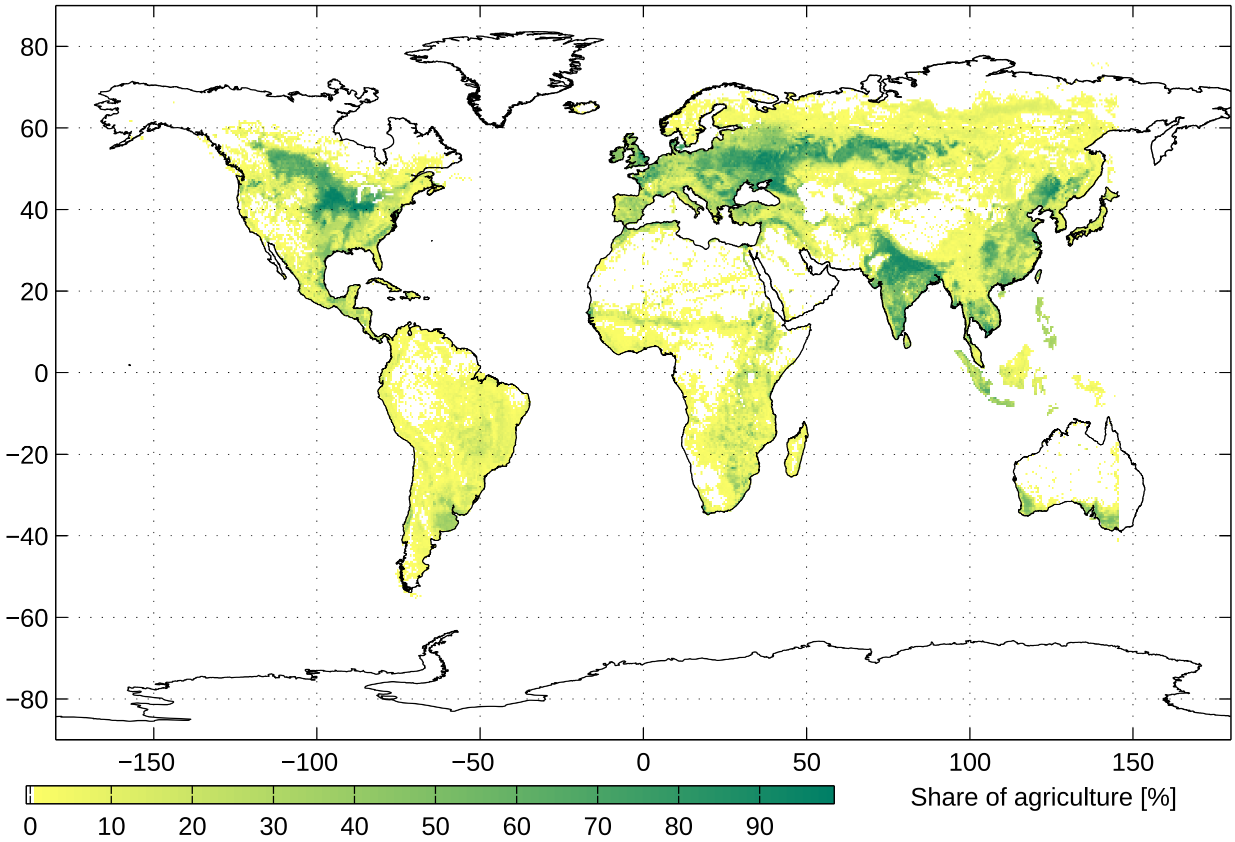

Figure 2.1: Agricultural land-use pattern of reference run, as derived from Ramankutty and Foley [1999] and Leff et al. [2004].

piration) is allocated to the different plant compartments (vegetation carbon) and enters the soil carbon pools (including litter pools) due to litter-fall and mortality. Runoff is generated if precipitation exceeds the water holding capacity of the two defined soil layers that supply water for evaporation from bare soil and for transpiration (interception loss from vegetation canopies is computed based on precipitation, potential evapotranspiration, and leaf area [Gerten et al., 2004]). Natural vegetation is represented by 10 different plant functional types (PFTs), of which 2 are herbaceous and 8 woody. These may coexist within each grid cell, but their abundance is constrained by climatic conditions, by competition between the different PFTs for resources and space, and by the fractional coverage with agricultural vegetation. Vegetation structure responds dynamically to changes in climate, including invasion of new habitats and dieback. Fire disturbance is driven by a threshold litter load and soil moisture [Thonicke et al., 2001]. The model has been extensively tested against site [Cramer et al., 2004; Gerten et al., 2005; Sitch et al., 2003; Zaehle et al., 2005], inventory [Beer et al., in press; Zaehle et al., 2006], satellite [Lucht et al., 2002; Wagner et al., 2003], atmospheric [Scholze et al., 2003; Sitch et al., 2003], and hydrological data [Gerten et al., 2004, 2005].

In LPJ/mL, agricultural land use is simulated within the same framework using crop functional types (CFTs) [Bondeau et al., 2007]. The world's most important field crops as well as pastures are represented by a total of 13 different CFTs (table 2.1) either rain-fed or irrigated. Grid cells may fractionally consist of both natural and agricultural vegetation, and several agricultural crops may be present within the same grid cell with individual cover fractions. Natural PFTs compete for resources, whereas each CFT has its own specific water budget. Management options such as irrigation, removal of residues, multiple cropping, intercropping, and grazing intensity are specified. LPJ/mL's crop modules simulate crop phenology, growth, and carbon allocation at a daily time step. Carbon is allocated to several plant compartments, including a storage organ that represents the economic yield at harvest.

The model estimates several crop variety-specific parameters as a function of climate, thereby taking into account the adaptation of crop varieties to spe-

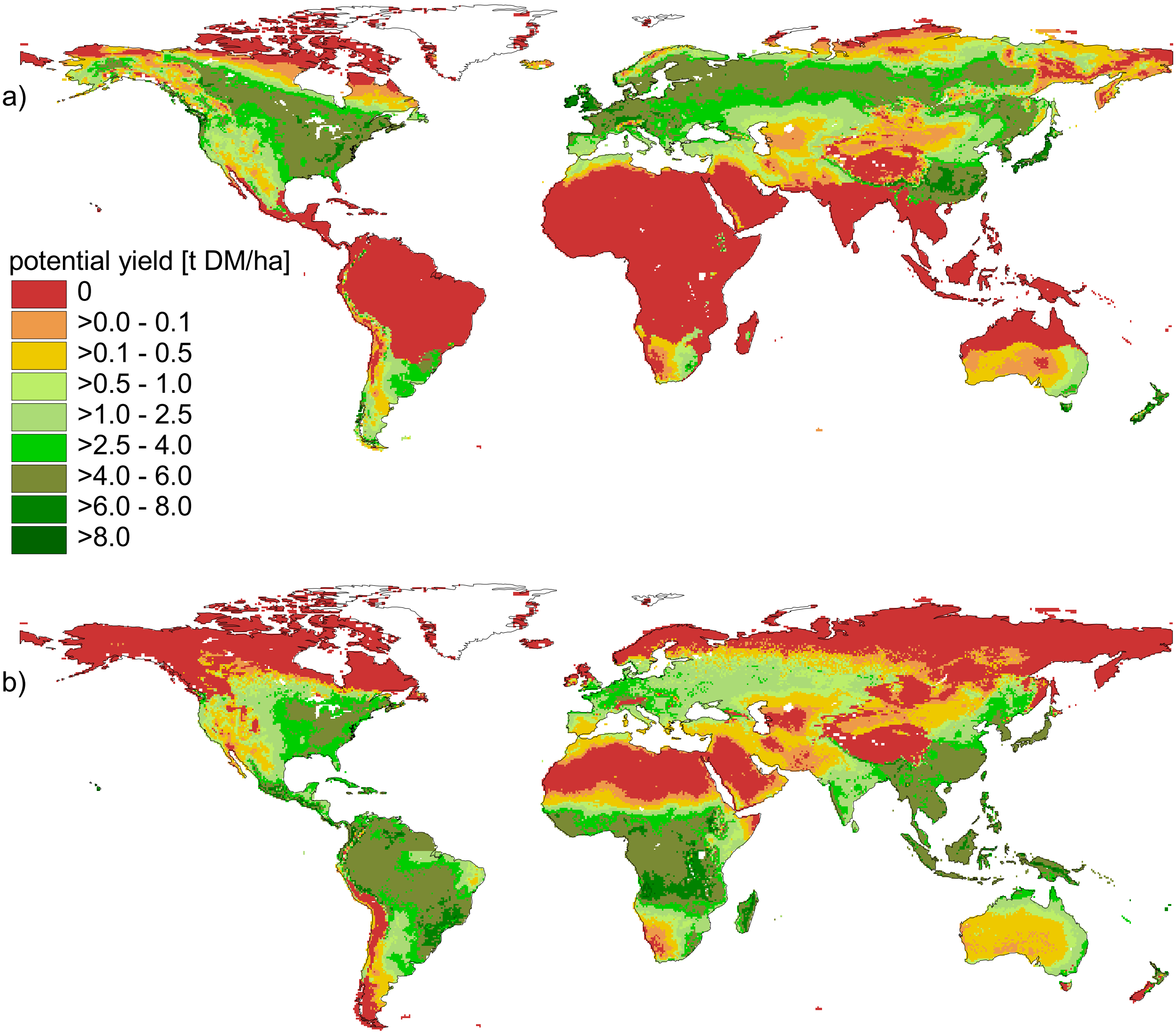

Figure 2.2: Rain-fed yields for temperate cereals (a) and maize (b) as simulated by LPJ/mL [Bondeau et al., 2007], averaged for 1991-2000. Note that yields here are not adopted to match current yield levels by country-specific parameterization as described by Bondeau et al. [2007].

cific climatic environments in which they are cultivated. The implementation of the crop-specific processes is described in detail and validated against the USDA crop calendar [USDA, 1994] and satellite data [Myneni et al., 1997] for phenology, against FAO data FAO [2005a] for yield simulations, and against eddy flux measurements [Lohila et al., 2004; Baldocchi et al., 2001] for carbon fluxes in the study of Bondeau et al. [2007]. Crop yield for each grid cell was simulated by LPJ/mL as limited by soil moisture and climate only (for exemplary spatial distribution of yield levels of temperate cereals and of maize see figure 2.2). To account for differences between current (1995) and simulated crop yields as caused by different management practices (pest control, fertilization), we employed national management factors (MF). To derive the MFs, we scaled the computed average yield of actual production sites according to Ramankutty and Foley [1999] and Leff et al. [2004] to national yield averages supplied by the FAO [FAO, 2005a] as in equation (2.1):

$$MF_{c,n} = \frac{Ycur_{c,n}}{\Sigma(Ysim_{c,i} * A_{c,i})/\Sigma A_{c,i}} \qquad (2.1)$$

where $MF_{c,n}$ is the management factor for CFT c in nation n; $Ycur_{c,n}$ is the current yield level of CFT c in nation n as supplied by the FAO; $Ysim_{c,i}$ is the yield as simulated by LPJ/mL for CFT c in grid cell i, with i being a grid cell within nation n; and $A_{c,i}$ is the area actually used for CFT c in grid cell i according to Ramankutty and Foley [1999] and Leff et al. [2004]. $Ysim_{c,i}$ is based on a mixture of irrigated and non-irrigated yields, based on the availability of installed irrigation equipment according to Döll and Siebert [2000] and a preference ranking as described by Bondeau et al. [2007]. We assume that 80% of an area equipped for irrigation is effectively irrigated if atmospheric demand for water exceeds soil water supply, resulting in higher assimilation and transpiration rates and lower runoff. It was assumed that water is sufficiently available where irrigation equipment is installed.

Computations were carried out on a regular global grid with 0.5° x 0.5° spatial resolution driven by the University of East Anglia's Climatic Research Unit (CRU) climate dataset [Mitchell et al., 2004], a monthly climatology of observed meteorological parameters that covers the period from 1901-2000, and annual atmospheric CO_2 concentrations [Keeling and Whorf, 2003]. A spinup of 900 years during which the first 30 years of the dataset were repeated cyclically brought all carbon pools into equilibrium. The spinup was followed by a transient simulation from 1901 to 2000. Only the period from 1990-1999 was evaluated, for which we present average numbers in the following to represent the target year 1995. We assumed static land-use patterns throughout the simulation period (spinup and 1901-2000), thus neglecting the biogeochemical consequences (e.g. impacts on the net land-atmosphere carbon flux) of historical land-use change processes, which are not the objective of this paper.

2.2.3 Computation of demand for agricultural products

We define total demand for agricultural commodities by the number of people and their per-capita consumption. We computed 6 different demand scenarios for agricultural products by changing population (table 2.2) and diet (table 2.3). For population, we used the population count of 1995 (5.6 billion) and scaled it to 12 billion, extrapolating national population growth projections for 2050 [U.S. Census Bureau, 2004]. A population of 12 billion marks the upper limit of the 80% confidence interval of potential population trajectories [Lutz et al., 2001]. We distributed total population to the grid cells based on the Gridded Population of the World (GPW) dataset [CIESIN et al., 2000] in order to determine local (i.e. 0.5° x 0.5° grid cells) demand.

For diets, we assumed three different settings, reflecting current global trends in lifestyle change towards increased meat consumption. Again, we used 1995 data as baseline and doubled or halved consumption of animal products respectively in order to explore the order-of-magnitude impacts. A doubling of per-capita meat demand is projected for China, India, and other countries by the year 2020 [Rosegrant et al., 1999]. For the world as a whole, a general assumption of doubled consumption of animal products may be a rather drastic increase, but one that is by no means completely out of range. Halving current meat consumption would require a considerable change in dietary habits in many cultures, or at least a regional decoupling of the historically prominent link between economic wealth and meat consumption. We used FAO data [FAO, 2004] to determine the regional demands in 1995 (setting 1 in table 2.3) for the most important agricultural products (table 2.4) for 11 regions (table 2.2), assuming diets to be homogenous in each region. Food demand as computed here accounts for direct human consumption and for losses during production and food processing. FAO food balance sheets [FAO, 2004] provide detailed information of origin (production, import) and usage (food, feed, seed, food manufacture, waste, export and other uses) for each commodity, summing up to a total supply. We subtracted feed use from total supply to determine total demand, implicitly accounting for losses in the process of food production. For Latin America, we reduced sugar crop demand by one third to account for the exceptionally large share of sugar exports. We computed total per-capita energy consumption for each region as the weighted sum of each commodity's energy content as reported by Wirsenius [2000]. We kept these energy consumption levels constant for all diets by scaling direct human crop consumption to counterweight the changed consumption of animal products (hereafter: meat consumption). In order to translate the demand for animal products into demand for field crops, we used regional feed mix data [FAO, 2004] and added demands for green fodder (grass and whole-maize) in the case of ruminant meat and milk based on Wirsenius [2000] and FAO [2004]. Whole-maize (for feed) is computed as the sum of grain yield and 90% of the harvested residues. Feed demand differs between regions as animal production systems vary between regions. We did not explicitly include the use of residues and by-products for feed since we assume that they are included in our definition of commodity demand (see above).

Table 2.2: Regional distribution of population based on national population counts for 1995 and extrapolated national population growth projections for 2050 U.S. Census Bureau [2004].

Region	Regional food balance sheets [FAO, 2004] to determine commodity consumption	Number of countries	Population count of 5.6 billion in 1995 (million)	Population count scaled to 12 billion (million)
Africa	Sub-Saharan Africa	46	575	2160
Centrally planned Asia	Cambodia, China, Laos, Mongolia, Vietnam	5	1308	1820
Eastern Europe	Eastern Europe	16	121	117
Former Soviet Union	USSR, former area of	12	291	299
Latin America	Latin America and Caribbean	27	484	1019
North-Africa & Middle East Asia	Region of Near East	18	468	1078
North America	North America, developed	2	296	615
Region of Pacific OECD	Australia, Fiji, Japan, New Caledonia, New Zealand, Vanuatu	7	148	102
Pacific Asia	East and South East Asia	9	478	998
South Asia	South Asia	8	1083	3438
Western Europe	Western Europe	20	385	351

Table 2.3: Global agricultural demand for direct human consumption. For halved and doubled consumption of animal products, the direct consumption of vegetal commodities was scaled to keep total energy consumption constant.

			Total global commodity demand (million tons dry matter)												
Setting	Population (billion)	Commodity consumption	Cereals	Maize	Rice	Roots and tubers	Pulses	Soybeans	Oil-crops	Sugar crops	Ruminant meat	Non-ruminant meat	Poultry	Milk	Eggs
1	5.6	As in 1995	551	172	328	124	38	118	69	327	29	38	22	60	15
2	5.6	Halved consumption of animal products	590	185	344	132	40	128	75	348	15	19	11	30	8
3	5.6	Doubled consumption of animal products	473	147	297	108	34	96	58	285	58	76	43	120	30
4	12	As in 1995	1029	365	676	272	95	218	125	684	54	54	37	108	24
5	12	Halved consumption of animal products	1090	388	705	285	99	236	132	720	27	27	19	54	12
6	12	Doubled consumption of animal products	909	318	620	245	87	180	109	611	107	108	74	217	48

Table 2.4: Agricultural products considered in this study, corresponding crop functional types and FAO categories used to determine the baseline demand. Feed mix assignments for animal products differ regionally, sugar case has been simulated as maize with a special MF assignment (see text).

Agricultural products	Crop functional types (CFT)	FAO categories for aggregate demand
Grain cereals	Temperate cereals (wheat), tropical cereals (millet)	Wheat, rye, barley, oat, millet, sorghum
Maize	Maize	Maize
Rice	Rice	Rice, paddy
Roots and tubers	Temperate roots and tubers, tropical roots and tubers	Roots and tubers
Pulses	Pulses	Pulses
Soybeans	Soybeans	Soybeans
Oilcrops	Rapeseed, peanut, sunflower	Rapeseed, peanut, sunflower
Sugar	Maize (sugar cane), temperate roots and tubers (sugar beet)	Sugar crops
Ruminant meat	Feed mix assignment	Bovine meat, sheep and goat meat
Non-ruminant meat	Feed mix assignment	Pig meat
Poultry meat	Feed mix assignment	Poultry meat
Milk	Feed mix assignment	Milk, cream, butter/ghee
Eggs	Feed mix assignment	Eggs

2.2.4 Land allocation

We developed two substantially different spatial patterns of global land use for each agricultural demand setting. To represent an unrestricted global market (no trade barriers, no transportation costs, no subsidies) as a first setting, production was allocated to the most productive grid cells as computed by LPJ/mL with MF (globalized production). The underlying idea is to grow food where this can be done most efficiently, that is at sites of least limiting climatic and management conditions. To achieve this, we minimized total production area, using the linear optimizer LP-SOLVE 4.0 [Berkelaar, 2003] to determine the most efficient spatial arrangements of the different CFTs. In this setting, we constrained production by current yield levels, computed by LPJ/mL and the MFs, and grid cell size only, allowing for grid cells with 100% agricultural land use and ignoring crop rotational constraints, which implicitly assumes high technological and chemical inputs.

In a second setting, production was allocated locally (localized production), i.e. we forced each grid cell to satisfy, as far as possible, its own demand (cell's population multiplied with the corresponding regional per-capita demand). Again, land was allocated with the objective to minimize production area, allowing 100% agricultural land use. If the grid cell's productivity was too low to satisfy the demand, we maximized production in that grid cell and distributed the remaining demand in two subsequent steps to the available land in neighboring cells (squares of 3.5° x 3.5° and 9.5° x 9.5° respectively). Neighboring cells could supply additional land, if their domestic demand could be met without utilizing the entire area. If a cell's demand could not be satisfied within its neighborhood, it was pooled globally. Demand that could not be satisfied within a grid cell at all, i.e., if current yield of the corresponding crops in that cell is zero, was pooled globally, too. The pooled global demand was located as in the globalized production scheme but constrained additionally by the production already allocated in the preceding steps.

2.3 Results

We assess the range of potential land-use impacts on global carbon pools and water fluxes (table 2.5) by comparing the results of the different land-use simulations. To supply a measure of relative importance, we compare the results to the effects of projected climate change by the period 2071-2100, given by Schaphoff et al. [2006] for the climate projections of 5 GCMs (CGCM1, ECHAM4, CCSR, CSIRO and HadCM3)

Table 2.5: Selected results: agricultural area, carbon and water budgets; 10-year averages (1990-1999). Impacts of climate change as reported by Schaphoff et al. [2006].

	Globalized production						Localized production								Climate change (IS92a), 2071-2100 average	
Population	12 billion			5.6 billion			12 billion			5.6 billion						
Consumption pattern	Doubled consumption of animal products	1995 consumption	Halved consumption of animal products	Doubled consumption of animal products	1995 consumption	Halved consumption of animal products	Doubled consumption of animal products	1995 consumption	Halved consumption of animal products	Doubled consumption of animal products	1995 consumption	Halved consumption of animal products	Reference run	Natural vegetation	Lower bound	Upper bound
Agricultural area [million km^2]																
Agricultural area	6.9	5.3	4.5	3.0	2.3	1.9	35.0	30.2	27.5	21.2	17.9	16.0	16.0	–	–	–
Pasture	1.4	0.7	0.3	0.6	0.3	0.1	7.5	4.4	2.4	3.9	2.2	1.2	6.5	–	–	–
Cropland	5.4	4.6	4.2	2.4	2.0	1.7	27.5	25.8	25.2	17.4	15.7	14.8	9.5	–	–	–
Terrestrial carbon pools [PgC]																
Vegetation carbon	658	676	685	696	705	710	557	583	596	624	642	652	633	725	653	958
Soil carbon	1480	1490	1496	1510	1515	1518	1275	1309	1326	1353	1383	1399	1392	1528	1484	1595
Total carbon	2138	2166	2180	2206	2220	2227	1832	1891	1922	1978	2025	2050	2013	2253	2162	2553
Net Primary Production (NPP) [PgC/a]																
NPP	66.6	66.3	66.2	66.5	66.4	66.4	60.7	60.9	61.0	62.9	63.1	63.2	65.3	66.2	71.8	84.4
Water flows [km^3/a]																
Actual transpiration	41564	41447	41394	41841	41837	41844	36412	36700	36842	38815	39077	39216	40688	42111	–	–
Evaporation	10315	10063	9944	9432	9286	9214	15567	15078	14827	12654	12239	12021	11452	8593	–	–
Interception	10879	11221	11384	11506	11668	11742	9431	9801	9985	10540	10774	10895	10515	11963	–	–
Runoff	43372	43400	43409	43353	43341	43332	44710	44542	44466	44118	44037	43996	43476	43424	–	–
Irrigation water	599	552	533	377	365	359	1610	1646	1649	999	940	906	–	–	–	–

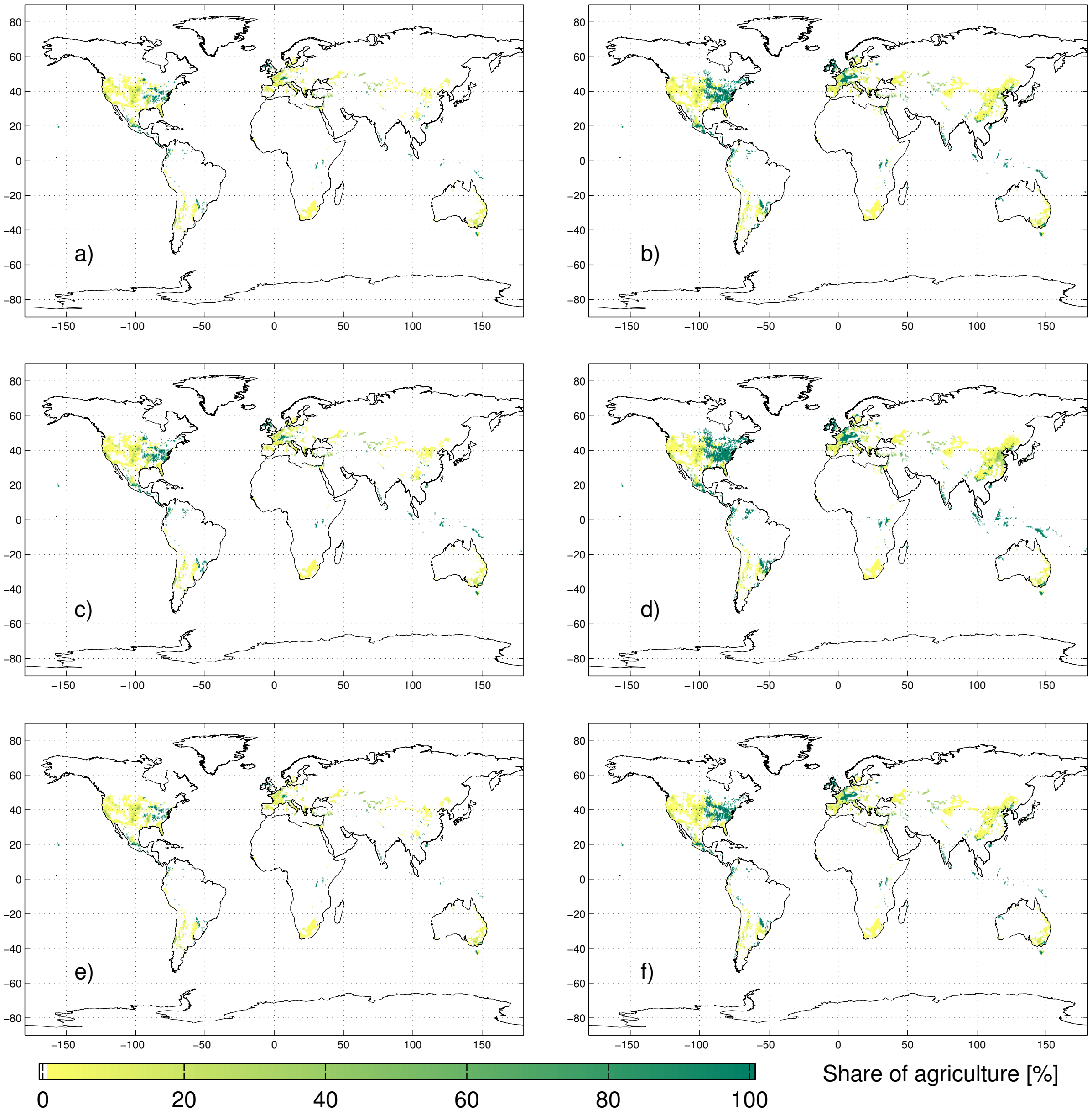

Figure 2.3: Agricultural land-use patterns for the globlized production scheme: a) population of 5.6 billion, diet of 1995; b) population of 12 billion, diet of 1995; c) population of 5.6 billion, doubled meat consumption; d) population of 12 billion, doubled meat consumption; e) population of 5.6 billion, halved meat consumption; f) population of 12 billion, halved meat consumption.

under the IS92a emission scenario; these projections were derived from the same model (LPJ) but without cropland. All results are expressed as averages of the period 1990-1999 and (except table 2.5) as differences to the reference run which is based on the actual area demand for the crops considered here, according to FAO [2005a]. Total agricultural area ranges between 2 and 35 million km^2 for the different settings (see figures 2.3, 2.4, table 2.5). Accordingly, the carbon and water budgets (table 2.5) show weak to strong responses, depending on the setting.

2.3.1 Terrestrial carbon fluxes and pools

The potential effects of changed land-use patterns on carbon pools are — depending on the setting — comparable to those of projected climate change by the end of the 21st century (figure 2.5) [Schaphoff et al., 2006]. Only NPP (table 2.5) is less sensitive to the different land-use scenarios than to CO_2 fertilization and climate change. NPP of cropland is similar to that of natural vegetation. Locally, it may be higher

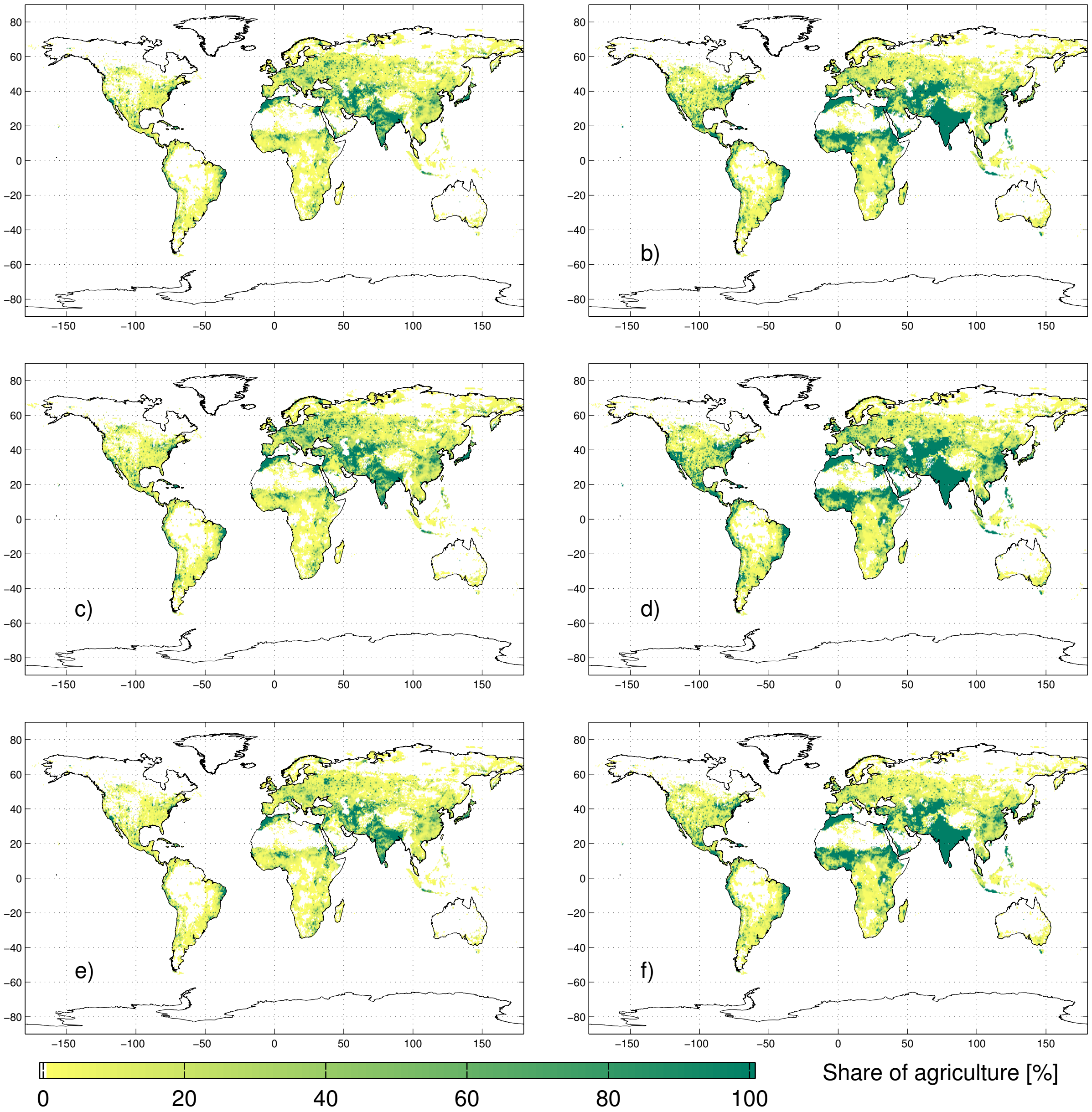

Figure 2.4: Agricultural land-use patterns for the localized production scheme: a) population of 5.6 billion, diet of 1995; b) population of 12 billion, diet of 1995; c) population of 5.6 billion, doubled meat consumption; d) population of 12 billion, doubled meat consumption; e) population of 5.6 billion, halved meat consumption; f) population of 12 billion, halved meat consumption.

or lower, depending on CFT, local conditions, and management (here irrigation only). Under the globalized scenarios, only highly productive areas are used agriculturally, in which cropland NPP tends to be higher than NPP of potential natural vegetation. If meat consumption increases, the size of agricultural area but also the share of highly productive pastures in total agricultural area increase. Thus, NPP increases with agricultural area in these cases, while it generally decreases with the size of agricultural area (table 2.5, figure 2.6). Carbon pools, however, change significantly under cultivation even with similar NPP because large parts of the accumulated carbon are removed at harvest, strongly reducing the turnover time. Carbon pool sizes are linearly determined by total agricultural area (figure 2.6). Agricultural land-use usually reduces both vegetation and soil carbon. Under the different scenarios, vegetation carbon ranges from 90 to 114% of the reference run and soil carbon from 92 to 109%, reflecting total agricultural area (table 2.5).

The sign and magnitude of the changes in car-

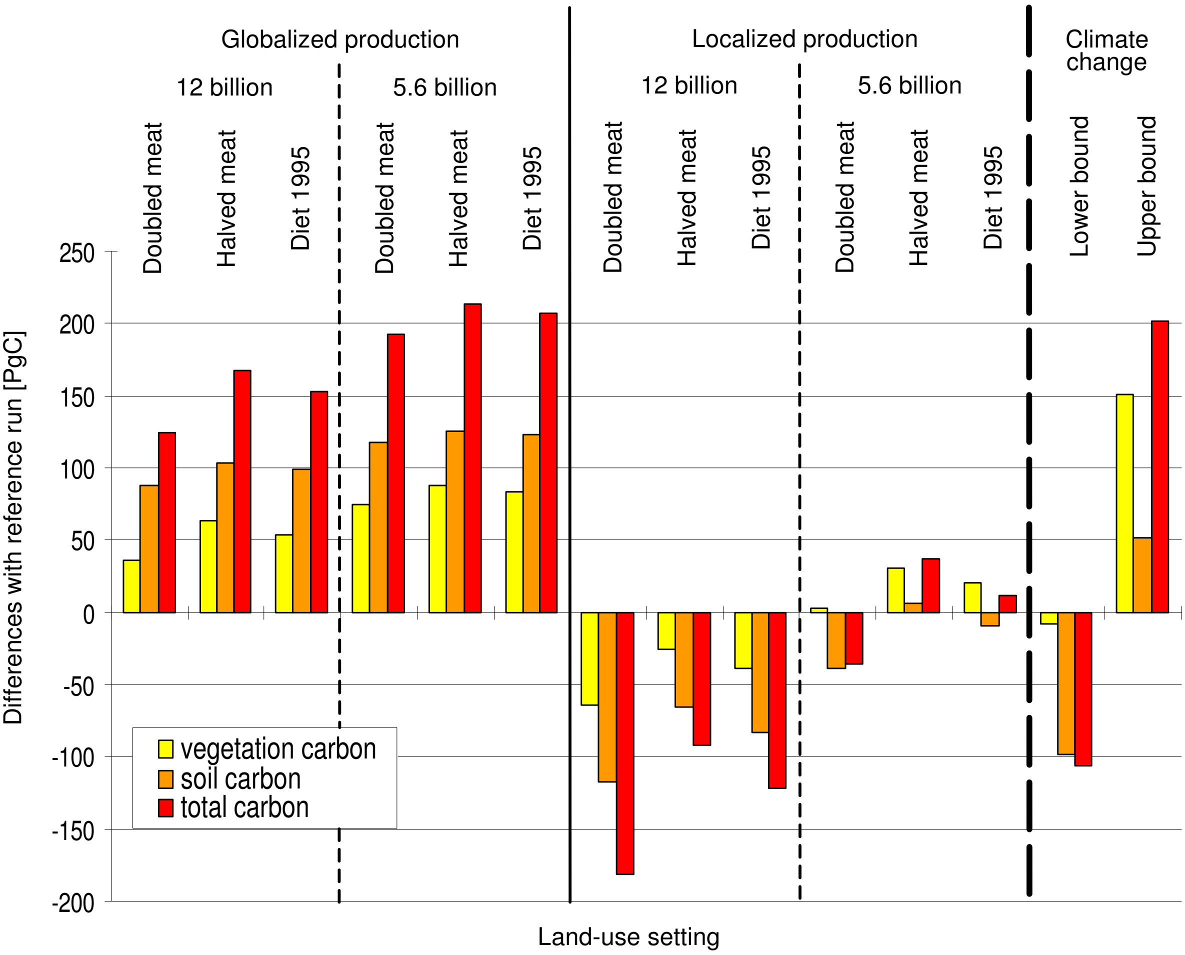

Figure 2.5: Effects of different land-use patterns on global carbon pools, presented as differences with the reference run. Estimates of climate change impacts (right of bold dashed line) from Schaphoff et al. [2006], representing the minimum (lower bound) and maximum (upper bound) of climate-change induced changes in carbon pool sizes. Total carbon is the sum of soil and vegetation carbon.

bon pools are mainly determined by the production scheme, which largely determines area demand. Carbon pools are significantly smaller than in the reference run under most localized scenarios, while they are much larger under the globalized production scenarios. Following the production scheme, population and diet also strongly affect the carbon pools, most prominently under the localized productions scenarios. NPP may differ between field crops and natural vegetation. Under the IS92a emission scenario and corresponding climate change projections, NPP increases by ~10 to ~21 PgC/a [Schaphoff et al., 2006], while we compute only small differences (-4.5 to 1.4 PgC/a) between the reference run and our land-use patterns. Correspondingly, CO_2 fertilization and climate change as studied by Schaphoff et al. [2006] mainly affect the vegetation carbon pool while the different land-use patterns also strongly affect the soil carbon pools (figure 2.5), because large parts of the NPP are removed at harvest and do not enter the litter pools.

2.3.2 Terrestrial water balance

As for the carbon cycle, the water cycle responds strongly to the different production schemes, especially to the localized production scheme (figure 2.7, table 2.5). The impact of land use on the water cycle is also mainly determined linearly by total agricultural area (figure 2.6). Generally, transpiration and interception are reduced by agricultural land use as compared to potential natural vegetation, while evaporation and runoff increase. In case of irrigated agriculture, however, runoff is reduced in comparison to rain-fed vegetation as irrigation water is taken from runoff. At the global scale, the corresponding reduction of runoff is counterbalanced by the general increase of runoff on arable land, leaving global runoff within narrow bounds (±3% compared to reference run, see figure 2.7). For transpiration, evaporation,

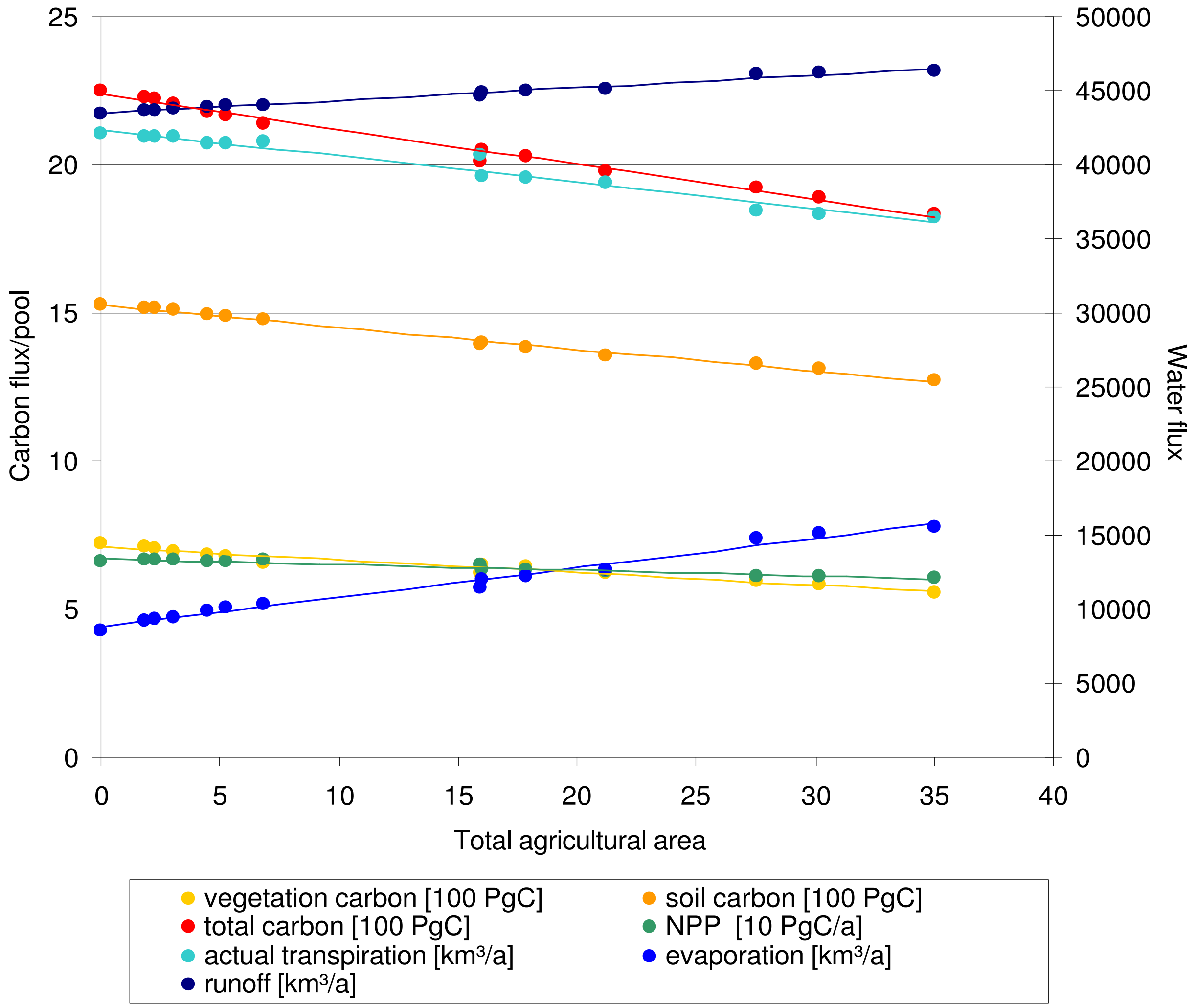

Figure 2.6: Linear relationships between total agricultural area and carbon pools/water fluxes.

and interception (not shown), stronger differences between the land-use patterns and the same general pattern as for the carbon cycle can be observed (figure 2.7, table 2.5). The production scheme mainly determines the sign and magnitude of land-use effects on the global water cycle, followed by the differences in population. Differences in diet are in our simulations of minor importance for the water cycle at the global level.

2.4 Discussion

Although based on stylized scenarios of possible global land-use changes, the present study clearly demonstrates that the individual effects of different drivers of land-use change (demography, diet, production pattern) are of major importance for the global carbon and water budgets. Their effects on the carbon cycle are comparable in size to the cumulative fossil-fuel emissions from pre-industrial times to the year 2000 of 280 PgC and to the total carbon loss of 200-220 PgC from land-use change in the same period House et al. [2002] (compare figure 2.5). It should be noted that our scenarios are designed to provide a first-order assessment of the range of potential impacts of land use and can thus be compared to the climate projections as studied by Schaphoff et al. [2006] only to gain an impression of the comparative magnitude of effects. To ensure direct comparability of the drivers of land-use change, we studied their effects in a static comparative setting, i.e. we excluded climate change and kept management constant at 1995 levels. For future land-use patterns, these two factors potentially amplify or counteract the effects studied here.

The general result that the land-use pattern is an important factor in the global carbon balance agrees with the findings of Gitz and Ciais [2004]. Levy

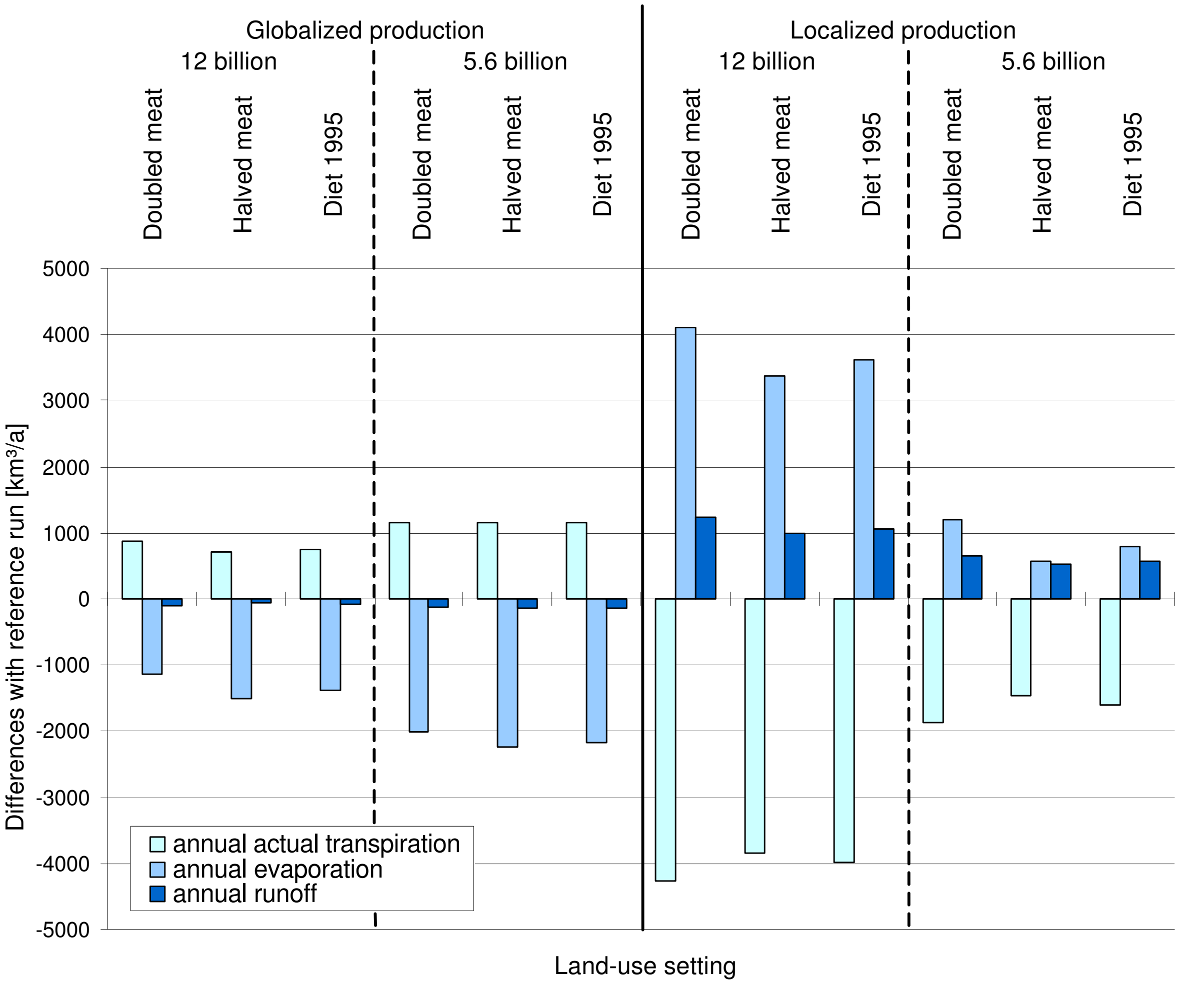

Figure 2.7: Effects of different land-use patterns on global water flows, presented as differences with the reference run.

et al. [2004a] attribute only smaller parts of projected changes in future carbon budgets to land-use change, based on 3 SRES scenarios that imply only slightly increasing or substantially decreasing total agricultural areas. Levy et al. [2004a] acknowledge that scenarios with substantial expansion of cultivated land should be considered (as in the present study), given the large uncertainties in the future development of land use.

Evaporation and transpiration are strongly affected by land-use patterns. Both processes are important components of the energy transfer between atmosphere and biosphere (latent heat flux) and affect local and regional climate conditions [Pielke et al., 2002]. Changes in global runoff are small at the global scale as the changes in evaporation and interception largely counterbalance the changes in transpiration. However, runoff is significantly affected by land-use change at the catchment level [Farley et al., 2005] and thus needs to be analyzed locally rather than globally. This, however, is beyond the scope of this assessment of first-order effects.

We note that the management factors (MF) used may lead to artifacts in local crop productivity if, for a certain CFT, the most productive cells of a country, as simulated by LPJ/mL, are currently not used for this CFT according to Ramankutty and Foley [1999] and Leff et al. [2004], i.e. $A_{c,i} = 0$ (compare equation 2.1). If there are no restrictions on including these grid cells in the land-use pattern, as e.g. in the globalized scenarios, these grid cells with unrealistically high yield levels will decrease total area demand. For grasslands no yield data are available to determine the MF. Also, the different land-use patterns are based on simple assumptions. Feed-mixes and consumption patterns are derived from coarse regional estimates for the most important commodities only (table 2.3) [FAO, 2004; Wirsenius, 2000] and changes in consumption are merely based on consumption of animal products and its implications for the consumption of vegetal products. Forestry and timber extraction are not considered. The different production schemes used reduce the complexity of land-use change processes [Heistermann et al., 2006, see Chapter 4] to the objective of area minimization.

Carbon pools and fluxes as well as water flows are linearly related to total agricultural area (figure 2.6), as the difference between natural and agricultural sites is much more important than the differences between different crops or different types of natural forest. For assessing the impact of land use on the terrestrial carbon and water cycles, it is therefore crucial to precisely determine the total size of the agricultural area. Total area demand, however, is not related to total demand for agricultural products but varies greatly between different production schemes and demand structures (table 2.5). Spatial explicitness is crucial to determine the area demand for agriculture, as crop productivity varies greatly between different sites and crops. Constraints on localization of production, as represented by the two different production schemes, strongly affect the area needed to meet the demand for agricultural products and thus determine the consequences for the carbon and water cycles. Climate change and technology development, which are excluded here, could significantly affect local productivity and thus land-use efficiency and agricultural area demand. By distributing agricultural production to the most productive grid cells, total agricultural area could be much reduced. All production schemes allocate land with the objective to minimize area, but are differently constrained, leading to strong differences in area demand. According to FAO, 9.5 million km^2 were under cultivation in 1995 to produce the field-crops (except green fodder) included in this study [FAO, 2005a]. If the agricultural commodities would be produced at average western European levels, this area could be reduced by 50% (20–80% for single crops). This reduction can be reinforced if production is allocated to the most productive sites, which may exceed the average western European levels 2 to 3 times. The current agricultural production is neither globalized nor localized. It is situated well between these two extreme assumptions that define the range of possibilities. It has to be noted that the reference run does not quite reflect the actual land-use pattern but is adopted to be consistent with our 1995-baseline demand.

Due to the feedbacks between the natural environment, land use, and society [Heistermann et al., 2006, see Chapter 4], the importance of demography, diet, and production patterns for the carbon and water cycle directly and also indirectly takes effect on the entire Earth System. Concentrating agricultural production to the most productive sites as in the globalized production scenarios has been proposed as a solution to the conflict between conservation and future food demands [Goklany, 1998; Green et al., 2005] — but will global trade patterns facilitate such changes? In 1995, inter-regional agricultural trade amounted globally to only about 10% of total agricultural production [FAO, 2005a]. Besides, globalizing (or localizing) agricultural production would have further major implications for the carbon cycle such as carbon emissions from transportation, fertilizer, and pesticide production etc. These, as well as changes in other biogeochemical cycles such as of nitrogen and phosphorus, pesticide consumption [Tilman et al., 2001], habitat destruction [Waggoner, 1994] etc. need to be considered in more integrated assessments.

2.5 Conclusions

Agricultural land use is a major factor influencing the global carbon and water cycles — in the case of carbon, potentially equally important to historic fossil-fuel emissions and projected climate change. The size of agricultural land is the most important aspect of agricultural land use for the terrestrial carbon and water cycles. It is therefore crucial for assessing effects of land use and land-use change to correctly determine the size of agricultural area, taking into account all drivers that determine land-use patterns. We could show that demand structures, driven by population and consumption patterns, significantly affect total agricultural area and the carbon and water budgets globally. Under the assumption of current climate and management, the spatial location of agricultural land is the most important determinant of area demand and thus of the biogeochemical impacts of land-use. Although the impacts of land-use on the global carbon and water budgets are strongly related to the extent of total agricultural area, they cannot be assessed with crude estimates of total area demand. Population, consumption patterns, and especially the spatial constraints on land use determine total area demand in a non-linear way.

Future studies on global change need to include spatially explicit patterns of human land-use. Land use has been shown to affect climate change [e.g. Sitch et al., 2005] and the global carbon and water budgets (this study). Although not included in this study, technology change, climate change, and their mutual interaction with land use and the biogeochemical cycles presumably affect the magnitude of each other's impact and need to be studied in a comprehensive framework.

Acknowledgements

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Chapter 3

Effects of changes in CO_2, climate, and land use on the carbon balance of the land biosphere during the 21st century[1]

The world changes, and all that once was strong now proves unsure.

J. R. R. Tolkien, The Two Towers

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Abstract

We study the effects of land-use change on the global terrestrial carbon cycle for the 21st century by driving a process-based land biosphere model (LPJ/mL) with twelve different dynamic land-use patterns and corresponding climate and atmospheric CO_2 projections, supplied from the IMAGE 2.2 implementations of the IPCC-SRES storylines for the A2, B1, and B2 scenarios. Each SRES scenario has been simulated in IMAGE 2.2 and LPJ/mL with climate patterns of four different GCMs to account for uncertainties in local climate change. The selection of SRES scenarios comprises a deforestation and an afforestation scenario, bounding a broad range of possible land-use changes. The projected land-use changes under different socio-economic scenarios have profound effects on the terrestrial carbon balance: While climate change and CO_2 fertilization cause an additional terrestrial carbon uptake of 100–220 PgC, land use change causes terrestrial carbon losses of up to 450 PgC by 2100, dominating the terrestrial carbon balance under the A2 and B2 scenarios. Our results challenge earlier study results on the carbon cycle dynamics that disregard land use and land-use change.

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[1] An edited version of this chapter is under revision for *Journal of Geophysical Reserach — Biogeosciences*: Müller C, Eickhout B, Zaehle S, Bondeau A, Cramer W, Lucht W: Effects of changes in CO_2, climate, and land use on the carbon balance of the land biosphere during the 21st century.

3.1 Introduction

Climate change during the 21st century will be determined by the trajectory of greenhouse gas (GHG) concentrations, biophysical interaction with the earth's surface and feedbacks with the Earth System. Changes in atmospheric CO_2 concentration are the net result of emissions from fossil fuel combustion, cement production, and carbon exchange with oceans and land ecosystems. Land-use and land-cover changes affect the carbon balance of the terrestrial biosphere Foley et al. [2005]; Houghton [1999]; Smith et al. [1993] and influence the distribution of terrestrial carbon sources and sinks Canadell [2002]; Dargaville et al. [2002]. The terrestrial carbon balance therefore is a function of socio-economic dynamics Lambin et al. [2001] as well as biogeochemical processes in plants and soil McGuire et al. [2001]. Recent studies on the future development of the global carbon cycle focus on the effects of climate change projections Schaphoff et al. [2006] and on the feedback between climate and the carbon cycle Berthelot et al. [2005]; Cox et al. [2000]; Dufresne et al. [2002]; Friedlingstein et al. [2003]; Matthews et al. [2005]. In these studies, carbon emissions from land-use change are summarily included in the driving carbon emission scenarios. Future changes in land-use are rarely addressed explicitly in carbon cycle studies at the global scale. Reasons for this are the large uncertainties connected with the drivers of land-use change Gitz and Ciais [2004], and the absence of numerical modules for carbon dynamics under cultivation in most global process-based models. First approaches to study the effects of future land-use changes on the carbon cycle at the global scale mainly focus on single aspects of land-use change: House et al. [2002] approach the topic by studying total de- and total afforestation in a bookkeeping model. DeFries [2002] analyzes the effects of past and future land-use changes on net primary production (NPP). Cramer et al. [2004] study tropical deforestation by extrapolating trends of deforestation rates. They employ different climate scenarios to account for uncertainties in climate change projections. Levy et al. [2004a] derive trends of land-use change from SRES storylines Nakicenovic and Swart [2000] that include feedbacks within the society-biosphere-atmosphere system. Sitch et al. [2005] employ spatially explicit land-use patterns also derived from the SRES storylines to drive their coupled climate-biosphere model (CLIMBER2-LPJ).

In this study, we cover a broad range of future Earth System projections and move one step forward by explicitly modeling the carbon dynamics of agricultural land. At local and regional scales, past and future land use was found to significantly affect the carbon cycle by changing carbon cycle processes Achard et al. [2002]; Haberl et al. [2001]; Ometto et al. [2005]; Schröter et al. [2005]: Soil- and vegetation carbon pools change after de- Fearnside [2000] and afforestation Caspersen et al. [2000]; Guo and Gifford [2002]. Carbon sequestration under cultivation is reduced as assimilated carbon is removed at harvest Post and Kwon [2000], accelerating carbon turnover times Gitz and Ciais [2003]. Differences in phenology and crop management Lal [2004] affect net primary production (NPP) and carbon fluxes Bradford et al. [2005]; DeFries [2002]; Jones and Donnelly [2004]. In this study, we use LPJ/mL ("LPJ for managed Land"), an advanced version of the process-based LPJ Dynamic Global Vegetation Model Gerten et al. [2004]; Sitch et al. [2003]. LPJ/mL has been extended to capture the most important processes of land-use change and cultivation and their effects on the carbon cycle, using a concept of crop functional types Bondeau et al. [2007]. The model explicitly simulates the fate of deforested carbon in product- and litter pools. The implementation of 13 crop functional types (CFTs) accounts for differences in phenology and in carbon allocation, between the different forms of land use. Environmental conditions and management affect simulated yields and, thus, the fraction of removed carbon at harvest. Management options implemented in LPJ/mL include irrigation, the removal of residues, and intercropping (see Bondeau et al. [2007] for details and validation).

We account for uncertainties in societal development and climate change in a consistent framework by studying a set of twelve different land-use patterns, their corresponding atmospheric carbon concentrations and climate scenarios for the 21st century, self-consistently computed by the IMAGE 2.2 model (Integrated Model to Assess the Global Environment) for the SRES scenario storylines A2, B1, and B2 IMAGE team [2001]. This selection comprises a scenario of substantial deforestation (A2), one of afforestation (B1), and one of moderate changes (B2). To account for the uncertainty in regional climate change, four different climate change patterns have been used to generate the land-use patterns for each SRES scenario. Within the IMAGE 2.2 model, the SRES scenario storylines have been implemented with consistent assumptions on trade, technological change, demographic, and economic growth and include feedbacks between society, climate, and the biosphere IMAGE team [2001]. However, processes in IMAGE 2.2 are often implemented in a reduced form, paying tribute to the complex interactions. Thus, we are studying the biospheric reaction to potential changes in climate, atmospheric CO_2 concentrations, and land-use in more detail, using the LPJ/mL model. We analyze the development of soil and vegetation carbon pools as well as the different components of the land-atmosphere carbon flux, going beyond the IMAGE-based study of Leemans et al. [2002]. To our knowledge, this is the first study to address different climate and land-use change projections consistently in a DGVM to study the effects on the global carbon cycle, explicitly accounting for carbon dynamics under cultivation.

In section 3.2, we elaborate on the methodology, and present the results of the scenario analyses in section 3.3. We conclude with a discussion of our findings in section 3.4 and conclusions in section 3.5.

3.2 Materials and Methods

3.2.1 Lund-Potsdam-Jena DGVM

The LPJ Dynamic Global Vegetation Model (LPJ-DGVM) Gerten et al. [2004]; Sitch et al. [2003] is a biogeochemical process model that simulates global terrestrial vegetation and soil dynamics and the associated carbon and water cycles. For this, the processes of photosynthesis, evapotranspiration, autotrophic and heterotrophic respiration, including the effects of soil moisture and drought stress, as well as functional and allometric rules are implemented Gerten et al. [2004]; Sitch et al. [2003]. Natural vegetation is represented by 10 different plant functional types (PFTs), of which 2 are herbaceous and 8 woody. Within each grid cell these may coexist, but their abundance is constrained by climatic conditions as well as by competition for resources and space. Vegetation structure reacts dynamically to changes in climate, through expansion into new habitats and dieback. Fire disturbance is driven by a threshold litter load and soil moisture Thonicke et al. [2001]. The model has been extensively tested against site Cramer et al. [2004]; Gerten et al. [2005]; Sitch et al. [2003]; Zaehle et al. [2005], inventory Beer et al. [in press]; Zaehle et al. [2006], satellite Lucht et al. [2002]; Wagner et al. [2003], atmospheric Scholze et al. [2003]; Sitch et al. [2003], and hydrological data Gerten et al. [2004, 2005].

Agricultural land use is simulated within the same framework using crop functional types (CFTs) Bondeau et al. [2007]: The world's most important field crops as well as pastures are represented by a total of 13 different CFTs that can either be simulated with realistic water-stress (rain-fed) or without (irrigated). Grid cells may fractionally consist of both natural and agricultural vegetation, and several agricultural crops may be present within the same grid cell with individual cover fractions. Natural PFTs compete for resources, whereas each CFT has its own specific water budget. Crop phenology, growth, and carbon allocation are simulated at a daily timestep. Carbon is allocated to several crop-specific plant compartments, including a storage organ that represents the economic yield at harvest. The model estimates several crop-variety specific parameters as a function of climate, thereby taking into account the adaptation of crop varieties to specific climatic environments in which they are cultivated. The implementation of the crop specific processes is described in detail and validated against the USDA crop calendar USDA [1994] and satellite data Myneni et al. [1997] for phenology, against FAO data FAO [2005a] for yield simulation, and against eddy flux measurements Baldocchi et al. [2001]; Lohila et al. [2004] for carbon fluxes in the study of Bondeau et al. [2007]. Irrigation is currently not constrained by water availability. Hence it is assumed that water is sufficiently available where irrigation equipment is installed. For this study, residues are removed after harvest and are assumed to be respired within the same year and there are no intercrops between harvest and the next crop cycle.

Managed forests are simulated assuming competition between tree individuals as described in Sitch et al. [2003], but with a prescribed PFT composition. This PFT composition is derived from the simulated PFT composition by LPJ for the period of 1990–1999, considering the two tree PFTs with the largest fractional grid cell coverage. Harvesting of trees, and thus carbon removal, is modeled based on prescribed, PFT-specific rotation times, and forest productivity Zaehle [2005b]. Harvested carbon enters litter pools or product pools, based on the partitioning used by McGuire et al. [2001].

3.2.2 The IMAGE 2.2 model

The IMAGE 2.2 model is a comprehensive Integrated Assessment Model that includes several sub-modules to cover society, climate, and the biosphere as well as major feedbacks between these systems. It was used for the implementation of one of the marker scenarios of the IPCC SRES scenarios Nakicenovic and Swart [2000] and also implemented the complete set of IPCC scenarios in a later stage IMAGE team [2001], focusing on the land-use system Strengers et al. [2004], the geographical explicit consequences for the carbon cycle Leemans et al. [2002], and its impacts on ecosystems Leemans and Eickhout [2004]. Simulations by the IMAGE 2.2 model are conducted for the time frame 1970–2100. Historical figures (1970–1995) are used to calibrate the model. The model runs at a geographical grid cell level of 0.5°x0.5°, longitude/latitude and supplies inter alia spatially explicit land-use patterns, temperature, precipitation, atmospheric CO_2 concentrations, and other parameters that are not used in this study. A detailed description of the IMAGE

Table 3.1: Scenario characteristics as supplied by IMAGE 2.2 [IMAGE team, 2001]. Temperature changes are computed as the difference between the 1971–2000 and 2071–2100 averages over land.

Scenario		Atmospheric $[CO_2]$ in 2100 [ppm]	Temperature increase 1970–2100 [°C]	Land area changes 1970 to 2100 [mill. km^2]		
SRES story-line	GCM pattern			Cropland	Managed Grassland	Managed Forest
A2	CGCM	865.7	3.4	17.02	4.17	4.08
	CSIRO	847.8	3.1	16.34	2.56	4.00
	ECHAM	859.5	3.8	17.51	3.91	4.06
	HADCM	863.3	3.5	16.69	3.90	4.24
B1	CGCM	521.7	2.2	1.02	-11.31	3.09
	CSIRO	514.6	2.1	0.93	-11.67	3.02
	ECHAM	518.3	2.4	1.01	-11.55	3.00
	HADCM	517.8	2.2	1.03	-11.53	2.96
B2	CGCM	609.6	2.7	7.09	-4.68	4.19
	CSIRO	599.7	2.6	6.79	-5.38	4.26
	ECHAM	605.6	3.1	7.26	-5.24	4.20
	HADCM	604.7	2.8	7.15	-4.91	4.23

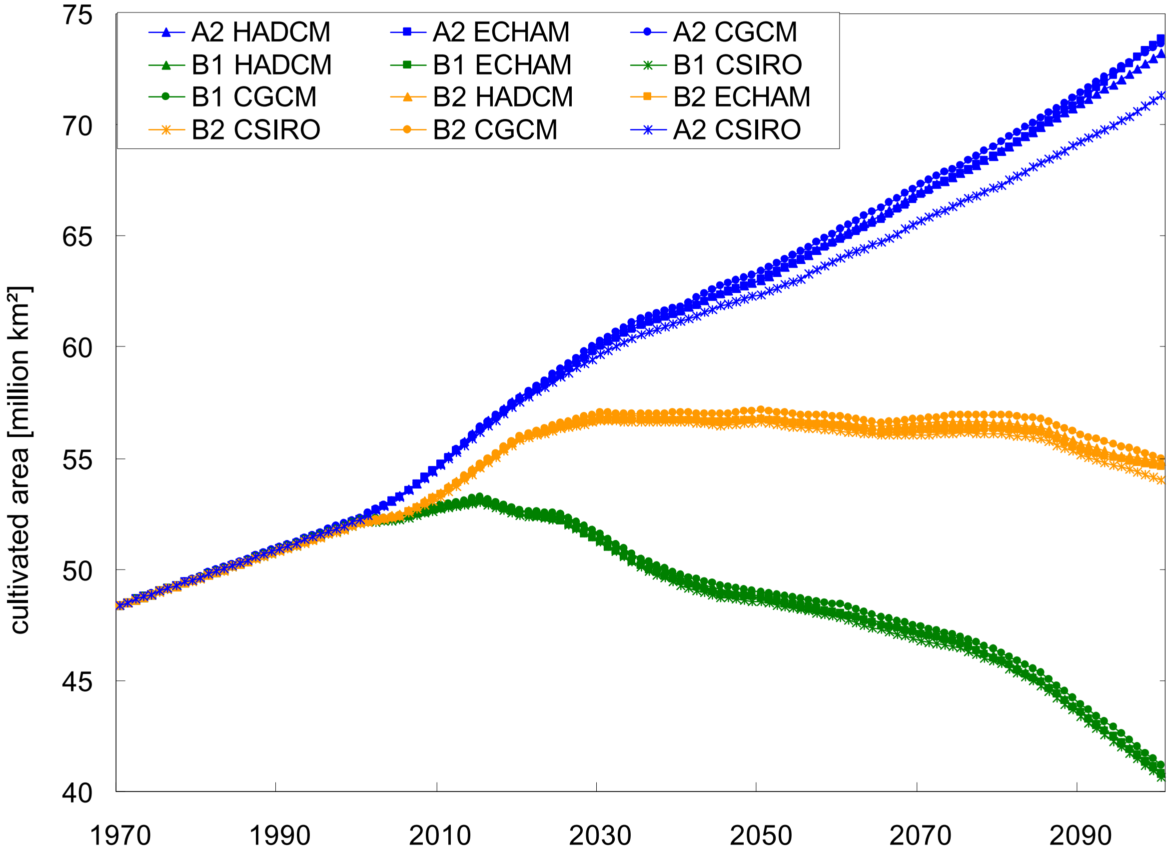

Figure 3.1: Temporal development of total cultivated area for the 12 scenarios.

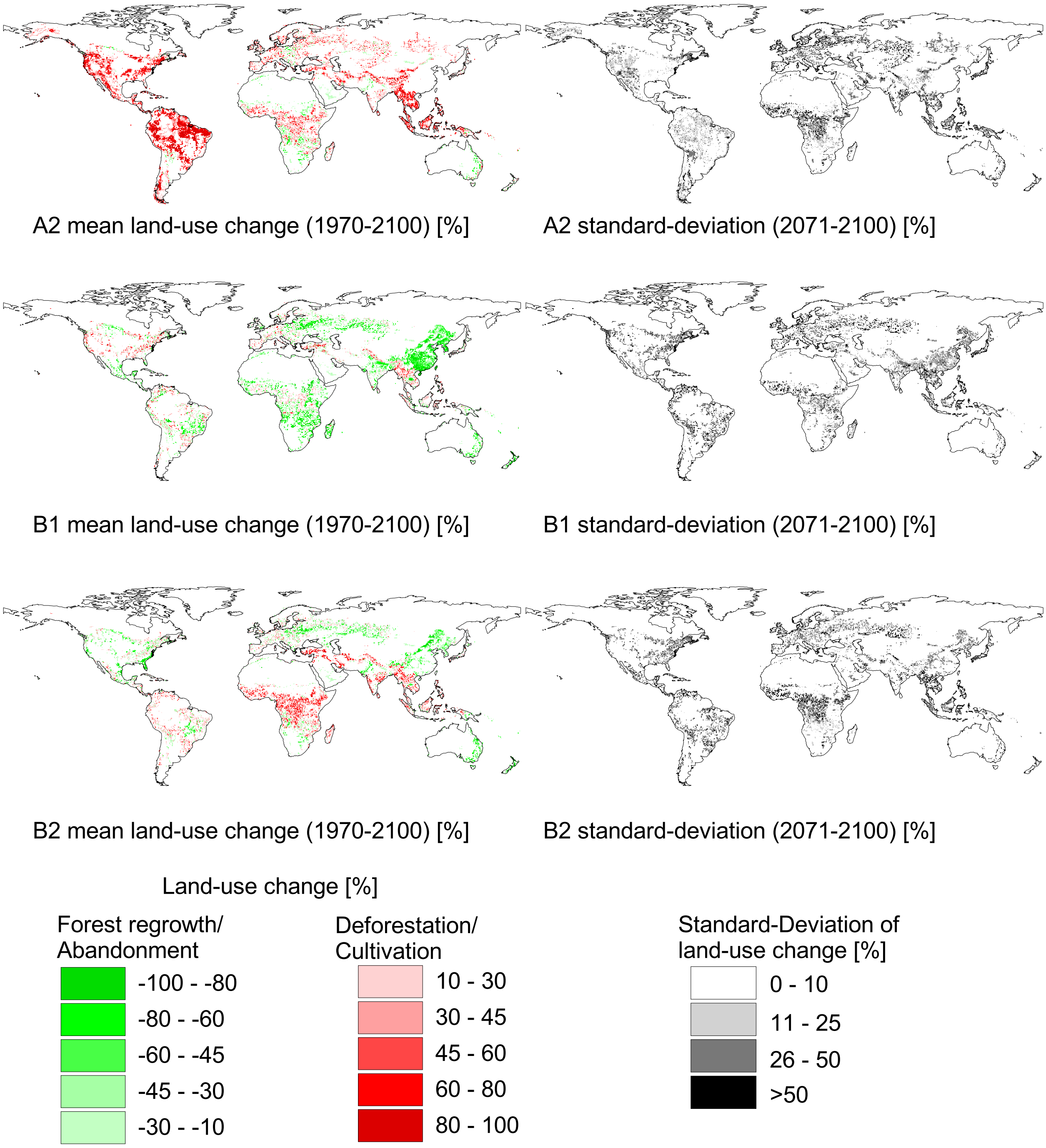

Figure 3.2: Mean land-use change from 1970 to 2100 for the SRES scenarios A2, B1 and B2, averaged over the 4 data sets for each scenario (see text). The local difference between these is shown on the right as the standard deviation, the regional differences, however, are very small.

2.2 model can be found in the publications of Alcamo et al. [1998] and IMAGE team [2001]. For this analysis, we used the A2 (economy oriented, regionally segregated), B1 (environment oriented, globalized), and B2 (environment orientated, regionally segregated) SRES scenarios IMAGE team [2001]; Nakicenovic and Swart [2000] to cover the range of different land-use and climate patterns (table 3.1; figure 3.1). The global-mean temperature change modeled by IMAGE was downscaled to 0.5°x0.5° grid cells, using the standardized IPCC scaling method Carter et al. [1994] supplemented by the scaling method of Schlesinger et al. [2000]Schlesinger et al. [2000] to take into account the non-linear climate effects of sulfate aerosols. To deal with uncertainties in local climate change, four GCM patterns were used to downscale the global-mean temperature change IMAGE team [2001]: HADCM2 Mitchell et al. [1995], ECHAM-4 Bacher et al. [1998], CGCM-1 Boer et al. [2000], and CSIRO-MK12 Hirst et al. [1996]. These differences in climate patterns affect the land-use patterns of each SRES scenario. The land use patterns for each SRES scenario are globally (figure 3.1 and regionally similar but differ locally (figure 3.2).

3.2.3 Data

LPJ/mL was driven by climate data from the University of East Anglia's Climatic Research Unit (CRU) climate data set Mitchell et al. [2004], a monthly climatology of observed meteorological parameters, and annual atmospheric CO_2 concentrations Keeling and Whorf [2003] for the period from 1970–1999. For the period 2000 to 2100, we used a downscaled IMAGE climatology and the IMAGE atmospheric CO_2 concentrations as described above. The monthly IMAGE climatology was supplied for the years 2000, 2025, 2050, 2075, and 2100. To generate time series with annual values for each month, we interpolated linearly between the 25-year time-slices and added the detrended 30-year variability of the 1970–1999 CRU data (absolute variability for temperature, relative variability for precipitation) to the linearly interpolated time series. For sunshine data, the CRU data for 1970–1999 were used repeatedly for the entire simulation period. The number of monthly rain days was kept constant after 1999 at the 1970–1999 average. IMAGE data on land-use and atmospheric carbon dioxide concentration were supplied at 5-year intervals, which we interpolated linearly to generate annual timeseries. Each model run was initialized by a spin-up of 900 years duration during which the first 30 years of the climate data set were repeated cyclically and the land-use pattern was kept static at the values of 1970 to bring all carbon pools into equilibrium.

The IMAGE land-use category *timber* was implemented as managed forests in LPJ/mL, extensive grassland as managed grassland, and regrowth as natural vegetation. The different land-cover types supplied by IMAGE for natural vegetation were ignored and simulated as natural vegetation with the PFT composition as determined internally by LPJ/mL. Crop shares were supplied for 1970 and 2100 and interpolated linearly, keeping crop shares constant in grid cells that are not agriculturally used in 1970 or 2100 and assigning regional default crop mixes to grid cells that are not agriculturally used in either one of these time slices. The crop categories used in IMAGE 2.2 were assigned to the different CFTs implemented in LPJ/mL as specified in table 3.2 and restricted to the 3 most dominant CFTs. For aggregate crop categories that include several CFTs (e.g. oil crops that incorporate sunflower, soybeans, rapeseed, and peanuts) the most productive crop was selected based on the average productivity as simulated by LPJ/mL for the period of 1990–1999. The crop area was reduced by shares of woody biofuels, which were simulated as managed forests and by a share of grassland, which was also simulated as managed grassland.

3.2.4 Experimental setup and simulations

We performed simulations with LPJ/mL for all 12 scenarios (3 SRES scenarios A2, B1, and B2, each with 4 GCM-derived climate patterns) on a regular global grid with 0.5° x 0.5° spatial resolution. The main characteristics of each scenario are summarized in table 3.1 (see also figure 3.1). We used two different simulations to study the marginal effects of climate and land-use changes on the terrestrial carbon balance: one (CC) with constant land-use patterns (1970 pattern) throughout the entire simulation but changing climate and atmospheric CO_2 concentrations, and a second (CCL), in which additionally land-use changed dynamically according to the scenarios. Thus, the difference between the CC-simulation and the CCL-simulation of each scenario (SRES + GCM) is completely attributable to the effects of land-use change.

3.3 Results

3.3.1 Effects of changes in climate and atmospheric CO_2 concentrations

Increasing atmospheric CO_2 concentrations and associated climate change cause increased biospheric carbon sequestration, summing up to 100 to 220 PgC additionally stored in the biosphere by 2100 (figure

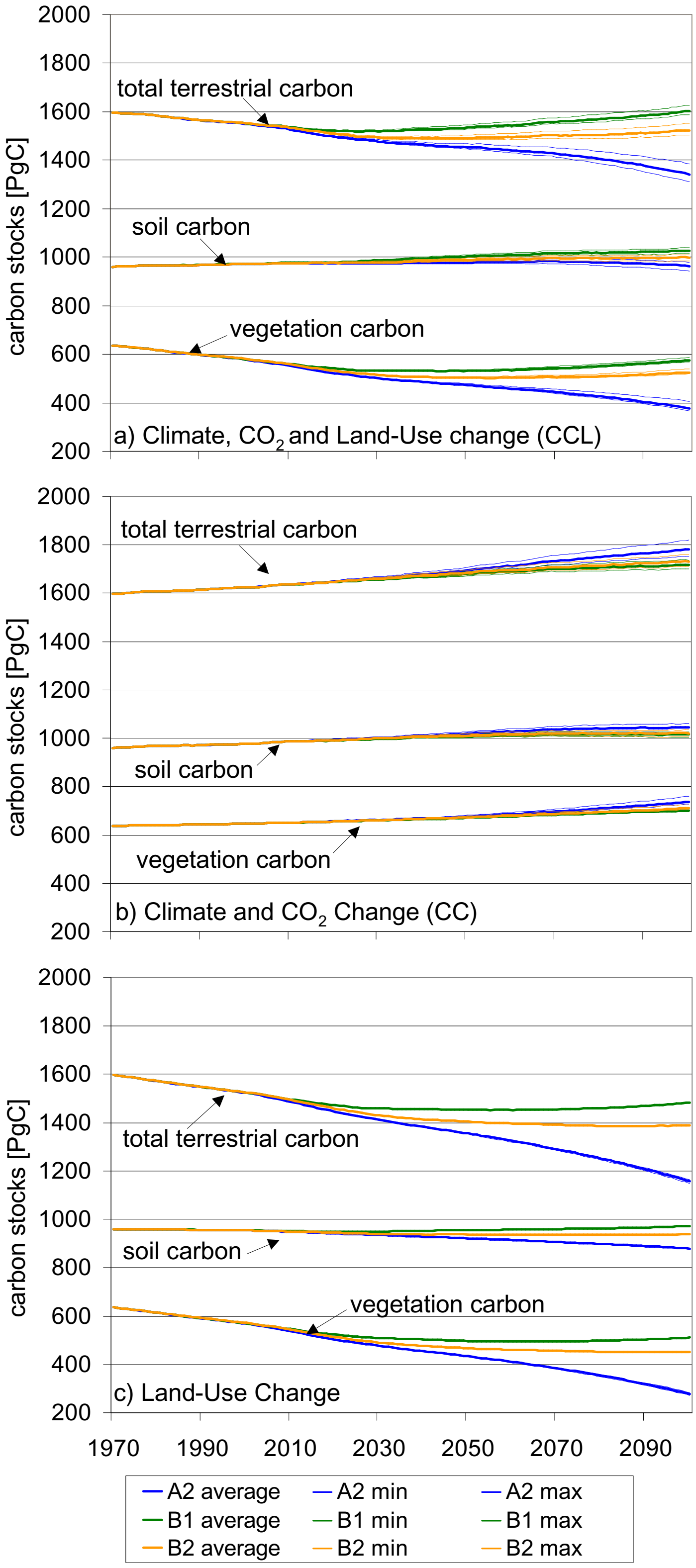

Figure 3.3: Terrestrial carbon stocks. Bold lines represent the average for each SRES scenario; thin lines represent the min/max range. Figure 3.3 c) represents the difference of a) and b) added to the initial value of 1970, in order to obtain the same scale in figures a)–c).

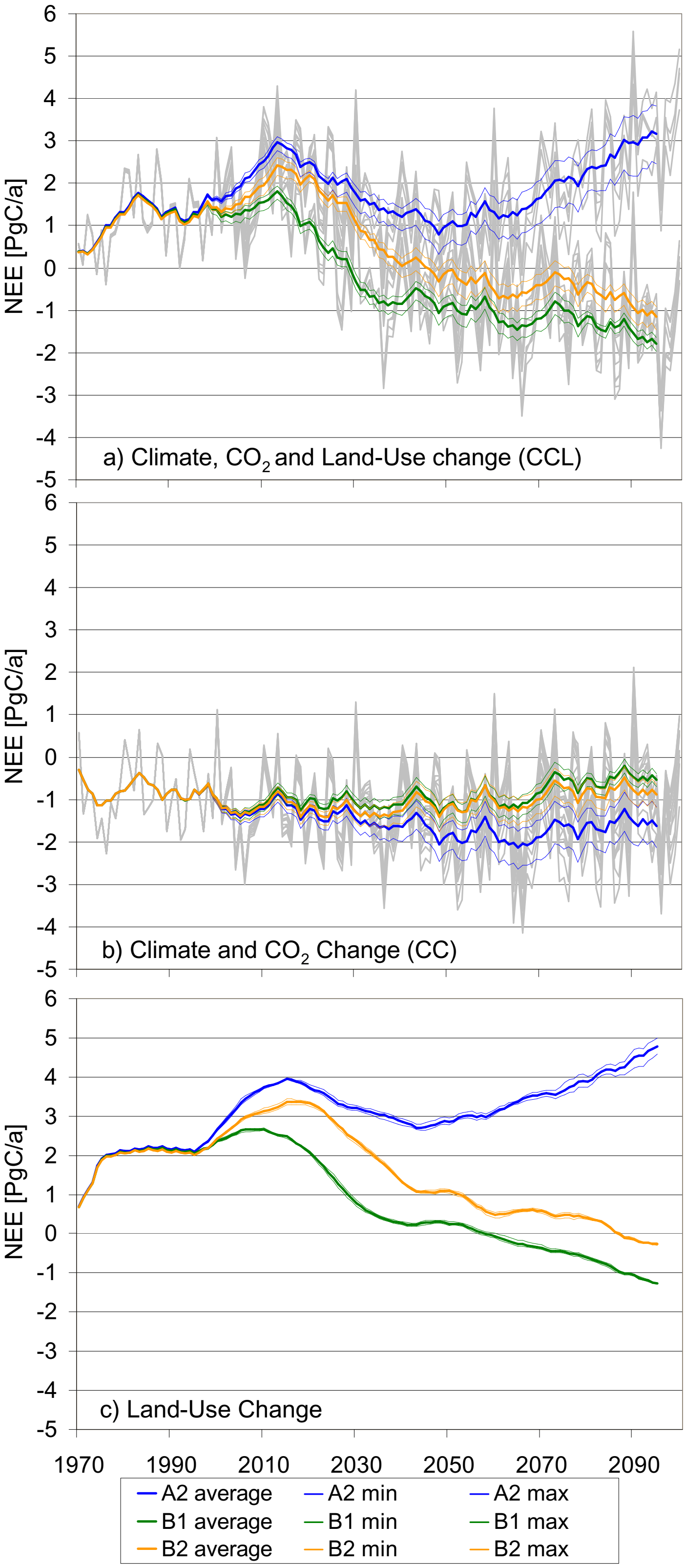

Figure 3.4: Net ecosystem exchange (10-year running mean). Bold lines represent the average for each SRES scenario; thin lines represent the min/max range; grey lines represent the annual fluctuations. Negative values indicate a carbon flux from the atmosphere to the biosphere. Figure 3.4 c) represents the difference of a) and b). Note that the 10-year average in 1970 is not necessarily zero as it includes values from 1970–1974 and the NEE flux fluctuates around zero during the spin-up as well, even though the carbon pools are in equilibrium.

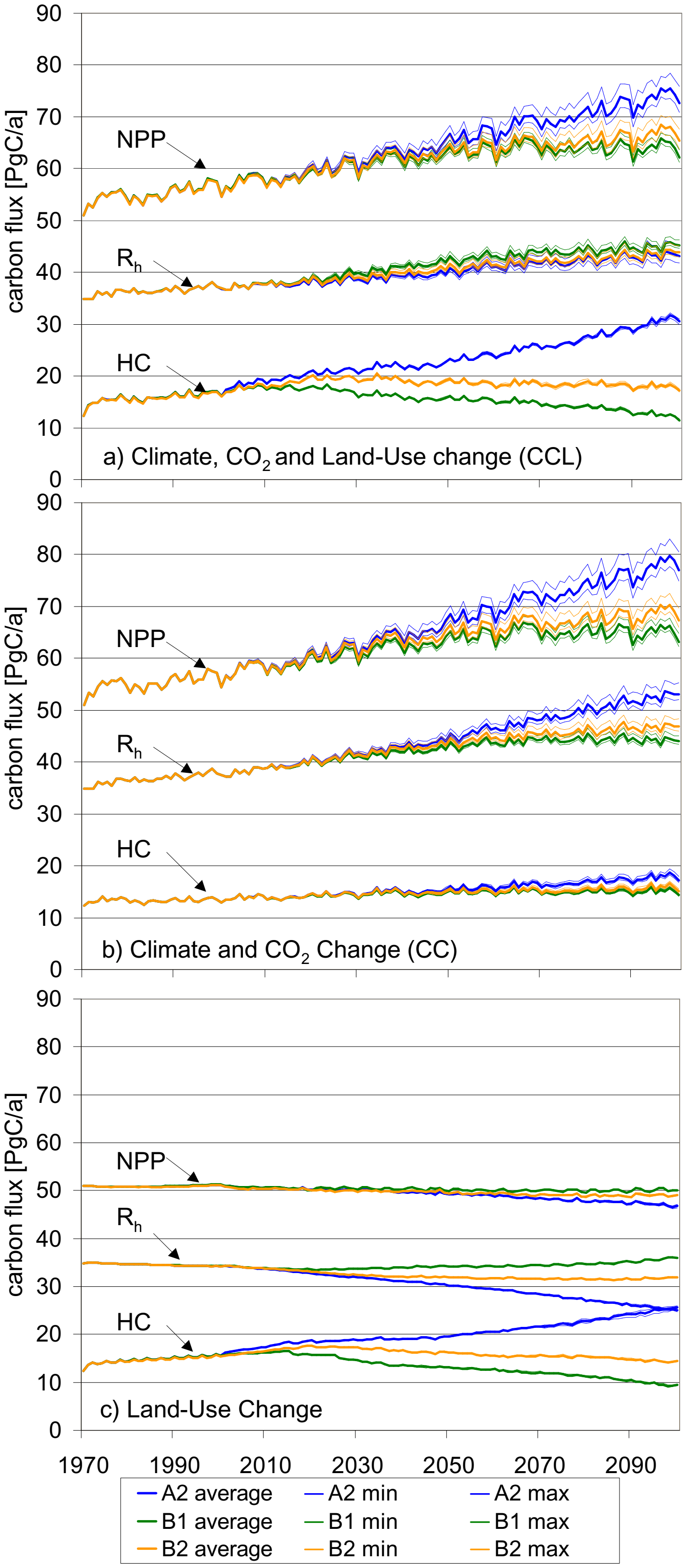

Figure 3.5: Land-atmosphere carbon fluxes. Bold lines represent the average for each SRES scenario; thin lines represent the min/max range. Fire emissions (< 5 PgC/a) are not shown. Note that R_h and HC represent carbon fluxes from the biosphere to the atmosphere. Figure 3.5 c) represents the difference of a) and b) added to the initial value of 1970, in order to obtain the same scale in figures a)–c).

Table 3.2: CFT assignment to the IMAGE crop categories.

IMAGE crop	LPJ/mL CFT
Grassland (rain-fed)	C_3 or C_4 grass, depending on suitability as determined by LPL (default: C_4 in the tropics, else C_3)
Temperate cereals (rain-fed)	Temperate cereals (rain-fed)
Rice (rain-fed)	Rice (rain-fed)
Maize (rain-fed)	Maize (rain-fed)
Tropical cereals (rain-fed)	Tropical cereals (rain-fed)
Pulses (rain-fed)	Pulses (rain-fed)
Roots and tubers (rain-fed)	Rain-fed temperate (Sugar beet) or tropical (Manioc) roots and tubers, depending on LPJ-suitability. Default setting: Manioc in the tropics, else Sugar beets
Oil crops (rain-fed)	Rain-fed soybeans, peanuts, sunflowers or rapeseed, depending on LPJ-suitability. Default setting: soybeans in the tropics, else rapeseed
Temperate cereals (irrigated)	Temperate cereals (irrigated)
Rice (irrigated)	Rice (irrigated)
Maize (irrigated)	Maize (irrigated)
Tropical cereals (irrigated)	Tropical cereals (irrigated)
Pulses (irrigated)	Pulses (irrigated)
Roots and tubers (irrigated)	Irrigated temperate (Sugar beet) or tropical (Manioc) roots and tubers, depending on LPJ-suitability. Default setting: Manioc in the tropics, else Sugar beets
Oil crops (irrigated)	Irrigated soybeans, peanuts, sunflowers or rapeseed, depending on LPJ-suitability. Default setting: soybeans in the tropics, else rapeseed
Sugar cane (biofuel, rain-fed)	Maize (rain-fed)
Maize (biofuel)	Maize (rain-fed)
Non-woody biofuels (biofuel, rain-fed)	C_3 or C_4 grass, depending on suitability as determined by LPL (default: C_4 in the tropics, else C_3)
Woody biofuels (biofuel, rain-fed)	No CFT assigned but treated as managed forest

3.3b). Annual uptake rates of the terrestrial biosphere reach up to 2.5 PgC/a (figure 3.4b) in the CC simulations. The additional carbon stored is distributed nearly equally between the soil and vegetation carbon pools. NPP, heterotrophic respiration (R_h), and the harvested carbon flux[2] (HC) increase under all scenarios (figure 3.5b; see table 3.3 for an overview).

The steady increase in NPP is followed by an increase in R_h as the litter input increases with NPP. Under the A2 scenarios, the biospheric uptake increases, as the CO_2-fertilization and climate effects on NPP outpace the increase in R_h, although the latter also accelerates due to climate change. For the B1 and B2 scenario, NEE remains about constant around -1.0 PgC/a (carbon sink). HC increases, despite the constant land-use pattern, for all scenarios (table 3.3, figure 3.5b) due to changes in climate and CO_2 fertilization that enhance crop performance at the global scale. Wildfire carbon emissions increase from 4.0 PgC/a in 1970 to 6.0 (± 0.5) PgC/a by 2100 (not shown). The superimposed interannual 30-year CRU-climate variability (see above) and the differences between the different CGM patterns can be clearly recognized in the temporal dynamics of NEE (figure 3.4b). Under all scenarios, carbon is sequestered in the biosphere in all regions. However, NEE increases (i.e. less sequestration or more emissions) in central Africa under the B1 and B2 scenarios as well as some parts of Siberia under the A2 and B2 scenarios (figure 3.6 d,e,f). Regional differences between the different GCM-patterns used are minor but there are some local differences, especially between the different A2 scenarios (e.g. in Siberia and

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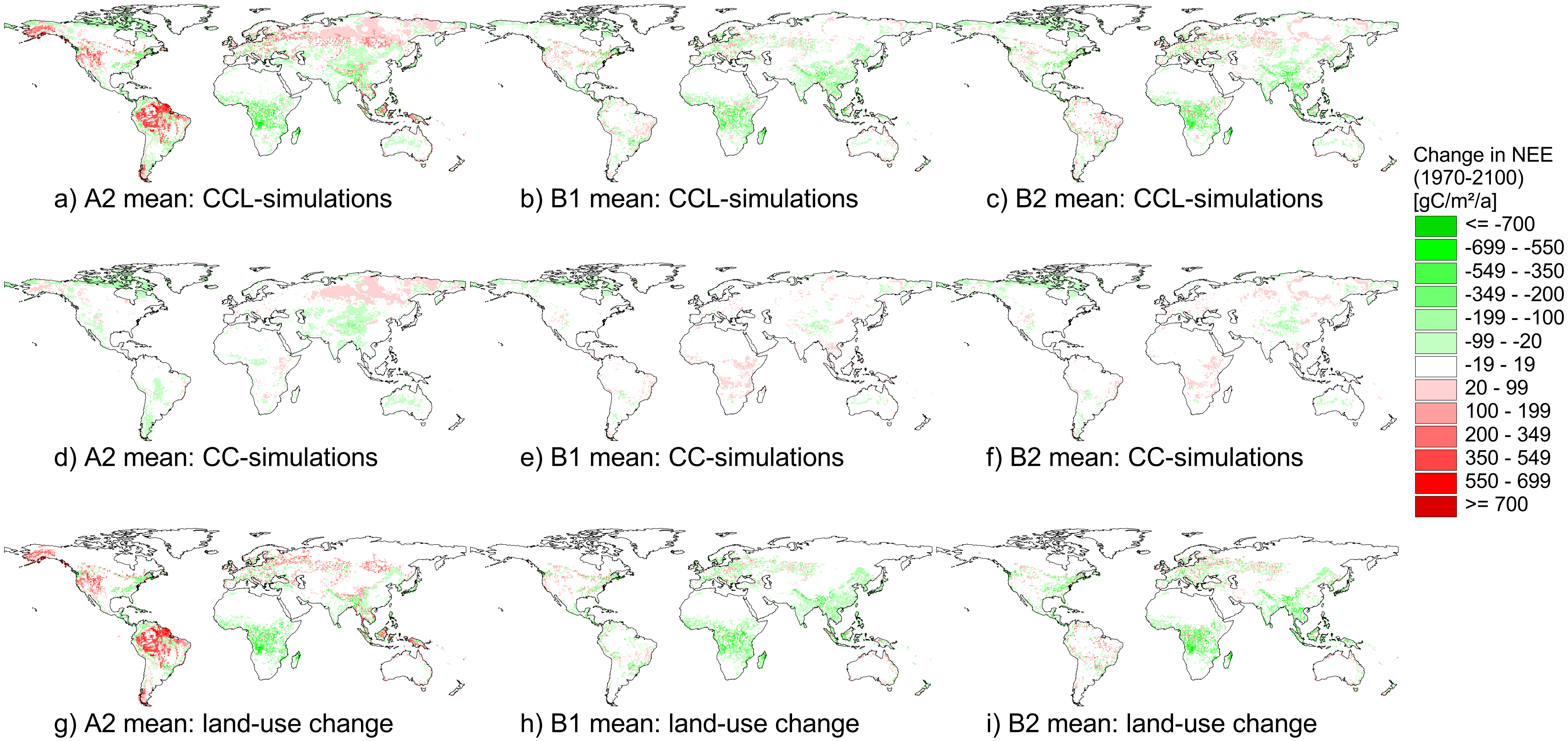
[2] Sum of decaying wood products from the product pools and harvest flux from grasslands and croplands, including the removed residuals in PgC/a.



a) A2 mean: CCL-simulations
b) B1 mean: CCL-simulations
c) B2 mean: CCL-simulations
d) A2 mean: CC-simulations
e) B1 mean: CC-simulations
f) B2 mean: CC-simulations
g) A2 mean: land-use change
h) B1 mean: land-use change
i) B2 mean: land-use change

Figure 3.6: Mean changes in NEE averaged over the 4 different GCM scenarios from 1971–2000 (averaged) to 2071–2100 (averaged) for each SRES scenario. Negative values (green) indicate increased carbon sequestration or reduced carbon emissions, positive (red) vice versa.

Table 3.3: Selected results of the CC-simulations.

Scenario		NPP [PgC/a]		R_h [PgC/a]		HC [PgC/a]	
SRES story-line	GCM pattern	1970 – 1979	2091 – 2100	1970 – 1979	2091 – 2100	1970 – 1979	2091 – 2100
A2	HADCM	54.4	75.8	35.8	51.4	13.4	17.5
	ECHAM		77.1		52.2		17.8
	CGCM		77.1		52.0		17.5
	CSIRO		80.8		54.5		18.5
	average		77.7		52.5		17.8
B1	HADCM	54.4	64.1	35.8	43.6	13.4	15.0
	ECHAM		64.9		44.0		15.2
	CGCM		64.7		43.9		14.9
	CSIRO		66.5		45.2		15.4
	average		65.0		44.2		15.1
B2	HADCM	54.4	67.5	35.8	45.9	13.4	15.6
	ECHAM		68.5		46.5		15.9
	CGCM		70.9		48.1		15.5
	CSIRO		68.3		46.3		16.3
	average		68.8		46.7		15.8

northern America).

3.3.2 Effects of land-use change

We present the effect of land-use change as the difference between the CCL and the CC scenarios. All scenarios, including the period of 1970–1999 that is driven by observed data, begin with agricultural expansion and deforestation in the late 20th and early 21st century, causing carbon emissions to the atmosphere (figure 3.4c). The shape of the curve corresponds to the rate of deforestation. For the A2 scenarios, deforestation rates (including clear-cuts for the expansion of managed forests) increase until mid 2010s to up to 0.34 million km^2/a, decline to 0.11 million km^2/a in 2040 and increase again to up to 0.28 million km^2/a by 2100 (see also figure 3.1). NEE closely follows these changes in deforestation rates under all scenarios, however with a temporal lag of a few years, since the soil carbon pools react slowly to the changes in vegetation cover. The same correlation can be observed for the B1 scenarios (under which deforestation rates of the 21st century are always smaller than during the late 20th century and switch to afforestation by 2015) and the B2 scenarios (under which deforestation rates also peak in the 2010s, decline to zero by 2030 and turn to afforestation by 2080). Under the B scenarios, the temporal lag between changes in deforestation rates and the NEE response can be seen most clearly when the scenarios change from de- to afforestation: Although afforestation starts in the 2010s (B1) and 2030s (B2), land-use change causes a carbon sink not until the 2050s and 2080s respectively. Accordingly, total terrestrial carbon stocks decline under all scenarios by up to 450 PgC in 2100 under the A2 scenarios. However, carbon stocks start to build up again late in the B1 scenarios (reflecting afforestation), partially compensating the loss of 145 PgC by 2050 to 115 PgC by 2100. For the B2 scenarios, total terrestrial carbon is reduced by 215 PgC by 2080, leveling off thereafter. The de- and afforestation patterns differ regionally and so do the carbon gains and losses. The land-atmosphere flux, however, may react differently, as land-use change may both increase or decrease NPP and R_h (figure 3.6 g,h,i). Again, the regional differences between the 4 different land-use patterns for each SRES scenario are minor but there are local differences (figure 3.2), which also appear in the local carbon dynamics.

Due to the assumed constancy of management[3] of cultivated areas, NPP decreases slightly in the 21st century due to land-use change (figure 3.5c). Het-

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[3] Management changes (consistent with the SRES story lines) are included in the dynamic land-use patterns as simulated by IMAGE 2.2. In LPJ/mL, however, changes in management — except irrigation — currently cannot be represented adequately and are therefore assumed to remain constant.

erotrophic respiration reacts differently under the different SRES scenarios (figure 3.5c): Under the B1 scenarios, R_h increases at the end of the 21st century, as human appropriation decreases and NPP increases, leaving more biomass to enter the litter pool. Under the A2 and B2 scenarios, however, R_h decreases, as the soil carbon pools decrease. Although the assimilation rates (NPP) of natural forests and agricultural land do not differ greatly, their impact on the soil carbon pools does. Larger shares of the assimilated carbon of pastures and cropland are removed at harvest, leaving less litter for decomposition. Thus, the relationship between soil carbon pool size and soil respiration is heavily impacted by land-use change. For the B2 scenarios, human appropriation decreases after 2020 and NPP levels off around 2060, but R_h reacts with a temporal lag as the soil carbon pool is still reduced and accumulates slowly (figure 3.3c). For the A2 scenario this temporal lag is not perceivable as there is no switch from de- to afforestation or vice versa. Wildfire emissions occur in natural forests only and decrease by 1.2 PgC/a (B2) to 3.0 PgC/a (A2) as the area of natural forests declines while they remain roughly constant for B1 (not shown).

3.3.3 Combined effects of changes in climate, atmospheric CO_2 concentrations and land use

The terrestrial biosphere remains a distinct carbon source throughout the simulated period under the A2 scenarios. Under the B scenarios, it changes to being a carbon sink in the late 2020s (B1) and the 2040s and 2050s (B2) (figure 3.4a). Here, land-use change (afforestation) reinforces the carbon uptake induced by climate change and CO_2 fertilization. These net changes in the global carbon balance are determined by counteracting processes: The land-use induced losses (figure 3.3c) are larger than the terrestrial carbon gains from changes in climate and atmospheric CO_2 concentrations (figure 3.3b) under the A2 and B2 scenarios, while they are balanced under the B1 scenarios (figure 3.3a). Vegetation carbon decreases under all scenarios, most pronounced under the A2 scenarios where up to 42 % of the initial carbon stock is lost by 2100. Soil carbon stocks react slightly but differently under the different SRES scenarios, decreasing under the A2 scenarios and increasing under the B1 and B2 scenarios (figure 3.3a). The increases in NPP caused by climate change and CO_2 fertilization outbalance the small reductions of NPP caused by land-use change, leaving a net increase of NPP by 11 to 29 PgC/a under all scenarios (figure 3.5a, see table 3.4 for an overview of NPP, R_h, and HC). The combined effects of changes in climate, atmospheric CO_2 concentrations, and land-use cause increasing R_h fluxes (figure 3.5a), even at decreasing soil carbon stocks under the A2 scenarios. This is caused by increasing R_h fluxes due to rising temperatures and by the increased input of slash wood to the litter pool. Since most of the deforestation takes place in tropical regions, these additional inputs are respired quickly and thus contribute to the soil respiration flux but do not significantly increase the soil carbon pools. Soil carbon pools decline due to the missing litter input from forests. Human appropriation of biospheric carbon in the 21st century corresponds to the development of the total cultivated area, i.e. a constant increase for the A2, roughly constant values for the B2 and decreasing values for the B1 scenarios (figure 3.5a). Wildfire emissions remain roughly constant for the B1 scenario, increase from 4.0 in 1970 to 5.0 PgC/a by 2100 under the B2 scenarios and decrease to 3.0 PgC/a under the A2 scenarios. Here, the climate and CO_2 induced increase in litter load is partly compensated (B1) and overcompensated (A2) by land-use change effects on the litter load and the reduction of natural forests. Land-use change effects dominate the resulting net ecosystem exchange (NEE) of the 21st century (figure 3.4a). The land-use change induced carbon losses under the A2 scenarios and also early under the B1 and B2 scenarios outweigh the climate change and CO_2 fertilization induced terrestrial carbon uptake.

Under the A2 scenarios, most regions and especially the tropical forests are strongly deforested (including large carbon losses; figure 3.2), but the change in land-atmosphere fluxes may be regionally different (figure 3.6a) as NPP and R_h may both increase and decrease due to land-use change. The same regional heterogeneity can be found under the B1 and B2 scenarios (figure 3.6b,c). As an example of the spatial differences between the different GCM patterns, the standard deviation of the changes in NEE (see figure 3.6) are shown in figure 3.7 for the combined effects of changes in climate, atmospheric CO_2 concentrations and land use under the A2, B1, and B2 scenarios.

3.4 Discussion

The 21st century carbon cycle strongly reacts to the projected changes in climate, atmospheric CO_2 concentrations, and land-use. In our simulations, land-use change exerts a strong control on the projected changes in the terrestrial carbon balance during the 21st century, especially under scenarios with high deforestation. The results of our study (covering a range of climatic and socio-economic scenarios) support the conclusion of Levy et al. [2004a] that for

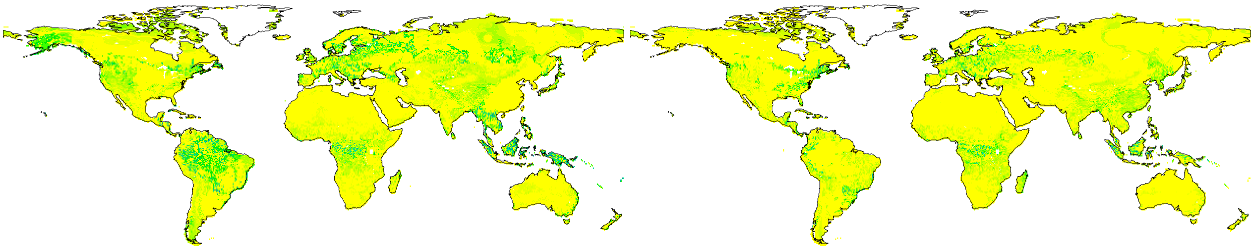
Table 3.4: Selected results of the CCL-simulations.

Scenario		NPP [PgC/a]		R_h [PgC/a]		HC [PgC/a]	
SRES storyline	GCM pattern	1970 – 1979	2091 – 2100	1970 – 1979	2091 – 2100	1970 – 1979	2091 – 2100
A2	HADCM	54.3	72.1	35.8	41.8	15.0	30.0
	ECHAM		73.5		43.2		30.8
	CGCM		73.0		42.4		30.6
	CSIRO		76.6		45.2		30.6
	average		73.8		43.2		30.5
B1	HADCM	54.3	63.2	35.8	44.3	15.0	12.3
	ECHAM		64.0		44.9		12.4
	CGCM		63.8		44.6		12.5
	CSIRO		65.4		45.9		12.7
	average		64.1		44.9		12.5
B2	HADCM	54.3	65.4	35.8	42.7	15.0	17.7
	ECHAM		66.7		43.5		18.0
	CGCM		66.4		43.2		17.9
	CSIRO		68.8		44.9		18.3
	average		66.8		43.6		18.0

carbon assimilation (NPP), land-use change plays a minor role compared to CO_2 fertilization and climatic change. For carbon stocks and the net carbon exchange (NEE), on the contrary, we find that land-use change may well be more important than climatic change, which corresponds well to the findings of Gitz and Ciais [2004], Cramer et al. [2004] (for the tropics only), and [Müller et al., 2006, see Chapter 2].

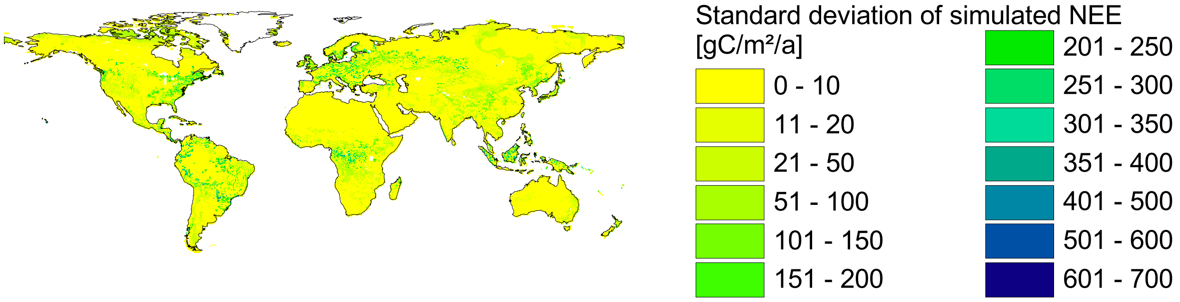
Still, the development of the future global carbon cycle remains highly uncertain. Besides the uncertainties in future projections of land-use patterns Levy et al. [2004b] and climate change Murphy et al. [2004], the response of the terrestrial biosphere to land use and land-use change is not uniform as simulated in different global model applications and needs to be studied in more detail: For example, Levy et al. [2004a] and Sitch et al. [2005] attribute only small carbon fluxes to land-cover and land-use changes that only marginally affect the terrestrial carbon balance. On the other hand, Gitz and Ciais [2004], Cramer et al. [2004] and we find land-cover change to significantly affect the terrestrial carbon budget. The currently remaining uncertainties in model projections derive from (i) lack of reliable data and consistent definitions of land-use types, (ii) insufficient process-understanding, especially concerning the effects of different management types on the carbon cycle Liebig et al. [2005], and (iii) the resulting deficiencies in model implementations. Based on the disagreements between the different studies as well as observations, we will discuss these aspects in the following.

We are able to reproduce the land-use fluxes of the late 20th century as computed by Houghton [2003a] with the land-use data sets used in this study. However, we could not reproduce a biospheric carbon sink Houghton [2003b]; House et al. [2003]; Malhi [2002]; Prentice et al. [2001] during this period. Transient simulations starting in 1901 instead of 1970 as simulated here, would reduce the land-atmosphere carbon flux by 0.2 to 0.4 PgC/a, which is not enough to explain the disagreement. There are two possible reasons for the observed disagreement: (a) the applied rates of land-use change and corresponding carbon fluxes may be overestimated and/or (b) the residual sink (without land-use change) as computed by LPJ/mL may be too small. The net rate of deforestation (or expansion of cultivated area) in the late 20th century is not well determined and differs considerably between different data sources, a difference that strongly affects the terrestrial carbon balance Jain and Yang [2005]. The expansion of croplands and the corresponding reduction of natural vegetation in the data set of Ramankutty and Foley [1999] slows down to 0.01 million km^2/a between 1980 and 1990. The expansion of area under cultivation in our study is comparable to the net deforestation rates of 0.13 and 0.12 million km^2/a for the 1980s and 1990s respec-



a) A2 standard deviation:
CCL-simulations

b) B1 standard deviation:
CCL-simulations



c) B2 standard deviation:
CCL-simulations

Figure 3.7: Standard deviation of changes in NEE for the 3 SRES scenarios A2, B1 and B2 with 4 different climate patterns each for the CCL-simulations to demonstrate regional and local variance between the 4 different data sets for each SRES scenario.

tively as reported by Houghton [2003a]. Using the same model as we do, but the data-set of Ramankutty and Foley [1999] extended by pastureland from the HYDE data-base Klein Goldewijk [2001], Bondeau et al. [2007] compute a much smaller carbon flux from land-use change in the late 20th century. On the other hand, they are able to reproduce a small biospheric carbon sink in the 1980s, which increases to approximately 1.0 PgC/a in the 1990s as a consequence of stagnation in land-use change. However, the very small rate of land-use change as reported by Ramankutty and Foley [1999] seems to be unrealistically small. The rates of land-use change under the IMAGE scenarios and as reported by Houghton [2003a], on the other hand, may well be too large, considering satellite-observed global deforestation rates of 0.06 (1980s) and 0.07 million km^2/a (1990s) Hansen and DeFries [2004] that mainly reflect topical deforestation Mayaux et al. [2005]. However, when halving the rate of land-use change and the corresponding land-use emissions, the biosphere in our simulations would still be a small carbon source or about neutral, suggesting that the residual sink as simulated by LPJ/mL may also be too small: The current knowledge about relevant processes under cultivation has not been implemented completely in global carbon models so far and some processes are not yet fully understood Lemaire et al. [2005]. For example changes in processes of carbon decomposition under cultivation Post and Kwon [2000], as well as management and especially management changes are unaccounted for in current global model simulations. Accounting for management is greatly hampered by the lack of suitable data sets on management such as grazing intensities, intercropping, and forest management [Heistermann et al., 2006, see Chapter 4]. Besides, global terrestrial biosphere models just recently have seen the beginning of implementing land-use dynamics in very different ways. Crops and grasslands are mechanistically simulated only in this study and the study of Bondeau et al. [2007], while Sitch et al. [2005] (based on McGuire et al. [2001]) and Levy et al. [2004a] prescribe special carbon allocation schemes for the NPP of natural vegetation as a proxy for harvest and land-management. We also account for managed forests and natural regrowth, however, the current version of LPJ/mL does not fully reproduce managed forest carbon dynamics: Regrowth of forests after clear-cut is slower than in reality, because age-structure and non-linear shifts in forest growth with stand age are not accounted for in the current version of LPJ/mL. Zaehle [2005a] demonstrated that this may lead to significant underestimation of carbon sequestration in vegetation after reforestation. This also shows in the slow carbon accumulation in our simulations of the B1 and B2 scenarios. For a European case study, Zaehle et al. [2006] have demonstrated that including these non-linear processes leads to more plausible estimates of terrestrial carbon balances. In addition, DGVMs such as LPJ have been developed originally to simulate natural vegetation only and perform well compared to observations, although land-use change is not accounted for. Thus, the effects of land-use change may be inherently included in the models' parameterization, which may need further adoptions now that land-use change is explicitly simulated.

Cox et al. [2000] and Schaphoff et al. [2006] show that climate projections of several GCMs produce a biospheric carbon source by 2050 for a business as usual emission scenario (IS92a). We find increasing total carbon pools and stable carbon sinks throughout the entire simulation period under climate and CO_2 change only (CC-simulations). These differences can be explained with the missing land-use signal in the studies of Cox et al. [2000] and Schaphoff et al. [2006] and the differences in the climate scenarios used Berthelot et al. [2005]. The IMAGE-derived mean temperatures over land of each SRES scenario (see table 3.1) are considerably lower than the GCM-derived temperatures of the IS92a emission scenarios (3.7–6.2 °C) as used by Schaphoff et al. [2006]. Thus, heterotrophic respiration in our simulations is not reacting as strongly as in the work of Schaphoff et al. [2006] and the net carbon flux between terrestrial biosphere and atmosphere remains a carbon sink. In addition, soil respiration is strongly determined by the size of soil carbon pools, which are considerably smaller under cultivation. Our CC-simulations are computed with the static land-use pattern of 1970, i.e. with an agricultural area of ~48 million km^2 (~37 %). Consequently, the soil carbon pools and heterotrophic respiration are smaller than under natural vegetation only. Thus, we find a larger carbon sink in the beginning of the 21st century in the CC-simulations than Schaphoff et al. [2006] do and a less prominent effect of increasing temperatures — which shows less effects on smaller soil carbon pools as well. If land-use change is included (CCL), the climate driven increase in R_h is strongly reduced under the A2 scenarios as soil carbon pools decline with the expansion of cultivated land. We therefore challenge the projections that the biosphere might shift from a sink to a source as reported by Cox et al. [2000] and Schaphoff et al. [2006] since they do not take land use and land-use change into account.

This study covers a broad range of socio-economic scenarios and climate projections. Still, the four different land-use patterns for each SRES scenario do not differ much at the global (see table 3.1, figure 3.1) and regional level but in their local specification only IMAGE team [2001]. Different spatial specifications of the land-use patterns, also accounting for uncertainties in global trade, lifestyle, and technological progress would be desirable since these yield the potential to strongly affect the terrestrial carbon balance [Müller et al., 2006, see Chapter 2]. In the current implementation of IMAGE 2.2, the differences in climate between the different GCMs are relatively small as they are used to downscale IMAGE-derived global mean temperatures only. However, IMAGE 2.2 takes into account a broad range of feedbacks and drivers to derive land-use patterns and thus, this study is — to our knowledge — the most comprehensive study on the effects of land-use change on the carbon budget at the global scale.

3.5 Conclusions

Our simulations have shown that projected land-use changes under different socio-economic scenarios have profound effects on the terrestrial carbon balance and potentially offset the effects of climate change. Land use and land-use change are therefore important drivers of the terrestrial carbon stocks and carbon fluxes between the terrestrial biosphere and the atmosphere during the 21st century. CO_2 fertilization and climatic change mainly determine the increase of NPP, while land-use change shows only small effects here. Studies of global change, including studies on the carbon cycle, and climate change need to account for land-use change. The exclusion of land use, which is still common in global biogeochemical modeling, significantly reduces the relevance of future projections of the development of the global carbon cycle and limits the insights gained in these studies. We show that the projected switch of the terrestrial biosphere from carbon source to sink is less likely when land-use patterns are accounted for (static patterns, no land-use change) and the source-sink behavior is strongly determined by land-use change (dynamic land-use patterns).

However, we stress that the inclusion of land use and land-use change into global simulations is currently still hampered significantly by data availability and reliability as well as a corresponding lack of implementation of relevant processes in models. The carbon balance of the 20th century can currently only be reproduced when assuming very small rates of land-use change, indicating that the residual sink as simulated by LPJ/mL may be to small and that datasets with high rates of land-use change may overestimate land-use change. Models need to account for more processes such as a more detailed characterization of land management. Future changes in land-use technology, global dietary life styles or the dynamics of large-scale bioenergy use are partially included in the SRES scenarios. Their dynamics beyond these assumptions will additionally alter the projections of the carbon cycle. Progress in our ability to model these processes should be a priority.

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Chapter 4

Land in Sight? Achievements, Deficits and Potentials of Continental to Global Scale Land-Use Modeling[1]

When we mean to build,
We first survey the plot, then draw the model;
And when we see the figure of the house,
Then must we rate the cost of the erection.

William Shakespeare, King Henry

Christoph Müller[*,a,b], Maik Heistermann[*,b,c], and Kerstin Ronneberger[*,b,d]

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Abstract

Land use plays a vital role in the earth system: it links human decision making to the terrestrial environment and is both driver and target of global environmental changes. However, decisions about how much land to use where and for what purpose (and the related consequences) are still poorly understood. This deficit is in contrast to the fundamental need for global analysis of future land-use change to answer pressing questions concerning e.g. future food security, biodiversity and climate mitigation and adaptation.

In this review we identify major achievements, deficits and potentials of existing continental to global scale land-use modeling approaches by contrasting current knowledge on land-use change processes and its implementation in models. To compare the 18 selected modeling approaches and their applications, we use the integration of geographic and economic modeling approaches as a guiding principle. Geographic models focus on the development of spatial patterns of land-use types by analyzing land suitability and spatial interaction. Beyond, they add information about fundamental constraints on the supply side. Economic models focus on drivers of land-use change on the demand side, starting out from certain preferences, motivations, market

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and population structures and aim to explain changes in land-intensive sectors. Integrated models seek to combine the strengths of both approaches in order to make up for their intrinsic deficits and to assess the feedbacks between terrestrial environment and the global economy. Important aspects in continental to global modeling of land use are being addressed by the reviewed models, but up to now for some of these issues no satisfying solutions have been found: this applies e.g. to soil degradation, the availability of freshwater resources and the interactions between land scarcity and intensification of land use. For a new generation of large-scale land-use models, a transparent structure would be desirable which clearly employs the advantages of both geographic and economic modeling concepts within one consistent framework to include feedbacks and avoid redundancies.

4.1 Introduction

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., 2002b] 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 and 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 and 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 and 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 and Kaimowitz [1999] provide a meta-analysis of 140 economic-based deforestation models. Van Tongeren et al. [2001], and similarly Balkhausen and 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 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 et al., 2001]: processes that are

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[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 earth's land, as vegetation or man-made features" [FAO and UNEP, 1999].

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 and Geist [2003] and Geist and 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 (section 4.2) and the implementation of this knowledge in current models (section 4.3). 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 4.2). In order to reflect the implementation of drivers, consequences and feedbacks into current models, we review existing land-use modeling approaches in section 4.3. We restrict our scope to modeling approaches that are implemented as computer models, excluding purely mathematical models as well as spreadsheet and accounting approaches. In section 4.4, we discuss to what extend the implementation of current knowledge is limited by data availability. Based on the insights of section 4.2 (What is known about land-use change?), section 4.3 (How is this knowledge implemented in global models?) and section 4.4 (To what extend is that implementation facilitated or hampered by data availability?), section 4.5 identifies the major achievements, deficits and potentials in global land-use modeling, section 4.6 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 and Fisher-Vanden [1997] in defining *Integrated Assessment* and also different from Briassoulis [2000] and Lambin et al. [2000], see above.

4.2 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 and Turner II [1994] and Dolman et al. [2003]. Globally significant land-use change processes include changes in forest cover — mainly in terms of deforestation [FAO, 2003b; Houghton, 1999] — and changes in agricultural areas and management [Geist and 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 is driven[3] 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., 2002b] 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; House et al., 2002; Lal, 2003; Saiko and Zonn, 2000; van der Veen and Otter, 2001; Zaitchik et al., 2002].

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 [Batistella, 2001; Pfaff, 1999]). Other factors include

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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.

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 and Kaimowitz, 1999; Geist and Lambin, 2001, 2004]. However, their impact on large-scale land-use change is unexplored so far.

4.3 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 [Alcamo et al., 1998], the CLUE model [Verburg et al., 1999a], and different versions of GTAP [Hertel, 1997]). We did 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 stand-alone 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 (table 4.1) 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 (see section 4.1 for a definition of integrated). Note that the structures to present geographic and economic approaches differ fundamentally (see table 4.2): 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 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 and 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].

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[4] such as e.g. in EPPA [Babiker et al., 2001] and AIM [Matsuoka et al., 1995]

Table 4.1: Land-use models covered in this review: Overview

Model/ Modeling Framework	Literature	Temporal resolution and coverage	Spatial resolution and coverage	Main mechanism	Motivation	Classification
CLUE-China	Verburg et al. [1999a,b]	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. [in press] (based on Verburg et al. [2002])	1-year steps; 1990–2010	Multi-scale: (Neotropics): national level, farming systems sub-units, 3x3 km; 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 and Lambin [2001a,b]	1-year steps; 1961–1997	Multi scale: (Sahel); country level; 2.5 lat/ 3.75 lon 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 and 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)

Model/ Modeling Framework	Literature	Temporal resolution and coverage	Spatial resolution and coverage	Main mechanism	Motivation	Classification
AgLU	Sands and 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 and corresponding GHG emissions to feed into integrated modeling framework	Economic
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[6] (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. [2002a]	comparative static; 1997–2020	36 regions; Global	Partial equilibrium	Analyze the world food situation	Economic
G-cubed (Agriculture)	McKibbin and 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

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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.

[6] Global coverage for trade

Model/ Modeling Framework	Literature	Temporal resolution and coverage	Spatial resolution and coverage	Main mechanism	Motivation	Classification
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	Economic
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 and 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 decisions	Analyzing the relation between land-use patterns and global agricultural markets	Integrated

Model/ Modeling Framework	Literature	Temporal resolution and coverage	Spatial resolution and coverage	Main mechanism	Motivation	Classification
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 EU-RURALIS	Klijn et al. [2005]; van Meijl et al. [2006]	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 and Sun [2001]; Hubacek and 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	Analyzing 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

Table 4.2: Selected properties of large-scale land-use models. Double-headed arrows represent bidirectional feedbacks; single-headed arrows represent causal chains that lack a feedback.

Model/ Modeling Framework	Land use/cover types	Land-use change processes	Land-using Sectors	Land-using Commodities	Inter-national 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 & Lifestock), 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

Model/ Modeling Framework	Land use/cover types	Land-use change processes	Land-using Sectors	Land-using Commodities	Inter-national trade	Feedbacks/ causal chains
GTAPE-L	—	De-/Reforestation, agricultural expansion/abandonment urban growth[7]	Agriculture (crops and livestock), Forestry, Others	3 agricultural (2 crops, 1 livestock) 1 forestry	Bilateral	Land use ⇔ commodity prices
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)	General equilibrium + refined transformation structure for 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	—	—

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[7] urban growth in the sense that a shift to industrial land use can be modeled

Model/ Modeling Framework	Land use/cover types	Land-use change processes	Land-using Sectors	Land-using Commodities	Inter-national trade	Feedbacks/ causal chains
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[7]	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[7]	Agriculture (crops and livestock), Forestry, others	4 Agriculture (3 crops, 1 livestock) 1 Forestry, 8 others	Bilateral	Climate ⇒ land use

4.3.1 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 (see reviews in section 4.1). In the following, we will concentrate on geographic models available on large spatial scales.

Empirical-statistical

The CLUE model framework [Veldkamp and 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., 1999b] and the Neotropics/Tropical Latin America [Wassenaar et al., in press]. 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 km^2) is assumed to reveal general relationships between land use and its determining factors over the whole study region, while finer assessments (32x32 km^2) are to capture variability within regions and landscapes (for details see Verburg et al. [1999a]).

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 implies 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 et al., 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 and Lambin, 2001b, 2004] is a zero-dimensional model designed to capture the characteristic processes in the Sahel Zone. It has been applied by Stephenne and Lambin [2001a] in order to simulate spatially explicit changes of land use on a 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 and 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 Lüdeke 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 (see section 4.1). 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.

4.3.2 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 and 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 and 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 and Keyzer [1997] and Hertel [1999]).

Examples of partial equilibrium models are IMPACT [Rosegrant et al., 2002a] and WATSIM [Kuhn, 2003], modeling only the agricultural sector, the Global Timber Market Model [Sohngen et al., 1999] describing the forestry sector, AgLU [Sands and Leimbach, 2003; Sands and Edmonds, 2004] and FASOM [Adams et al., 2005; McCarl, 2004] 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 and Lee, 2003] and the G-cubed

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

model[8] [McKibbin and 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 and Banse [2004].

Economic land-use models differ in sectoral and regional resolution (see tables 4.1 and table 4.2) 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. 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 in 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 management 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. The disadvantage of such a nonlinear 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 and 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. 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] allows an inclusion of environmental changes, as e.g. climate change, by altering the distribution of land among different classes, which are defined by the dominant climatic and biophysical characteristics. A project is close to its completion, which includes land-use and land cover data in a new version of the GTAP database, allowing for the definition of several AEZ [GTAP, 2005b].

GTAPE-L captures another aspect of 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 and Tol, 2002]. For a more technical discussion on the topic see Greenhut and Norman [1995a], Greenhut and Norman [1995b], Greenhut and Norman [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 (see section 4.2), 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 for e.g. 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 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.

4.3.3 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; RIVM, 2001; Zuidema et al., 1994] 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 and Yanagishima, 1996] to the EPIC model [Williams and Singh, 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 and 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 [ACCELERATES, 2004; Rounsevell et al., 2003]. For this purpose, the SFARMOD farm model [Annetts and 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], an agro-climatic, process-based simulation model. 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 IFPSIM/EPIC 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, 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. Six 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 [Klijn et al., 2005; 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 4.3.2). 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 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 and Sun, 2001; Hubacek and 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.

4.4 Data availability in large-scale land-use modeling

Data for land-use modeling can be structured in four classes (exemplary data sets, collections and reviews are listed accordingly in tables 4.3–4.6): (a) Current and historical land-use data are needed to initialize, calibrate and validate models and to analyze the determinants of spatial land-use patterns. It includes land cover characterization as well as management information such as (for agriculture) dominant crops, fertilization or irrigation (table 4.3); (b) environmental data are needed to determine environmental suitability for different land-use types mainly as a result of climate, terrain and soil conditions (table 4.4); (c) socio-economic data are needed in manifold respects: factors determining suitability for land use (such as infrastructure, access to markets), and as drivers and consequences of land use and land-use change (market structures, population and economic development, governance) (table 4.5); (d) scenario data for future driving forces (table 4.6). These can be environmental or socio-economic, however, they are not accessible via measurement or census, but heavily rely on assumptions on future development. Scenario methodologies may range from simple ad-hoc assumptions, expert judgment or extrapolations up to sophisticated combinations of qualitative storylines with quantitative modeling [Alcamo et al., 2006]. As they are not measurable in a strict sense, scenario data will not be discussed in further detail as we do in the following for the first three categories.

4.4.1 Current and historical land-use data

Land-use data are mostly based on census, either available for entire countries [FAO, 2005b] or at various sub-national resolutions. In contrast, land-cover data are often derived from remote sensing (e.g. IGBPDiscover, GLC2000). However, geographic modelers are interested in the spatial patterns of land use: These can be derived by combining the two data sources above, making use of simple allocation algorithms [Leff et al., 2004; Ramankutty and Foley, 1998]. However, major inconsistencies between the two data sources indicate their limited quality. This deficit is substantiated by Young [1999], who fundamentally criticizes existing estimates of cultivated land and land still available for cultivation.

Another problem is the availability of spatially explicit time series of land use and cover, needed to analyze actual changes. Lepers et al. [2005] provide only a limited solution to that problem by geo-referencing regional studies of land-use changes, partly based on 20-year time series of AVHRR data. From that, they derive so-called "land-use change hot spots" which indicate regions with significant land-use dynamics. Ramankutty and Foley [1999] and Klein Goldewijk [2001] provide historical land-use patterns, but only by applying backward simulation on the basis of coarse historical records.

Finally, the management aspect of land-use is insufficiently reflected by available data. Data on fertilization rates are only provided on the country level which is too coarse for large countries. Data on irrigation [Siebert et al., 2002] have a higher spatial resolution, but only indicate the area equipped for irrigation (no information about irrigation intensity and irrigated crops). Other missing data comprise for example forest management, logging practices, and agricultural management aspects, such as crop-livestock integration, livestock farming with zero-grazing, planting dates, typical crop rotations, and multiple cropping. A more integrated view on the different aspects of agricultural land use is provided by the *farming systems* concept: A farming system is characterized by similar resource bases, enterprise patterns, household livelihoods and constraints of farms within a region. Dixon et al. [2001] compiled a geo-referenced database of farming systems for developing and transition countries.

4.4.2 Environmental data

Environmental data are usually provided on a regular grid, either derived from remote sensing (as for topography), interpolation of point data (as for climate and soil data) or gridded polygon data (as for soil properties). Although environmental data are associated with large uncertainties, general data availability has to be considered as less limiting than for the other data categories. However, there are still deficits: e.g. there is a strong need for quantitative data about soil degradation going beyond the GLASOD study [Oldeman et al., 1990]. Climate data are only available on a monthly basis, forcing users to generate artificial daily values e.g. for crop modeling [Tan and Shibasaki, 2003].

4.4.3 Socio-economic data

Socio-economic data are rarely available at high resolutions. Mostly, data are provided on the national or — at best — sub-national level. Only population-count data (e.g. LandScan [Dobson et al., 2000]), which is also acquired by the help of remote sensing of city night-lights, is available at high spatial resolutions (1 km x 1 km). The collection of socio-economic data is more costly, more susceptible to uncertainty and of low comparability due to more intransparent and unstandardized collection methods. In addition, data quality differs between regions. Generally, economic data on prices, trade volumes, production and consumption are easier available than rather qualitative data: there are virtually no large-scale data about land tenure systems (e.g. traditional/communal vs. private), the role of subsistence farming, market access, development policies, governance, or institutional enforcement. Such information would already be useful at low spatial resolutions in order to characterize regional differences in land-use dynamics. However, the fuzziness of the variables hampers quantification and application.

4.4.4 Data integration

As can be seen from all data categories, a limited volume of raw data in terms of census, remote sensing or station measurements is increasingly processed by modeling techniques in order to derive spatially explicit data for land-use models. Processing techniques include simple allocation schemes using remote sensing or proxy data in order to derive spatial patterns from census data (e.g. Leff et al. [2004] for major crops; [Siebert et al., 2002] for irrigation; Wood and Skole [1998] for deforestation). Dobson et al. [2000] apply a set of eight proxies to derive human population density (including e.g. slope, road proximity).

Moreover, more complex models provide input data to land-use models such as the global distribution of potential yields or vegetation, again being based on complex environmental data, including the output of climate models. Against this background, it is a major challenge for land-use modelers to carefully reflect on their input data and their origin in order to avoid artifacts in the analysis of land-use patterns or in calibration of model parameters. Nevertheless, the strategy to merge data from remote sensing with ground census still seems to bear large potentials to boost data availability and quality [Perz and Skole, 2003].

Table 4.3: Selected Example reviews and data sets describing global land use and land-use changes.

Name	Reference	Source type	Relevant contents	Spatial format	Spatial coverage and resolution	Temporal coverage and resolution
PAGE Agroecosystems	Wood et al. [2000]	Review	Lists data sets describing extent, distribution and change of agroecosystems	Various	Various	Various
PAGE Grassland Ecosystems	White et al. [2000]	Review	Lists data sets describing extent, distribution and change of grassland ecosystems	Various	Various	Various
PAGE Forest Ecosystems	Matthews et al. [2000]	Review	Lists data sets describing extent, distribution and change of forest ecosystems	Various	Various	Various
GLC2000	Joint Research Centre [2003]	Map	Global land cover distribution	Grid	Global; 30 sec. lon/lat	2000
IGBPDiscover	Loveland et al. [2000]	Map	Global land cover distribution	Grid	Global; 30 sec. lon/lat	1992
MODIS	Friedl et al. [2002]	Map	Global land cover distribution	Grid	1x1 km	From 2000
Global Forest Resources Assessment	USGS EROS Data Center [2000]	Map	Describes state and conditions of forest resources for the year 2000 and changes over the last 20 years	Grid	Global; 30 sec. lon/lat	2000
FAOSTAT	FAO [2005b]	Database	Comprehensive data collection about land use and cover, management, agricultural markets	—	Global; national level	1961–2003; annual

Name	Reference	Source type	Relevant contents	Spatial format	Spatial coverage and resolution	Temporal coverage and resolution
—	Ramankutty and Foley [1998]	Map	Maps worldwide distribution of croplands by combining sub-national census data with remote sensing	Grid	Global; 5 min. lon/lat	1992
—	Ramankutty and Foley [1999]	Map	Maps worldwide historical distribution of croplands	Grid	Global; 30 min. lon/lat	1750–1992; variable timestep
—	Leff et al. [2004]	Map	Maps worldwide distribution of 17 field crops by combining sub-national census data with remote sensing	Grid	Global; 5 min. lon/lat	1992
—	IFA [2002]	Spreadsheet	Crop specific fertilizer application rates	—	Global, but incomplete; national level	Mid 1990s
Map of irrigated areas	Döll and Siebert [2000]; Siebert et al. [2002]	Map	Maps distribution of areas equipped for irrigation	Grid	Global; 5 min. lon/lat	Mid 1990s
Global Farming Systems Map	Dixon et al. [2001]	Map	Applies a methodology to define predominant farming systems dependent on a variety of criteria such as predominant crops, management level, crop-livestock integration, dominant livelihood	Polygon	Developing and transition countries	Mid 1990s

Name	Reference	Source type	Relevant contents	Spatial format	Spatial coverage and resolution	Temporal coverage and resolution
Agro-MAPS	FAO [2003a]	Map	Sub-national census data about cultivated crops (area, production)	Polygon	Africa (to be extended globally); size of polygons depends on administrative unit	1981–2002; annual timesteps
HYDE	Klein Goldewijk [2001]	Map	Distribution of historical land cover (rather backward modeling)	Grid	Global; 30 min lon/lat	1700–1990; variable timesteps
FARM Database	Darwin et al. [1995]	Data Collection	Crop, livestock, and forestry commodity production agricultural water withdrawals for livestock and irrigation; length of growing season and thermal regime; land cover	Geodatabase	Global; national and 30 min. lon/lat	1997
—	Thornton et al. [2002]	Map	Distribution of poverty and livestock in developing countries	Grid	Developing and transition countries; 2.5 min lon/lat	Mid 1990s
Human Footprint Map	Sanderson et al. [2002]	Map	Maps the influence of human by overlay of several proxies for human influence such as distance to roads and rivers, land cover etc.	Grid	Global, 30 sec. lon/lat	Mid 1990s

Name	Reference	Source type	Relevant contents	Spatial format	Spatial coverage and resolution	Temporal coverage and resolution
Areas of rapid land-use change	Lepers et al. [2005]	Map	Maps hot spots of rapid land-use change between 1981 and 2000, including change of croplands, deforestation, dryland degradation, tropical wild fires	not documented	Global	1981–2000

Table 4.4: Exemplary reviews and data sets describing environmental conditions.

Name	Reference	Source type	Relevant contents	Spatial format	Spatial coverage and resolution	Temporal coverage and resolution
Global Agroecological Zones	Fischer et al. [2002]	Map	Modeling results describing the global distribution of suitability for several agricultural land utilization types, based on a variety of global data sets which are listed here as well; additionally a number of climate characteristics such as length of growing period etc.	Grid	Global; 5 min. lon/lat	1961–1990 climate normal period; one time period
CRU Baseline Climate	New et al. [2000]	Map	Climate indicators on monthly basis including precipitation, temperature, number of wet days, cloudiness, radiation etc.	Grid	Global; 30 min. lon/lat	1901–1995; climate normals and monthly time series
GTOPO30	United States Geological Survey [1998a]	Map	Digital elevation model from remote sensing	Grid	Global; 1x1 km	—
HYDRO1K	United States Geological Survey [1998b]	Map	Derivative data based on GTOPO30: aspect, slope, flow directions, flow accumulation, comouind topographical index	Grid	Global; 1x1 km	—
FAO Digital Soil Map of the World	FAO [1995]	Map	Global map of dominant soil types and derivative class data including e.g. pH, texture, organic carbon, nitrogen, effective soil depth	Grid and Polygon	Global; variable polygon sizes; 5 min lon/lat	—

Name	Reference	Source type	Relevant contents	Spatial format	Spatial coverage and resolution	Temporal coverage and resolution
ISRIC-SOTER	UNEP et al. [1995]	Data Collection	Comprehensive soil data portal with geo-referenced soil profile data, soil unit maps, derived soil properties, soil degradation (GLASOD, ASSOD, SOVEUR)	Grid, point, polygon	Continental to global; variable resolution	—

Table 4.5: Selected reviews and data sets describing socioeconomic conditions.

Name	Reference	Source type	Relevant contents	Spatial format	Spatial coverage and resolution	Temporal coverage and resolution
LandScan 2002	Dobson et al. [2000]; Bhaduri et al. [2002]	Map	Population density derived from several proxies such as night-time lights, infrastructure and others	Grid	Global; 30 sec. lon/lat	2002
FAOSTAT	FAO [2005b]	Database	Indicators related to agricultural and timber markets	—	Global; country level	1961–2003; annual
VMAP Level 0	NIMA [1998]	Map	Major road and rail networks, hydrologic drainage systems, utility networks (cross-country pipelines and communication lines), major airports, elevation contours, coastlines, international boundaries and populated places	Vector arcs, points	Global; 1:1000,000	—
Human Development Reports	UNDP [2003]	Report and spreadsheet	Among other development indicators: time series of human development index (aggregate figure of live expectancy, education and income)	—	Global; country level	1975–2002; five year timesteps

Name	Reference	Source type	Relevant contents	Spatial format	Spatial coverage and resolution	Temporal coverage and resolution
World Development Reports	World Bank [2005b]	Report and spreadsheet	Comprehensive collection of socio-economic variables on country level, including e.g. GDP/GNI, gender issues, governance, infrastructure, poverty, rural development and many others	—	Global; country level	1960–2003; annual
ICRG Risk Ratings	PRS-Group [2005]	Spreadsheet	Commercial data portal offering risk indicators such as conflicts, corruption, bureaucracy quality etc.	—	Global; country level	1984–2003; annual
GTAP	GTAP [2005a]	Model/ Database	Global data base describing bilateral trade patterns, production, consumption and intermediate use of commodities and services	—	Global; various, latest version with 87 regions	CGEs for several time slots, starting in the 1990s

Table 4.6: Selected reviews and data sets describing future scenarios of driving forces.

Name	Reference	Source type	Relevant contents	Spatial format	Spatial coverage and resolution	Temporal coverage and resolution
World Agriculture Towards 2015/30	FAO [2002]	Report	Projection of future areas for specific crops, irrigation and others	—	Global; country level	2015 and 2030
Fertilizer requirements in 2015 and 2030	FAO [2000]	Report	Projection of future fertilizer requirements	—	Global; world regions	2015 and 2030
—	IPCC [2001]	Data Collection	Collection of climate change scenarios, based on different socio-economic scenarios	Grid	Global; various	1990–2100; monthly
Special Report on Emissions Scenarios (SRES)	Nakicenovic and Swart [2000]	Report	Socio-economic scenarios of population growth, economic development and others, based on modeling outputs	—	Global; 11 regions	—
SEI Scenarios	Raskin et al. [2002]	Report	Socio-economic scenarios of population growth, economic development and others, based on modeling outputs	—	Global; 11 regions	1990–2050

4.5 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 4.2) 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 4.2). 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 (agriculture 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 4.3.2) 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 IFPSIM/EPIC 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[9]. 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 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 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.

4.6 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 depen-

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

dence by tracking inventories of land and their productive potential. Beyond, they are flexible and open to integrate socio-economic drivers and their synergies [Geist and 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.

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Chapter 5

Robustness of terrestrial carbon and water cycle simulations against variations in spatial resolution[1]

> *TELESCOPE, n. A device having a relation to the eye similar to that of the telephone to the ear, enabling distant objects to plague us with a multitude of needless details. Luckily it is unprovided with a bell summoning us to the sacrifice.*
>
> Ambrose Bierce, The Devil's Dictionary

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Abstract

Dynamic Global Vegetation Models (DGVMs) of the terrestrial carbon and water cycle have been developed and validated at specific spatial resolutions (mostly 0.5°) but are increasingly being coupled to climate models at coarser spatial resolutions. Is this permissible? We ran the LPJ-DGVM at different spatial resolutions (0.5° x 0.5° to 10.0° x 10.0° in 0.5° intervals) to assess the robustness of terrestrial carbon and water flux simulations to changes in spatial resolution. We show that global model results are robust with only small deviations in the single-digit percent range from a benchmark run at 0.5°. The magnitude of the deviation increases with grid coarseness. Temporal dynamics are largely unaffected by grid cell size. The deviations from the benchmark are mostly spread evenly in space, and otherwise concentrated in areas with strong environmental gradients. We conclude that for coarse-resolution model coupling (such as with climate models) as well as for specific global-scale applications (such as global agroeconomic modeling or integrated assessment modeling) the spatial resolution of DGVMs can be reduced to coarser grids with little biogeochemical error.

5.1 Introduction

Models of terrestrial biogeochemistry and vegetation dynamics are increasingly being coupled to general circulation climate models (GCMs). The uncoupled versions for these terrestrial models, Dynamic Global Vegetation Models (DGVMs), however, have commonly been developed, operated and validated at a higher spatial resolution (typically 0.5°) than is usually the case for GCMs (several degrees typically). Are the simulated terrestrial carbon and water fluxes robust against this change of spatial resolution? The answer to this question is not just relevant to the use of DGVMs in GCMs but equally to the use of vege-

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[1] An edited version of this chapter was published in *Journal of Geophysical Reserach — Atmospheres*, Copyright (2007) American Geophysical Union.: Müller C, Lucht W: Robustness of terrestrial carbon and water cycle simulations against variations in spatial resolution, Journal of Geophysical Reserach — Atmospheres, 112, D06105, doi:10.1029/2006JD007875.

Table 5.1: Characteristics of regular grids at different spatial resolutions.

Resolution [degree]	Average number of cells (Range of alternative aggregations)		Computation time [% of benchmark]	Max. number of 0.5°x0.5° cells included	Grid positions considered (possible)	
0.5[a]	59199	(59199)	100.0	1	1	(1)
1.0	16039	(15965–16097)	27.0	4	4	(4)
1.5	7612	(7608–7620)	12.9	9	9	(9)
2.0	4506	(4498–4517)	7.6	16	16	(16)
2.5	3022	(3009–3035)	5.1	25	25	(25)
3.0	2192	(2186–2203)	3.7	36	36	(36)
3.5	1667	(1659–1675)	2.8	49	49	(49)
4.0	1319	(1308–1330)	2.2	64	64	(64)
4.5	1079	(1072–1084)	1.8	81	81	(81)
5.0	898	(894–901)	1.5	100	100	(100)
5.5	759	(756–762)	1.3	121	36	(121)
6.0	660	(655–665)	1.1	144	36	(144)
6.5	574	(569–580)	1.0	169	49	(169)
7.0	510	(506–515)	0.9	196	49	(196)
7.5	454	(446–457)	0.8	225	64	(255)
8.0	408	(405–412)	0.7	256	64	(256)
8.5	371	(369–374)	0.6	289	81	(289)
9.0	338	(334–342)	0.6	324	81	(324)
9.5	310	(306–313)	0.5	361	100	(361)
10.0	285	(278–289)	0.5	400	100	(400)
2.5x3.75	2112	(2093–2131)	3.6	40[b]	35	(35)

[a] benchmark
[b] 35 0.5° cells + five 0.5° cells to 50%

tation models in socioeconomically and agroeconomically oriented Integrated Assessment Models (IAMs), which equally lack high spatial resolution (typically they operate on 10–20 socioeconomic regions).

Process-based Dynamic Global Vegetation Models (DGVMs) are the state-of-the-art in simulating the global terrestrial biosphere. They are applied to studying the carbon cycle [Bachelet et al., 2001; Cramer et al., 2001; Dargaville et al., 2002; House et al., 2003; Schaphoff et al., 2006; Woodward and Lomas, 2001], the water cycle [Gerten et al., 2004; Kucharik et al., 2000; Leipprand and Gerten, 2006] and as land surface schemes in climate models [Brovkin et al., 2004; Cox et al., 2000; Dufresne et al., 2002; Foley et al., 1998; Friedlingstein et al., 2006; Joos et al., 2001; Krinner et al., 2005; Sitch et al., 2005]. DGVMs are applied at multiple spatial resolutions, ranging from 0.5° x 0.5° to 2.5° x 4.0° and beyond [Wang et al., 2004]. While the lower bound is determined by the resolution of suitable global climatological datasets, the upper bound is determined by the spatial resolution of coupled models, and/or computational requirements. If coupled to climate models, climate data may be downscaled to 0.5° x 0.5° resolution [e.g. Sitch et al., 2005] while DGVM output is aggregated to the climate models resolution [e.g. Foley et al., 1998]. Alternatively, the DGVM may be run at the spatial resolution of the climate model, avoiding up- and downscaling problems [Brovkin et al., 1997; Cox, 2001; Foley et al., 1996]. This also speeds up the DGVM calculations, because the number of grid cells largely determines computation time. Thus, studies with high computational demands such as model intercomparisons [e.g. Cramer et al., 2001], sensitivity analyses [e.g. Zaehle et al., 2005] and scenario studies [e.g. Levy et al., 2004b] are often performed at coarser spatial resolutions. DGVMs also need to be quickly computable in integrated assessment studies, because differences between participating modules in scale, data employed

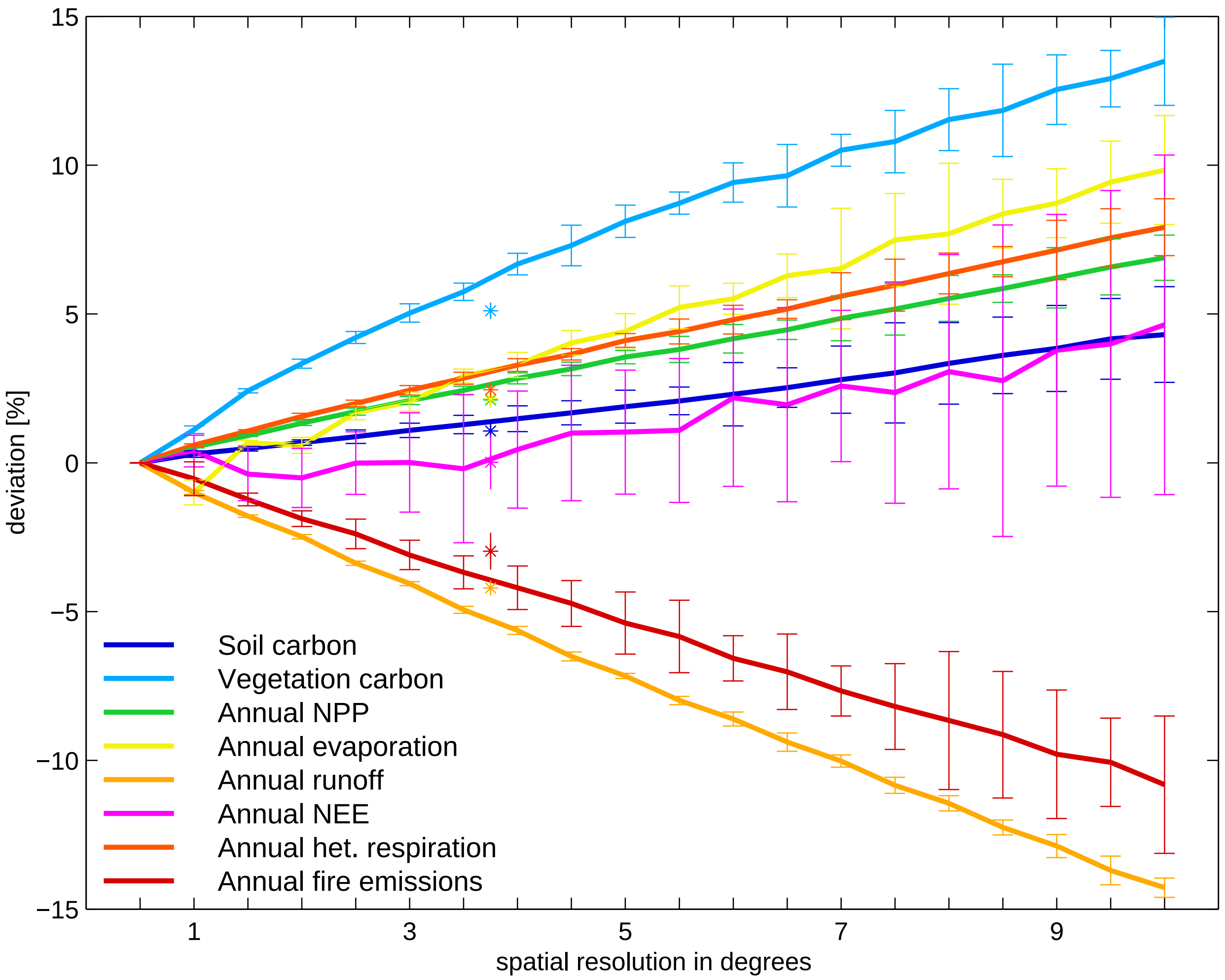

Figure 5.1: Percent deviation from benchmark run of selected results at different regular grids. The deviation of the asymmetric 2.5°x3.75° grid is shown as asteriks. The error bars show the standard deviation of the model results due to differences in grid positioning.

and simulation methods often require iterative procedures.

Although DGVMs are used at different resolutions, the robustness of their results against changes in spatial resolution has not been systematically investigated at the global scale. Suitability at different resolutions has mainly been assumed or derived from ad-hoc comparisons [e.g. Krinner et al., 2005]. Some DGVMs have been partially validated against global observations at specific coarser resolutions [e.g. Foley et al., 1996; Friend and White, 2000] and Wang et al. [2004] found very coarse resolutions (4.5° x 7.5°, R15) to be unsuitable. Much validation work is done against site data [Friend and White, 2000; Friend et al., 1997; Sitch et al., 2003; Zaehle et al., 2005] or at 0.5° resolution [Le Toan et al., 2004; Sitch et al., 2003]. The hydrology module of *ORCHIDEE* has been tested at different resolutions at a sub-continental scale [Verant et al., 2004]. The importance of vegetation heterogeneity at the km-scale for the dynamics of the Planetary Boundary Layer has been demonstrated by Woodward and Lomas [2001].

In this study, we investigate the effect of spatial resolution on global results of DGVMs, by simulating global vegetation dynamics with the LPJ model [Gerten et al., 2004; Sitch et al., 2003] at different regular grids, ranging from 0.5° x 0.5° to 10.0° x 10.0°. Since biogeochemical processes are represented in a comparable manner in other DGVMs [Cramer et al., 2001] it may be assumed that they will respond similarly to spatial aggregation of input data.

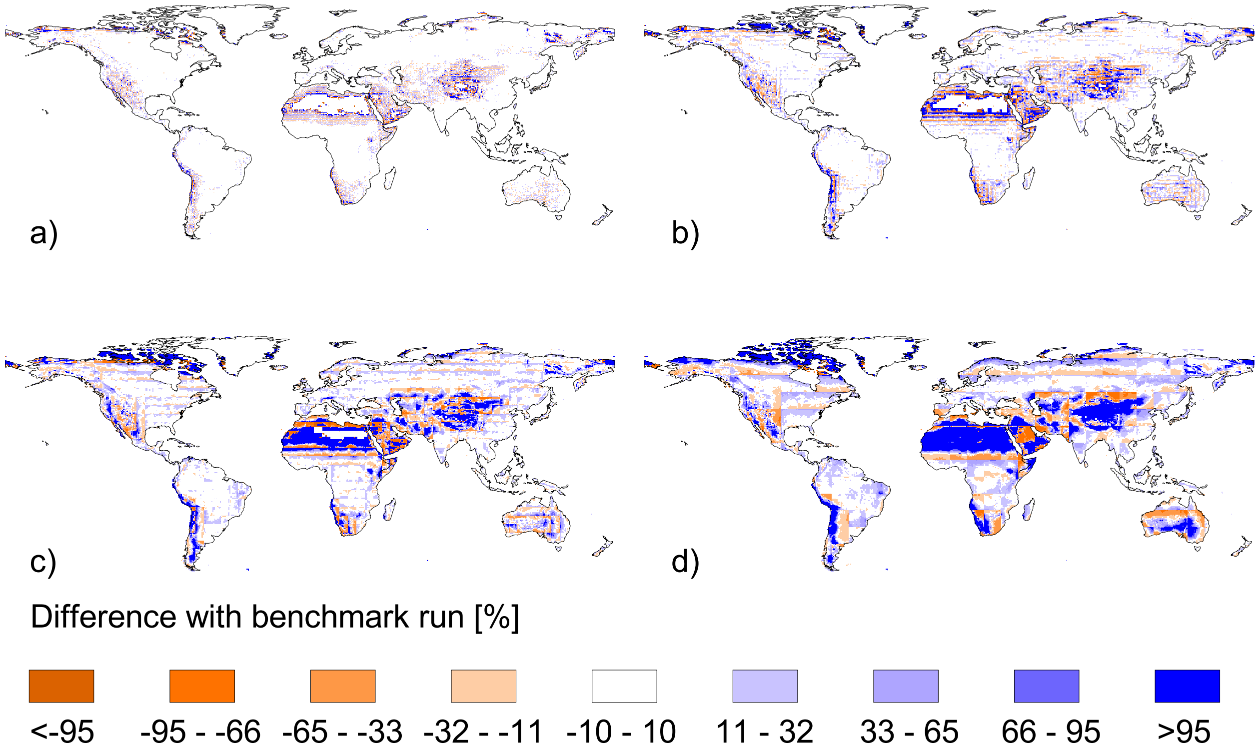

Figure 5.2: Map of pixel deviation of annual transpiration from benchmark at (a) 1.0°, (b) 2.5°, (c) 5.0°, and (d) 10.0°. Note that large increases (dark blue) in areas with very low transpiration (e.g. deserts) in the benchmark run may be low increases in absolute numbers.

5.2 Methods

5.2.1 LPJ-DGVM

The LPJ Dynamic Global Vegetation Model (LPJ-DGVM) is a coupled biogeochemical-biogeographical process model that simulates global terrestrial vegetation and soil dynamics and the associated carbon and water fluxes [Gerten et al., 2004; Sitch et al., 2003]. For this, the processes of photosynthesis, evapotranspiration, and autotrophic and heterotrophic respiration, including the effects of soil moisture and drought stress, as well as a set of functional and allometric rules describing vegetation are implemented. Natural vegetation is represented by 10 different plant functional types (PFTs), of which 2 are herbaceous and 8 woody. Within each grid cell these may fractionally coexist. Their abundance is constrained by climatic conditions and by competition between the different PFTs for resources and space. Vegetation structure reacts dynamically to changes in climate, including invasion of new habitats and dieback. Fire disturbance is driven by a threshold litter load and soil moisture [Thonicke et al., 2001]. The model has been extensively tested against site [Cramer et al., 2004; Gerten et al., 2005; Sitch et al., 2003; Zaehle et al., 2005], inventory [Beer et al., in press; Zaehle et al., 2006], satellite [Lucht et al., 2002; Wagner et al., 2003], atmospheric [Scholze et al., 2003; Sitch et al., 2003] and hydrological data [Gerten et al., 2004, 2005].

5.2.2 Modeling protocol

We use LPJ results at the finest resolution available (0.5° x 0.5°) as a benchmark to assess model results obtained at coarser spatial resolutions. For input, we use monthly data for mean temperature, precipitation, number of wet days, and sunshine hours for 1901–2003, which are based on the *CRU05* observations-derived climatology [New et al., 2000; Österle et al., 2003], atmospheric CO_2 concentrations [Keeling and Whorf, 2003], and soil classes derived from the FAO soil data set [FAO, 1991; Zobler, 1986].

To generate coarser resolution data, we aggregated the 0.5°-raster data for climate and soil in 0.5° intervals to regular grids ranging from 1.0° x 1.0° to 10.0° x 10.0° in spatial resolution (table 5.1), by averaging climate data weighted by area and using the dominant soil class. The total area simulated as land is equal for all grids by allowing for fractional areas. Atmospheric CO_2 concentrations are global values.

The coarser grids can be positioned differently with respect to the finer baseline grid, which gives rise to a number of alternative aggregation schemes for each coarse resolution. We computed all possible alternatives for the resolutions 1.0° to 5.0° and one out of four alternatives for the regular grids of 5.5° to 10.0°, by shifting the grid 1° in latitudinal and/or longitudinal direction. Besides the regular resolutions of 1.0° to 10.0°, we also consider the 3.75° x 2.5° resolution used by a number of climate models and by Joos et al. [2001], also in all alternative grid positions.

5.3 Results

The aggregation of data to coarser grids leads to a quadratic decrease in the number of grid cells and thus in computation time (table 5.1). It also leads to deviations from the benchmark run at 0.5° resolution. We compare the results of coarser resolution runs with the benchmark run regarding total global values (30-year averages, 1974–2003), spatial patterns and temporal variations of these global values.

5.3.1 Global values

The deviation from the benchmark values increases linearly with increasing coarseness. The slope of this increase is small (less than 1.5 % per degree). Only the deviation of the land-atmosphere carbon flux does not increase strictly with coarseness but still displays a gentle linear trend. Figure 5.1 shows the deviation in percent of the benchmark value for selected model results. Annual runoff shows the largest deviations from the benchmark of all variables investigated (up to 14.2 percent at the coarsest resolution (10.0°)) and the land-atmosphere carbon flux (not including land-use change fluxes) the smallest (not more than 4.6 percent even for the coarsest resolution). The error bars in figure 5.1 show the standard deviation of the model results due to differences in grid positioning. It increases with cell size. For annual transpiration, interception, and runoff the grid position is of minor importance while it significantly affects the variation of deviations in NEE and fire emissions. Table 5.2 summarizes the slope of linear regression lines to the deviations from the benchmark and their coefficients of determination for each parameter; the intercept is zero in all cases.

5.3.2 Spatial patterns

We compare values in each 0.5° grid cell of the benchmark run with their coarser-scale representatives in order to determine the effects of spatial resolution on the spatial pattern of deviations in each parameter. As shown exemplarily for annual transpiration in figure 5.2, the deviation from the benchmark is mostly distributed evenly in space (see also figure 1.3 for the spatial pattern of deviations in NPP). However, in areas with strong environmental gradients (i.e. borders of mountains, deserts etc.), coarser grid cells can differ substantially from the benchmark value. With increasing coarseness of the grid, the number of these ill-represented cells increases and streaky latitudinal patterns emerge and become more prominent. These patterns derive from an overestimation of values at the coarser grid cell's sides towards the poles and an underestimation at the coarser grid cell's side that is pointing to the equator (or vice versa, depending on the parameter). Histograms of the deviation from the benchmark values therefore show a bias towards enhanced plant performance, or a greener terrestrial biosphere (larger carbon uptake/pools, more evapotranspiration and interception, less runoff) that emerges and increases with coarseness of the grid (see figure 5.3 for an exemplary histogram of annual runoff).

Table 5.2: Slope (deviation from benchmark value in percent per degree resolution) and coefficient of determination (R^2) for the regular grids of 0.5° to 10.0°. R^2 is computed with the intercept set to zero.

Model output [unit]	Slope	Coefficient of determination (R^2)
Soil carbon [PgC]	0.449	0.996
Litter carbon [PgC]	0.480	0.997
Vegetation carbon [PgC]	1.364	0.981
Annual transpiration [km/a]	0.829	1.000
Annual evaporation [km/a]	1.123	0.991
Annual interception [km/a]	0.982	0.969
Annual runoff [km/a]	-1.491	0.999
NPP [PgC/a]	0.707	0.998
NEE [PgC/a]	0.511	0.770[a]
Rh [PgC/a]	0.812	0.998
Fire emissions [PgC/a]	-1.133	0.999

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[a] For NEE, the intercept had to be forced to zero, reducing R^2.

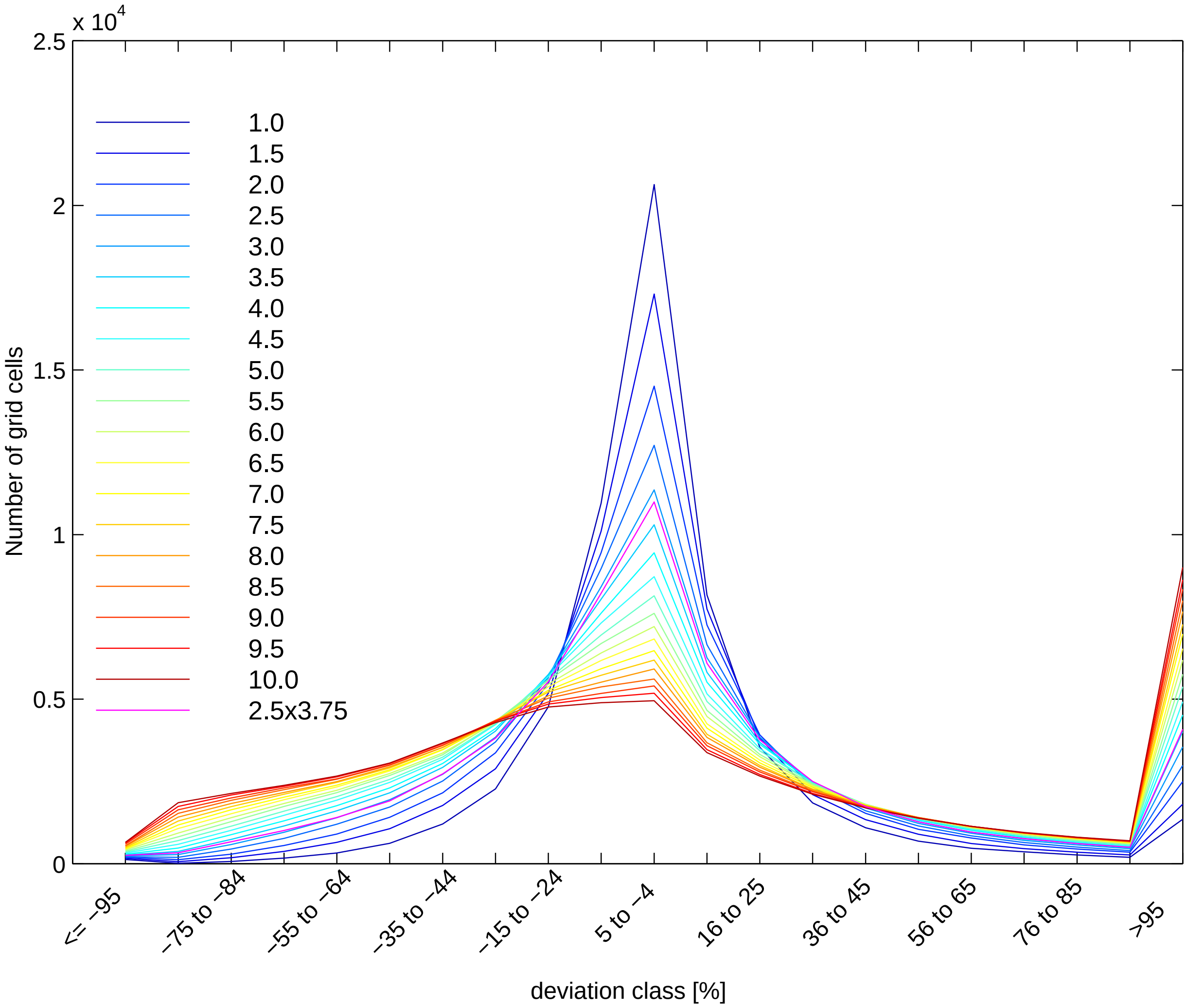

Figure 5.3: Histogram of difference between each 0.5° grid cell and their corresponding coarser grid cell in percent, exemplary for annual runoff. The asymmetric 2.5°x3.75° grid is shown in magenta.

5.3.3 Temporal dynamics

The temporal dynamics of model results are hardly affected by the grid's resolution. The interannual variation is almost identical for all grids but their intercept differs (see above). Correlation coefficients of the correlations between the time series of the benchmark run and corresponding time series at coarser resolutions range between 1.0 and 0.84 (1.0 to 0.93 for resolutions up to 5.0°). Figure 5.4 exemplarily shows the time series of net primary production (NPP) at different resolutions.

5.4 Discussion

We find that overall, model results are surprisingly robust against changes in spatial resolutions from 0.5° to 10°. They show a persistent linear trend with larger deviations at larger resolutions, but the slope is small. There are no climate input data available at finer spatial resolutions than 0.5°, inhibiting an exploration of this trend at finder resolutions. The 0.5° grid is often used in DGVM studies — but for historical and not scientific reasons. This is also demonstrated here: The 0.5° resolution does not differ qualitatively from coarser resolutions. Utilizing the 0.5° grid as a benchmark may thus be debatable but can be justified by the extensive validation of LPJ, the DGVM used here, at this spatial resolution.

Nonetheless, differences between the benchmark run at 0.5° resolution and simulations at coarser grids occur. The deviation of the global values only partially reflect the deviations at grid cell level, since these include both negative and positive deviations and are largely compensated in the global values. Streaky patterns for example emerge and grow at coarser spatial resolutions. They reflect the importance of solar radiation, which is computed as a func-

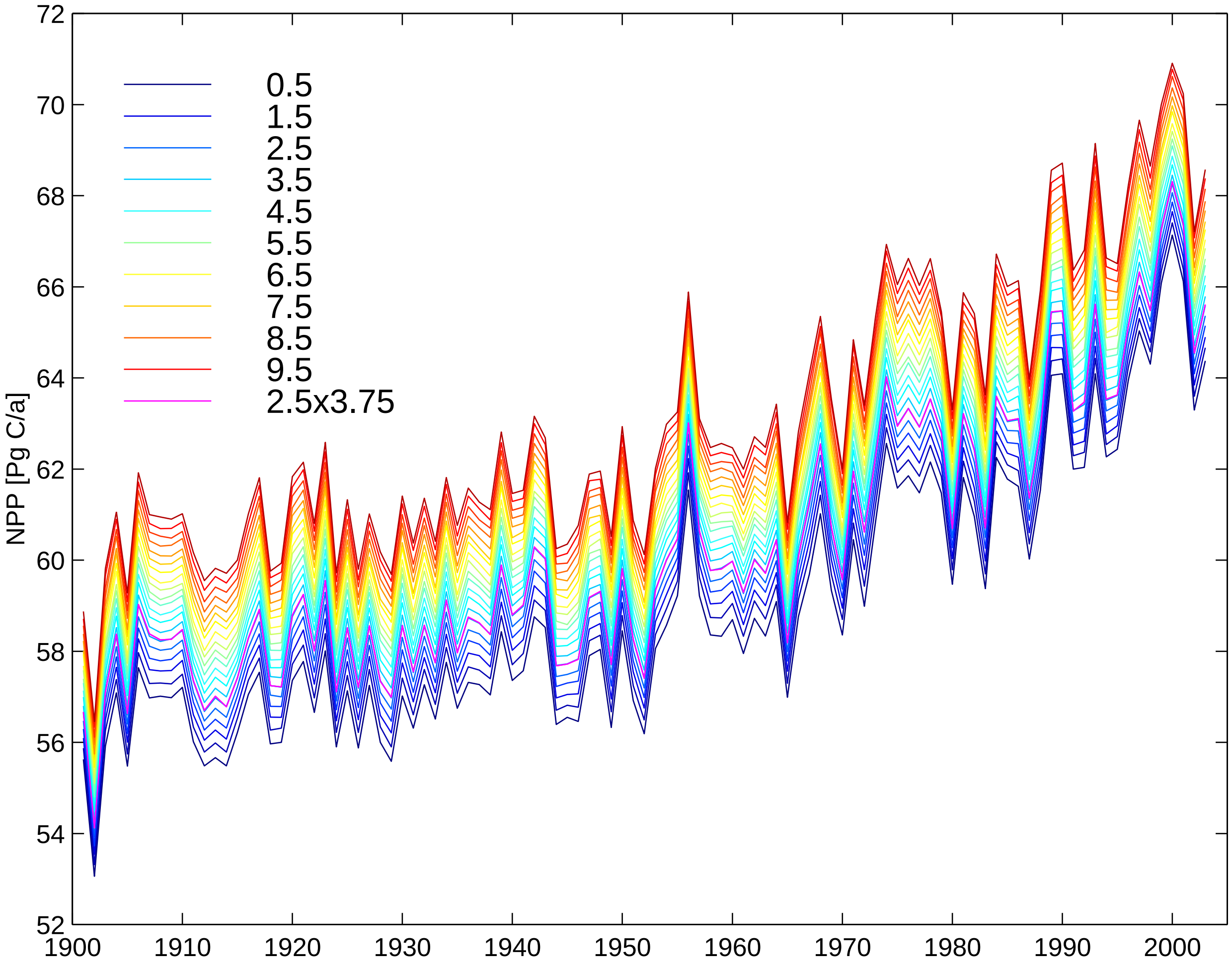

Figure 5.4: Time series of NPP at different resolutions. Note that all resolutions are shown in the figure, while the legend is reduced to every second grid; NPP increases linearly with grid coarseness. The asymmetric 2.5°x3.75° grid is shown in magenta.

tion of latitude for cell centers in our model. Within a coarse cell, the insolation of the cell's center is used for the entire grid cell, leading to over- and underestimated insolation values at its borders. However, such finer-scale deviations are compensated overall within each coarser grid cell.

On the other hand, averaging within a coarse grid cell of extreme climatic conditions that are unfavorable for vegetation growth, such as aridity, with less extreme conditions in neighboring areas increases total vegetation growth at the coarse scale. Averaging the opposite extreme, in this case high humidity, with less extreme neighboring cells, does not normally compensate for this effect within each coarse grid cell. As a consequence, the terrestrial biosphere becomes "greener" or more productive at coarser spatial resolutions. Model results at coarser spatial resolutions can therefore not necessarily be interpreted locally or regionally but need to be carefully analyzed with respect to the softening of extremes in the process of spatial aggregation.

The temporal dynamics of model results are barely affected by grid coarseness. Hence, model results may need some scaling to match, for example, observed values but their reaction to climatic fluctuations — and thus their interannual variation — remain largely unaffected. Coupling DGVMs to climate or other models is therefore not problematic in this respect.

We here studied biogeochemical cycles only and cannot judge the effects of grid coarseness on biophysical parameters such as on albedo and energy fluxes. These may well be affected by grid coarseness in coupled DGVM-climate model applications, causing additional feedbacks on biogeochemical cycles. Systematic testing of these effects would require a coupled climate-vegetation model that can be run at fine spatial resolution (see Woodward and Lomas [2001], for an example at the km-scale).

Based on these results, the choice of a spatial resolution suitable for a specific DGVM application is not straightforward. There is no threshold resolution above which model results begin to markedly deviate from the benchmark values. Overall, the uncertainty present in recently published estimates for carbon fluxes [Bopp et al., 2002; Plattner et al., 2002; Schimel et al., 2001] and pools [Batjes, 1996; Eswaran et al., 1993; Olson et al., 1985; Post et al., 1982; Saugier et al., 2001; WBGU, 1998] is with error ranges of up to 50 percent significantly larger than the deviations found here due to grid coarseness, rendering coarse-resolution terrestrial carbon cycle simulations suitable to investigations of processes. In contrast, published hydrological estimates vary by roughly ± 10 % [Gerten et al., 2004], a level of uncertainty smaller than the deviation found for runoff, for grids coarser than 7.0° x 7.0°.

Regular grids are an arbitrary choice of gridding pattern. The world is characterized by spatial heterogeneity. Regular grids average smaller-scale differences and artificially separate larger homogenous (in terms of the characteristics of interest) areas. Consequently, polygonal or irregular grids that are based, for example, on the spatial patterns of factors that determine plant growth should — in principle — be able to reproduce the model's benchmark run with a smaller number of grid cells. We performed several such experiments and find that the error incurred for irregular grids, in comparison to the benchmark, is dominated by the error incurred for the largest cell of the irregular grid. The overall deviation is found to be larger than that of a regular grid with the same number of grid cells. The reason is that deviations generally increase exponentially with pixel size, with an exponent that is larger than unity. Hence for grids with varying cell size, the error of large cells enters the global error with large values than that of small cells. The largest cells dominate the deviation of irregular grids from the benchmark. Regular grids therefore always produce smaller deviations than irregular grids with the same number of grid cells. We conclude that irregular patterns, even when selected to follow natural patterns such as climate or vegetation zones, are not an advantage over regular grids in terms of their ability to provide accuracy in coarse-scale simulations.

Our study does not investigate whether the benchmark simulation is accurate in comparison to data. Rather, we investigated whether results depend on spatial resolution. The model we used was the LPJ DGVM but processes in most DGVMs are implemented in a broadly similar manner [Brovkin et al., 1997; Cox, 2001; Foley et al., 1996; Friend and White, 2000; Krinner et al., 2005; Woodward and Lomas, 2004; Sitch et al., 2003]; see also Cramer et al. [2001] and Le Toan et al. [2004]. It is therefore reasonable to assume that our findings will hold for other DGVMs as well.

5.5 Conclusions

The spatial resolution of DGVM simulations can be much reduced for specific global applications since model results are largely robust against changes in spatial resolution, with deviations from a full-resolution run of less than 5 percent in most variables even for very coarse resolutions. However, specific cells and areas with strong environmental gradients cannot be represented well at coarser resolutions. Coupling of DGVMs to models that operate a coarser grids, such as climate models, is unproblematic with respect to the temporal dynamics of DGVMs, which are mainly unaffected by spatial resolution. Especially applications with a focus on regional/local criteria need to balance the error in the representation of single cells and gradients with the benefits of coarser grids such as reduced computational demands. Irregular spatial grids should be explored for the best trade off between computation time and spatial accuracy.

Acknowledgements

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Chapter 6

Outlook: Food demand, productivity growth, and the spatial distribution of land and water use: a global modeling approach

Farming looks mighty easy when your plow is a pencil, and you're a thousand miles from the corn field.

Dwight D. Eisenhower, September 11, 1956

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Abstract

In the coming decades, an increasing competition for global land and water resources can be expected, driven by three major trends: (1) rising food demand due to population growth, economic development, and dietary changes; (2) rising area demand for biomass-based energy production and biodiversity conservation; (3) changing production conditions due to climate change. The potential of technological change in agriculture to adapt to these trends is subject to considerable uncertainty. In order to simulate these combined effects in a spatially explicit way, we have developed a "*Management model of Agricultural Production and its Impact on the Environment*" (MAgPIE). MAgPIE is a linear programming model covering the most important agricultural crop and livestock production types in 10 economic regions worldwide. It takes regional economic conditions as well as spatially explicit data on potential crop yields, land and water constraints into account and derives specific land-use patterns for each grid cell. Shadow prices for binding constraints can be used to valuate resources for which in many places no markets exist, especially irrigation water. In this paper we describe the model structure and validation runs for the years 1995 and 1970 and discuss the model's characteristics, potential and limitations.

6.1 Global land use challenges in the 21st century

World population will grow to about 10–14 billion people by the year 2100, with a median projection at 8.8 billion for the year 2050 [Lutz et al., 2001]. As income rises, people tend to consume more calories in total, and the share of animal calories increases, especially the consumption of animal fats. Global meat consumption can be expected to rise by up to 3 percent annually over the next decades [Keyzer et al., 2001]. While global food supply may still outpace demand up to 2020, the assumption of exponential growth paths instead of logistic curves has been questioned for projections in the very long run [Harris and

Kennedy, 1999; Rosegrant and Ringler, 1997]. The potential of biotechnology and genetic engineering for accelerating agricultural productivity growth remains unclear and subject to strong public debates [Qaim and Zilberman, 2003]. The total land area available for agricultural production is partly determined by land requirements for other purposes, like infrastructure development, urbanization, bio-energy production, or biodiversity protection [Sands and Leimbach, 2003] but also by soil degradation [McNeill and Winiwarter, 2004; Oldeman et al., 1990]. Water may pose the most serious limitation to future global food supplies. Irrigated areas account for nearly two-thirds of world rice and wheat production. Rising irrigation output per unit of land and water is essential to feed growing populations. However, the size of potential water savings in agricultural irrigation systems is unclear. While specific water uses can be made more efficient through better technology, the potential overall savings in many river basins are probably much smaller, because much of the water currently lost from irrigation systems is re-used elsewhere [Rosegrant and Cai, 2003]. The future global challenge with respect to agriculture and water implies that over the next 25 years food production has to be increased by about 40 percent while reducing the renewable water resources used in agriculture by 10-20 percent [Rijsberman and Molden, 2001]. An additional constraint to agricultural production in the second half of the 21st century is global climate change. A rise in atmospheric CO_2-levels and a corresponding rise in global temperatures will not only affect plant growth and yields, but will also alter the regional patterns of precipitation and water availability as well as land erosion and fertility. Regional impacts of climate change vary quite significantly and the combined effects of various changes are still uncertain [IPCC, 2001].

Global land-use patterns will change in the future, reacting to the pressures described above. Projecting their future development is important to study both their impacts on the Earth System as well as the limitations of land use, since water and fertile land are available in limited amounts only.

6.2 Projecting global land-use patterns

Agricultural land-use patterns are determined by a plentitude of environmental, economic and societal conditions and their interaction. The challenge of projecting future land-use patterns is to account for the socio-economic framework that largely determines the agricultural demand and for the spatial heterogeneity of the land's suitability to supply these goods within the same modeling framework. Land suitability for agricultural production is largely determined by environmental conditions, but also by the socio-economic situation such as land tenure and management. Demand, on the other hand, is determined by the number of consumers and their per-capita consumption, which is strongly modulated by their income, market access, and cultural background. The disciplines involved, however, differ significantly in methodologies and data used. Land-use models that address both the processes that constitute the demand side as well as supply side constraints need to overcome differences in thematic, temporal and spatial scales.

Economic data at the global scale, as for example on production costs, market prices, and demand usually do not differentiate between agricultural raw products delivering the same processed good, such as vegetable oil taken from soybean, oil palm, rapeseed, sunflower, or olives. Besides this aggregation of different field crops, the same agricultural crop may be accounted for in different economic commodities, as soybeans for example are used for direct human consumption, vegetable oil, and animal feed. The different crops that can supply this commodity, however, may differ significantly from each other: physiology and climatic requirements of, for example, oil palms and sunflowers are significantly different, although both supply the same commodity — vegetable oil. In order to determine the supply side constraints, it is of crucial importance to know which crop is used to satisfy the demand. Land use models therefore need to evaluate the different options to produce an agricultural commodity and internally select the most appropriate one, accounting for societal, economic and environmental constraints. Furthermore, economic data on the production of aggregate agricultural commodities need to be matched with the individual crops that contribute to the corresponding commodity group.

For future land-use projections, economic and biospheric models are needed to provide essential inputs. However, the temporal scales in economic and biospheric models differ fundamentally. This hampers the dynamic coupling of these models, especially for long-term projections (i.e. more than 1-2 decades). Biospheric models can principally project the long-term future development as a chronological sequence of time steps, because they are based on chemical and physical processes that are not subject to changes over time. This is different in economic models. Macroeconomic growth models are able to project the economic development over a century, but compute all time steps of a development simultaneously by optimizing the development path. This impedes a dynamic coupling of economic growth models with biospheric models, as it is needed, for example, to study the mutual interaction between biospheric and economic development. This structural mismatch can only be solved by conducting computationally expensive iterations. Furthermore, these models are usually highly aggregated and do not explicitly address the demand and supply in different sectors, like agriculture. They are, instead, concerned with investment, technological change and the overall economic development. Comparative-static and recursive-dynamic equilibrium models are capable of supplying detailed information on agricultural production and demand and they are based on sequential time steps. However, they are not suitable for future projections of more than one or two decades because of their static assumptions on market structures that are not necessarily constant over time.

Economic and biospheric models also differ in their spatial resolution. Biospheric models typically operate on geographic grids. These divide the terrestrial biosphere into distinct spatial units that are exactly localized and usually assumed to be homogenous, although sub-grid differentiations are possible. Economic models, on the contrary, typically operate on administrative spatial units — countries or regional groups of countries in the case of global models. For projecting future land-use patterns, the spatial heterogeneity of land suitability, which is largely captured by the highly resolved geographic grids, is an important factor that strongly determines the size of agricultural area [Müller et al., 2006, see Chapter 2]. This needs to be reflected in the economic structure of land-use models. However, the exchange of goods between regions and sectors is a highly parameterized process in economic models, inhibiting drastic increases in spatial resolutions. These spatial scales need to be harmonized, in order to project meaningful spatially explicit land-use patterns.

6.3 Current modeling approaches

Current large-scale land-use modeling approaches pursue different strategies to project future land-use patterns. Disciplinary approaches concentrate on either the supply side or the demand side and exogenously prescribe the missing side — or ignore it. So-called geographic approaches, like the CLUE [Verburg et al., 1999a,b] and SALU [Stephenne and Lambin, 2001a,b] models, concentrate on the supply side and compute land-use patterns based on spatially explicit data on land suitability and on external assumptions on agricultural demand. They are strong in capturing the spatial determination of land use and in quantifying supply side constraints based on land resources. However, they lack the potential to treat the interplay between supply, demand, and trade endogenously.

Economic models, on the other hand, as for example different version of the GTAP model [Hertel, 1997] or the WATSIM model [Kuhn, 2003] can consistently address demand, supply and trade via price mechanisms. However, they are limited in accounting for resource constraints, in reflecting the impact of demand on actual land-use change processes, and in representing behavior not related to price mechanisms. Land is usually implemented as a constraint in the production of land-intensive commodities, and economic competition of different types of production within one sector is represented endogenously. The simulation of management types as well as the competition for land (and water) among different sectors are supported by the structure of such models but seldom actually included. This limits the representation of land-use change processes.

Integrated approaches aim to make up for the deficiencies of disciplinary approaches by accounting for both economic and environmental processes. In order to achieve this, these models pursue different strategies: Some employ land allocation schemes, which use demand or price information from economic models to update land-use patterns in detailed environmental models (ACCELERATES [Rounsevell et al., 2003], IFPSIM/EPIC [Tan and Shibasaki, 2003; Tan et al., 2003]), while others improve the representation of resource constraints in detailed economic models, as in the FARM model [Darwin et al., 1996]. The dynamic coupling of the IMAGE and GTAP-LEI models [Klijn et al., 2005; van Meijl et al., 2006] is the first approach at the global scale that addresses the trade-off between spatial expansion of agricultural production and intensification. GTAP-LEI [van Meijl et al., 2006] introduces so-called *land-supply curves*, representing the impact of land scarcity on land rent. If land rent increases too strongly, the model endogenously switches to intensified agricultural production, which demands higher levels of inputs. This information is transferred to IMAGE [IMAGE team, 2001], where the actual spatially explicit land-use pattern is computed. However, the separate representation of land-use in both models yields the risk of inconsistencies and redundancies.

6.4 The land-use model MAgPIE

In contrast to these available models, we have chosen an economic optimization approach to simulate spatially explicit land-use patterns. This approach provides most flexibility to integrate various types of biophysical constraints into an economic decision-making process, i.e. it provides a straightforward way to link monetary and physical units and processes. The dual solution of such optimization models provides valuable insights into the internal use value of resource constraints: The optimization model computes a shadow price for all binding constraints (in the case of land-use models like water, land, or trade). The shadow price represents the price that a land-manager would be willing to pay for relaxing the constraint by one unit, because total production costs could then be equally reduced.

Our globally applicable land-use model, MAgPIE, is a linear-programming model with a focus on agricultural production, land, and water use. The objective function of the program is to minimize total cost of production for a given amount of food energy demand. Regional food energy demand is defined for an exogenously given population in ten food energy categories (cereals, rice, vegetable oil, pulses, roots and tubers, sugar, ruminant meat, non-ruminant meat, and milk), based on regional diets [FAO, 2001]. Food and feed energy for the ten demand categories can be produced with 20 cropping activities (temperate cereals (food/feed), maize (food/feed), tropical cereals (food/feed), rice, five oil crops, pulses, potatoes, cassava, sugar beets, sugar cane, vegetables/fruits/nuts, two fodder crops) and 3 livestock activities (ruminant meat, non-ruminant meat, milk). Feed for livestock is produced as a mixture of grain, green fodder, and pasture, which is taken care of internally in the model. Fibers can be produced with one cropping activity (cotton). Variable inputs of production are labor, chemicals, and other capital (all measured in US$), which are assumed to be in unlimited supply to the agricultural sector at a given price. Cropland, pasture and irrigation water are fixed inputs in limited supply in each grid cell, measured in physical units (hectare (ha) and cubic meter (m^3)). Crop yields for each grid cell are supplied by the LPJ/mL Dynamic Global Vegetation Model (DGVM) [Bondeau et al., 2007]. They are computed as a weighted average of irrigated and non-irrigated production, if part of the grid cell is equipped for irrigation according to the global map of irrigated areas [Döll and Siebert, 2000]. In case of pure rain-fed production, no additional water is required, but yields are generally lower than under irrigation. If a certain area share is irrigated, additional water for agriculture is taken from available water discharge in the grid cell. However, available water discharge is not affected by land use at this stage. Instead, water discharge is computed as the runoff generated under natural vegetation within the grid cells and its downstream movement according to the river routing scheme implemented in LPJ/mL. In these simulations, 50 % of discharge is withdrawn in each grid cell that is equipped for irrigation, reducing the available discharge in downstream cells in order to compensate for the missing land-use feedback.

In order to keep the MAgPIE model size within reasonable limits, spatially explicit data on yield levels and freshwater availability for irrigation is provided on a regular geographic grid, with a resolution of three by three degrees, dividing the terrestrial biosphere into 2178 discrete grid cells of an approximate size of 300 km by 300 km at the equator. Population [CIESIN et al., 2000; FAO, 2001] and economic data on production costs [Hertel, 1997; McDougall et al., 1998], self-sufficiency ratios [FAO, 2001], and gross domestic product (GDP) [World Bank, 2005a], as well as data on food energy demand [FAO, 2001] per capita are provided for ten world regions (Sub-Saharan Africa (AFR); Centrally-planned Asia including China (CPA); Europe including Turkey (EUR); Newly Independent States of the Former Soviet Union (FSU); Latin America (LAM); Middle East/North Africa (MEA); North America (NAM); Pacific OECD including Japan, Australia, New Zealand (PAO); Pacific (or Southeast) Asia (PAS); South Asia including India (SAS); see figure 6.1), and each cell of the geographic grid is assigned to one economic region. Trade between regions is simulated endogenously, if agricultural commodities can be produced at lower costs in other regions. Trade is constrained by minimal self-sufficiency ratios that specify the minimal share of each demand category that needs to be produced within its own region. Land conversion activities have been included for simulating potential expansion and shifts of agricultural land in specific locations. For 1995, as the initial year, agricultural land is constrained to the area currently used within each grid cell, according to Ramankutty and Foley [1999]. However, if additional land is required for fulfilling demand, this can be taken from the pool of non-agricultural land at additional costs. These land-conversion costs force the model to utilize available land first, and land conversion will become relevant only if land becomes scarce in a certain scenario and location or if the marginal cost reductions by producing crops on converted land outweigh the costs of conversion. For future projections, land conversion is limited to a maximum of 5 % of the available non-agricultural land per decade, representing the slow processes involved (decision making, capital acquisition, risk aversion etc.). LPJ/mL can provide potential crop yields and irrigation water requirements for the 20th and 21st century, taking effects of climate change into account [Bondeau et al., 2007]. Under plausible scenarios on population and income growth, MAgPIE allows for future projections of spatially explicit land-use patterns and for valuating limiting constraints such as land, water, or trade limitations. If no detailed data on future demand patterns are available, MAgPIE computes food demand as a function of income (GDP per capita), based on an empirical relationship as shown in figure 6.2.

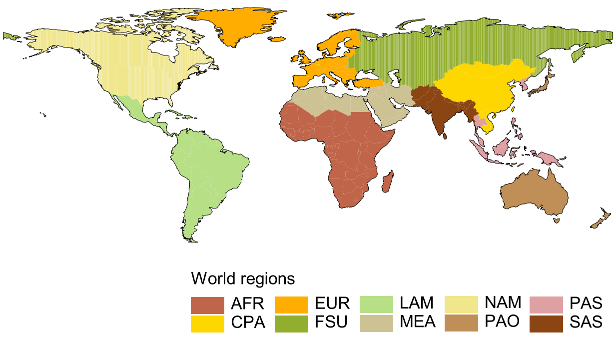

Figure 6.1: World regions as used in MAgPIE.

6.5 Calibration and Validation of the model

MAgPIE has been parameterized for the base year 1995, using data from FAOSTAT [FAO, 2001], World Development Indicators (WDI) [World Bank, 2005a] and the Global Trade Analysis Project (GTAP) database (version 4) [Hertel, 1997; McDougall et al., 1998]. Based on these data, a comprehensive global database with data on agricultural production, trade, food consumption and land use has been constructed for the base year 1995. Figure 6.3 describes the regions in terms of their GDP per capita and food intake in kilo-calories in 1995. In order to ensure consistency of the database, the net trade position in terms of food energy units of all regions has been determined by balancing the food demand in different categories, total production of major crops and livestock types, and related demand for concentrate feed and green fodder. Figure 6.4 describes the current net trade position of each region. Differences in the net trade position in energy terms compared with value terms may be explained by the different value/energy ratio between regional exports and imports, i.e., agricultural goods with high energy contents are not necessarily highly priced goods and vice versa.

The GTAP data have been used to define the costs of production for each crop and livestock type. Production costs are region-specific and are calculated by dividing total costs of production (labor, chemicals, capital) from GTAP by the area harvested from FAOSTAT. This gives a constant parameter per hectare and production activity for each region. Although production costs per hectare are assumed to be homogenous within each region, production costs per unit produced vary greatly over space due to yield variation between the grid cells within each region. Through international trade the regions compete with each other based on their comparative cost advantages. The extent of international trade is controlled by trade constraints, which limit the regional trade balance to a prescribed self-sufficiency rate (e.g. at the 1995 level, see figure 6.4). Besides interregional trade, production costs determine the crop mix within each region as different production activities that satisfy the same demand category may differ in economic efficiency, even at similar yield levels.

Using potential crop yields from LPJ/mL for 1995, the model has been calibrated to represent the share of cropland in total area for each region as well as the shares of individual crops in total cropland (i.e. area harvested). MAgPIE has been calibrated with two sets of parameters:

1. *Rotational constraints*: a maximum share in total cropland in each grid cell has been defined for each crop type. This reflects technological constraints within an average crop rotation. For example, certain crops like potatoes or sugar beets usually can be grown every 3–4 years only, for reasons of pest control. This would imply an upper limit of 25–33 percent in the average cropland share. For cereals the rotational constraint is set in most cases to 70 percent, see table 6.1.

2. *Yield correction at regional level*: potential crop yields as derived by LPJ/mL differ from actual crop yields observed in the FAO statistics, because crop management is not yet fully reflected in LPJ/mL simulations. We adjust average yields on the regional level by a regional management factor, but fully maintain yield variability between grid cells as provided by LPJ/mL.

With these two sets of calibration parameters we are able to adjust the MAgPIE model to match average cropland shares in 1995 reasonably well. At the global average, MAgPIE uses about 96 percent of the observed crop area. Regional crop shares differ between a minimum of 87 percent in region PAO and 105 percent in region FSU (figures 6.5, 6.6, table 6.2). Figure 6.7 shows the land-use pattern computed by MAgPIE for 1995 and as observed by Ramankutty and Foley [1999]. Pasture demand for ruminant meat and milk was calibrated regionally to be satisfied with current pasture area, which was derived by Bondeau et al. [2007] from the data sets of Ramankutty, Leff and Hyde. However, the level of uncertainty of global data sets on managed grassland is high [FAO, 2001], impeding a better parameterization of the model.

In order to validate the model, it is used for conducting a ”backcasting” exercise to the year 1970.

Table 6.1: Regional rotational constraints for the different cropping activities, implemented as maximum cropland share per cropping activity.

	AFR	CPA	EUR	FSU	LAM	MEA	NAM	PAO	PAS	SAS
Temperate cereals (food/feed)	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
Maize (food/feed)	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
Tropical cereals (food/feed)	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
Rice	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Soybean	0.25	0.25	0.40	0.40	0.25	0.25	0.40	0.40	0.25	0.25
Rapeseed	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Groundnut	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Sunflower	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Oilcrops, other	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Pulses	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Potato	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Cassava, sweet potato	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Sugar cane	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Sugar beet	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Vegetables, fruits, nuts	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Green fodder	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Cotton	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50

Table 6.2: Regional cropland shares 1995 as observed by Ramankutty and Foley [1999] and FAO [2001] and simulated by MAgPIE.

Region	Observed 1995	Simulated 1995	Ratio 1995	Observed 1970	Simulated 1970	Ratio 1970
World	0.11	0.11	0.96	0.10	0.08	0.81
AFR	0.07	0.06	0.92	0.06	0.03	0.51
CPA	0.17	0.16	0.92	0.17	0.16	0.93
EUR	0.23	0.21	0.93	0.22	0.24	1.06
FSU	0.13	0.13	1.05	0.12	0.08	0.64
LAM	0.07	0.07	1.00	0.07	0.05	0.75
MEA	0.03	0.03	0.96	0.02	0.02	0.69
NAM	0.10	0.09	0.91	0.09	0.10	1.03
PAO	0.04	0.04	0.87	0.02	0.03	1.28
PAS	0.14	0.14	1.03	0.10	0.10	1.01
SAS	0.37	0.36	0.97	0.36	0.26	0.74

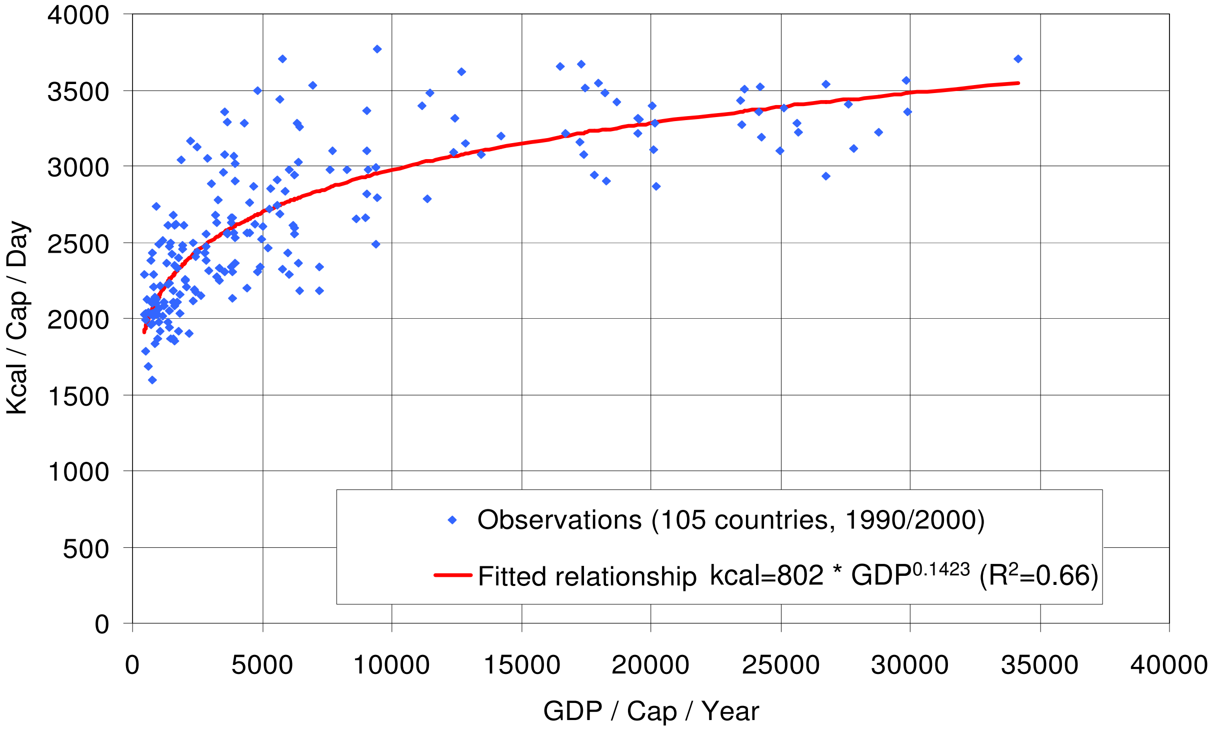

Figure 6.2: Regression of calorie intake against income (GDP per capita) (data for 105 countries in 1990 and 2000).

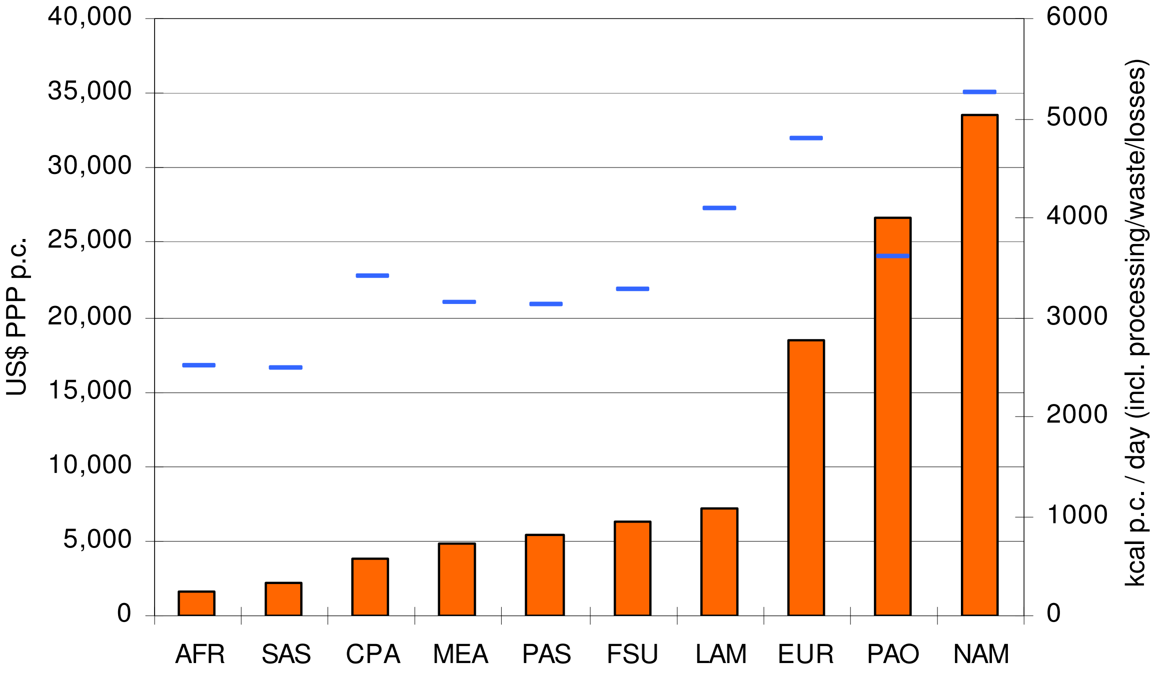

Figure 6.3: Structure of model regions: GDP per capita (red column) and calorie intake (blue dash) in 1995.

Comparing the results with statistical data from Ramankutty and Foley [1999] and FAO [2001], we thus demonstrate the general suitability of the model's basic mechanisms. As detailed economic data for future projections are not available, we here use the same simplifying assumptions as would be used for future projections, although more detailed data are available for 1970. As the model is based on energy units in demand and supply, we derive changes in food energy demand based on a regression of food energy intake

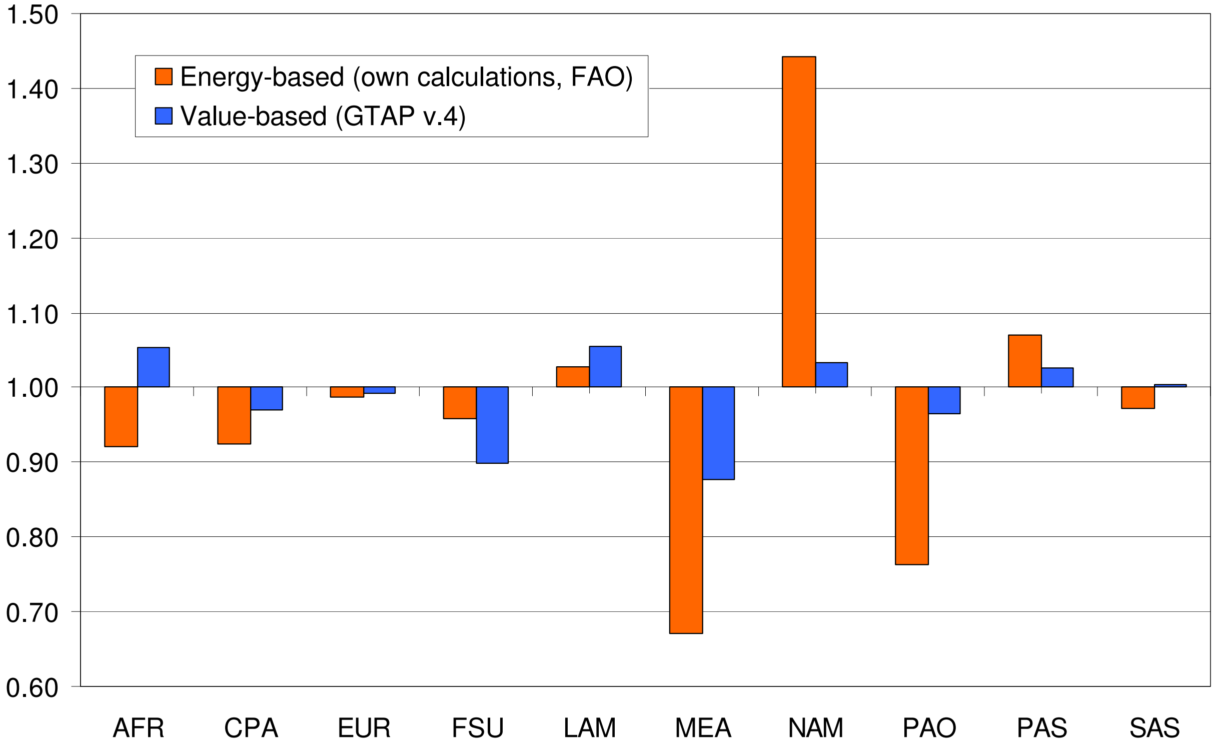

Figure 6.4: Self-sufficiency ratios in 1995 — calorie- vs. value-based.

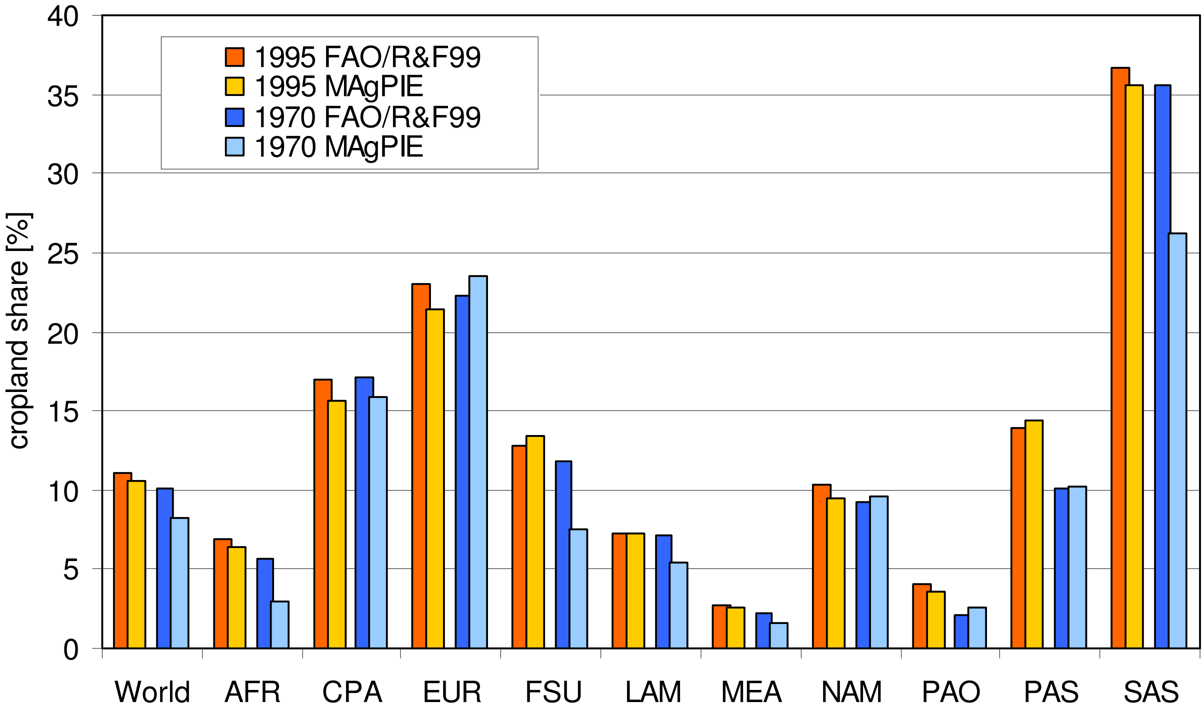

Figure 6.5: Share of cropland in total area as observed (red 1995/orange 1970) [FAO, 2001] and simulated (dark blue 1995/light blue 1970) by MAgPIE.

on GDP per capita (for 105 countries and two points in time) (see figure 6.2) and on changes in population only. The resulting food energy demand values compare well against FAO statistics (6.8). Changes in

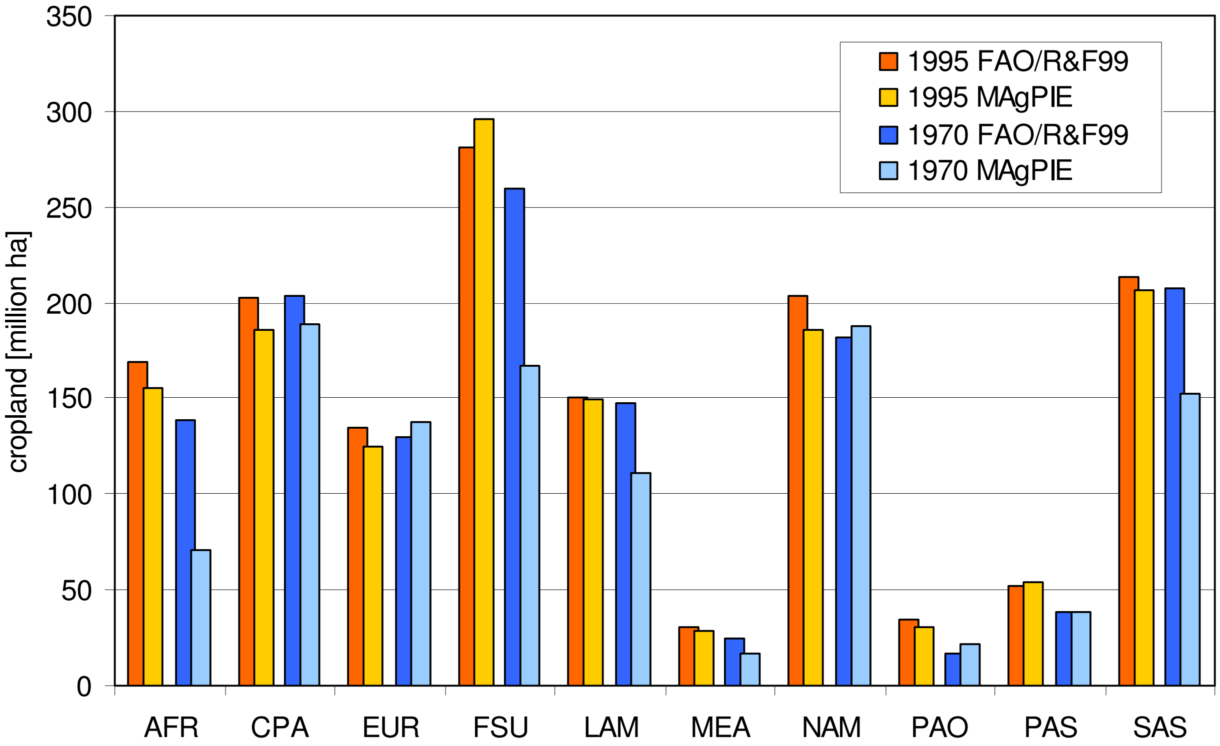

Figure 6.6: Cropland area as observed (red 1995/orange 1970) [FAO, 2001] and simulated (dark blue 1995/light blue 1970) by MAgPIE.

population and income are taken from FAO and WDI. Trade balances (or self-sufficiency rates) are kept constant at 1995 levels here. Changes in yields are taken from FAO production statistics. However, only the average rate of yield change across all crops in one region is used, in order to avoid occasional extreme values from the statistics (see table 6.3). The average yield of all crops across the world has increased by 1.5 percent per year between 1970 and 1995 (minimum: 0.04 percent in FSU, maximum: 2.69 percent in CPA). The value for CPA (i.e. China) is remarkable as it is equivalent to a doubling of yields within 26 years.

The link between two periods in the model is established through the land-use pattern. The optimized land-use pattern of one period is taken as the initial land constraint in the next. If necessary, additional land from the non-agricultural area can be converted into cropland at additional costs. Hence, the model works to a certain extent in a recursive dynamic mode.

6.6 Validation Results for 1970

Based on these inputs, the model is solved for 1995 and 1970 sequentially and cropland shares are evaluated against observed data. Globally, MAgPIE simulates the share of cropland in total area to be 19 % smaller than recorded in the land-use data of Ramankutty and Foley [1999] for 1970. However, the correspondence of simulated and observed cropland share differs between regions (table 6.2, figures 6.5, 6.6).

In most regions, the simulated cropland shares agree reasonably well with observed records (see figure 6.5), however, there are larger mismatches between simulated and recorded cropland shares in AFR, FSU, and SAS. In these regions, the share of cropland in total area is significantly underestimated. This dominates the global underestimation of the share of cropland, as the size of their cropland area is large in absolute numbers (see figure 6.6), especially in FSU and SAS, accounting for the largest part (16 %) of the overall mismatch (19 %). In the recorded data, cropland area increases in all regions except CPA from 1970 to 1995; however, in our simulations it also decreases in EUR and NAM (see figure 6.9). Moreover, a spatial concentration in the simulated land-use patterns can be observed in 1995 (e.g. on the US-Canadian border and in south-east Africa), while agricultural production is partially shifted from south-east LAM to north-west LAM in 1995 and 1970 (figures 6.10, 6.7).

However, these mismatches between recorded and simulated land-use patterns can be explained. First

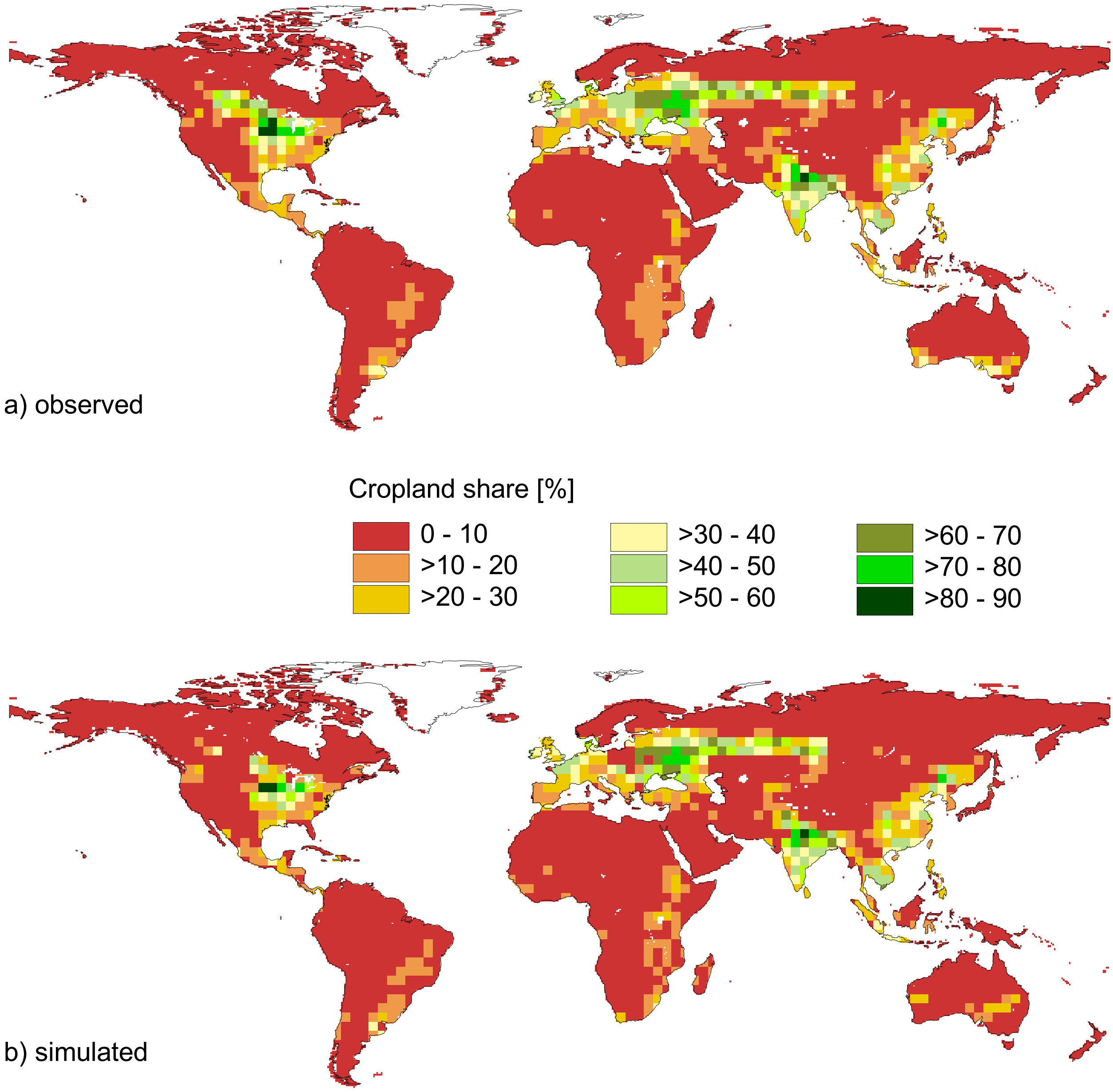

Figure 6.7: Observed (a) and simulated (b) cropland shares [%] for 1995.

of all, FSU as the main contributor to the overall mismatch (6.9 % globally) has undergone significant political and economic changes between 1970 and 1995 that are not accounted for in our data: The political transition from the communist regime has presumably affected the quality of data recorded, but has also strongly affected agricultural production, trade, and the relationship of caloric intake and income due to huge price distortions. Using self-sufficiency ratios of 1995 also for 1970 and assuming low consumption rates because of low nominal GDP values does not adequately represent the situation of agricultural production and demand in FSU in 1970.

Contrary to the observed trend in EUR and NAM, simulated agricultural area is larger in 1970 than in 1995. This can be explained by changes in the net trade positions of these regions during this period (which we have not considered here). Due to high

Table 6.3: Relative yield changes from 1970 to 1995 [FAO, 2001].

	World	AFR	CPA	EUR	FSU	LAM	MEA	NAM	PAO	PAS	SAS
Average all crops	1.50	0.64	2.69	1.40	0.04	1.71	1.91	1.22	1.08	1.66	1.79
Temperate cereals (food/feed)	1.64	2.23	4.52	1.71	0.20	2.08	2.69	0.76	1.42	-0.21	2.68
Maize (food/feed)	1.98	0.96	3.65	1.85	-0.29	2.27	2.44	1.73	3.16	2.37	1.36
Tropical cereals (food/feed)	0.66	0.46	3.18	2.22	-1.03	1.31	0.76	0.83	0.32	0.76	1.80
Rice, paddy	1.87	0.70	2.34	0.94	-1.00	2.34	1.32	1.05	0.75	1.72	1.99
Soybean	1.43	1.98	2.02	3.60	0.30	2.15	2.68	1.36	1.31	1.71	2.65
Rapeseed	2.09	1.17	2.79	1.34	-1.89	0.65	0.00	1.10	0.99	2.05	2.12
Groundnuts in shell	1.56	0.14	3.19	-0.51	5.48	1.58	1.14	1.04	0.91	1.18	1.15
Sunflower seed	0.15	1.32	2.74	0.22	-1.32	3.56	0.39	1.55	0.95	0.00	-1.83
Oilcrops, other	3.26	0.49	2.31	-0.84	0.55	4.43	0.06	1.82	2.64	2.45	2.61
Pulses, total	0.69	0.40	1.74	3.44	-0.01	0.45	-0.31	0.86	-0.57	1.25	0.54
Potato	0.52	0.67	1.08	0.79	-0.18	1.89	2.14	1.56	1.66	1.70	2.20
Cassava sweet potato	0.65	1.07	1.53	0.99	0.00	-0.46	0.08	1.94	0.87	1.41	1.53
Sugar cane	0.61	-0.94	1.27	-0.14	0.00	0.68	0.23	-0.56	0.70	-0.52	1.19
Sugar beet	0.51	0.00	2.65	0.92	-1.00	2.44	1.16	0.45	1.13	0.00	2.70
Vegetables, fruits	0.75	0.36	0.45	0.64	0.17	0.10	0.99	1.37	0.43	1.65	1.13
Fiber crops, primary	1.55	1.00	2.71	1.79	0.08	2.07	1.03	1.59	2.78	-0.28	1.32
Tree crops	1.07	0.39	1.07	0.00	0.00	0.72	-1.08	5.47	0.00	1.27	1.72

and even increasing levels of subsidization, NAM has become a larger exporter and EUR has turned from a net importer to a net exporter in some important products. By prescribing the higher self-sufficiency rate from 1995 to 1970, we force the model to produce more in these regions than actually occurred. With lower yield levels in 1970, this implies larger crop areas. As global trade has to be balanced in total, too much production in EUR and NAM in 1970 in the model implies too little production in other regions. This partly explains low crop areas in regions like AFR, FSU and LAM. In additional runs we were able to confirm the distorting effect of fixed trade patterns by relaxing the constraints on regional self-sufficiency. As a result, cropland decreased in EUR and NAM, as regions with high production costs, and increased in FSU and AFR as regions with low production costs. These effects improve regional and overall model simulations. However, simply relaxing the constraints on trade does not compensate for lacking data on trade patterns. This simply causes a shift from regions with high production costs to regions with low production costs, which is not necessarily a realistic trade pattern.

The largest spatial shifts in agricultural production can be observed in AFR and LAM. This may be explained by inadequate spatial patterns of crop yields simulated by LPJ/mL in these regions. Another factor may be that market and production structures in poorer countries are not well represented in the model. With high levels of subsistence agriculture, low levels of productivity, and limited market access, land use patterns are more diverse than can be represented by broad rotational constraints and aggregate regional demands in our model. As the optimization model tends to specialize, it will always concentrate agricultural production in the most productive cells of a region as much as possible, which is the case for example in AFR and LAM (figures 6.10, 6.7).

The regional average crop mix within the cropland area is represented well by the model (figures 6.11, 6.12), even in the regions with larger errors in the simulation of total cropland shares (see table 6.2, figure 6.5).

Besides supplying spatially explicit land-use pat-

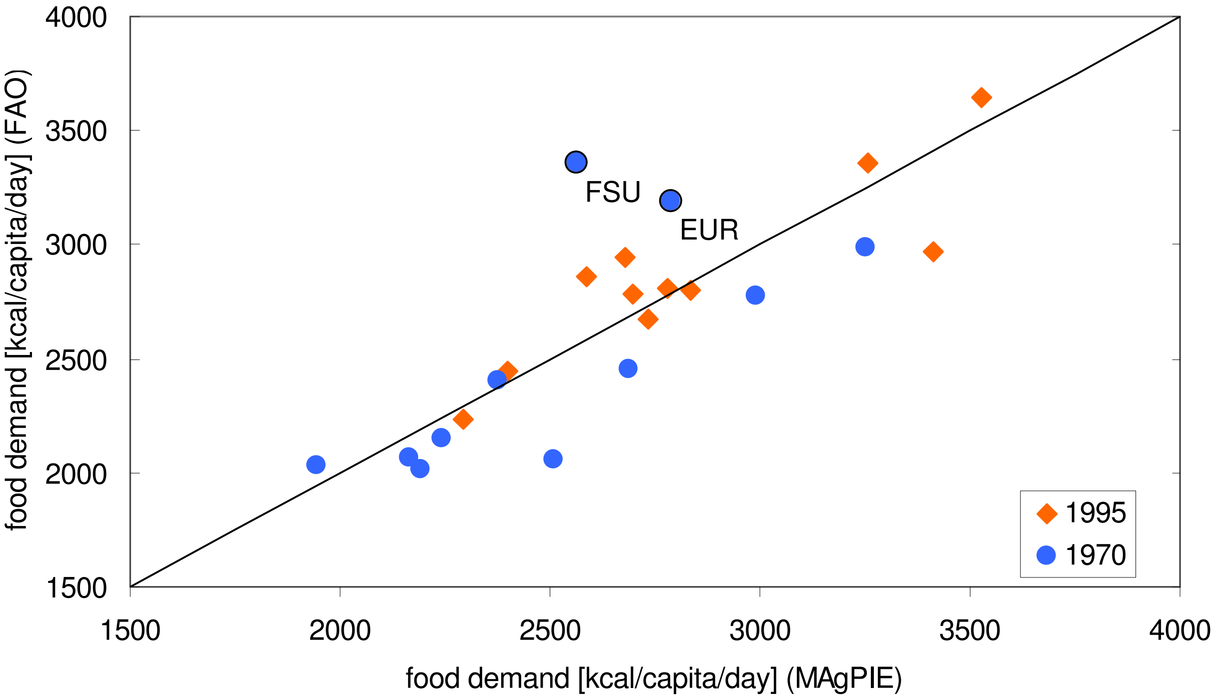

Figure 6.8: Food demand agreement between observed [FAO, 2001] and simulated regional food demand. The underestimation of food demand for EUR (including east Europe) and FSU in 1970 (black circles) are caused by price-distortions in food markets in the social market economy.

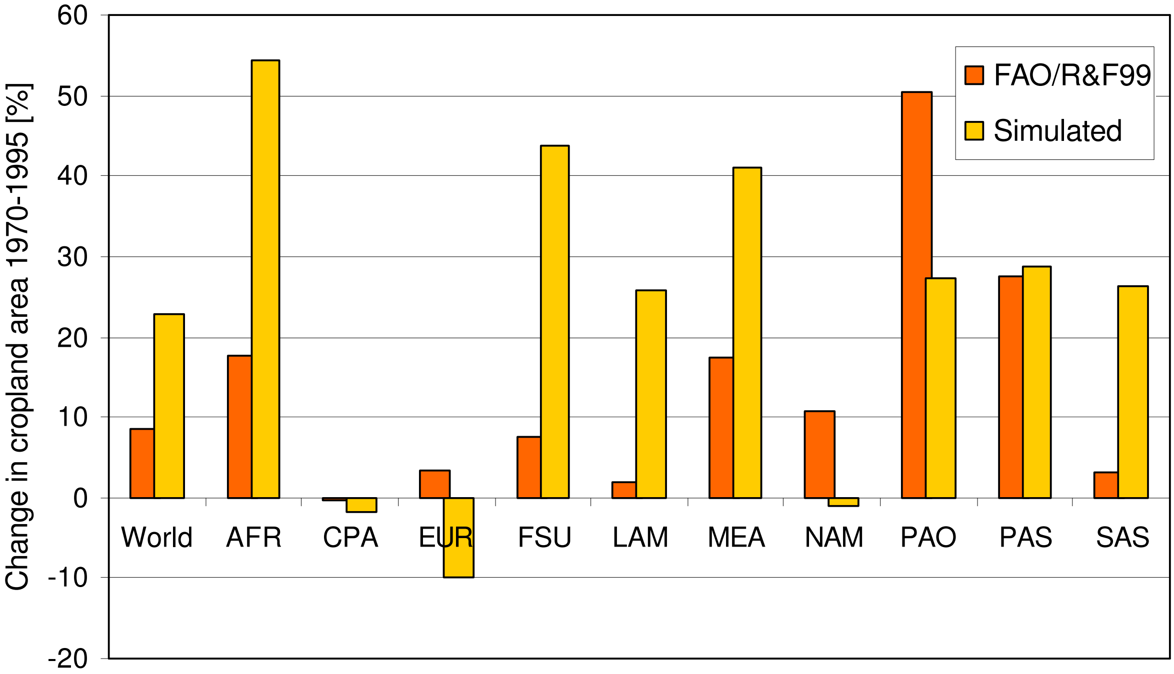

Figure 6.9: Development of cropland area from 1970–1995 relative to 1995 [%].

terns, MAgPIE allows for valuating supply side constraints such as water shortages or trade limitations. Figure 6.13 shows the shadow price for irrigation water in US\$/m^3 for all cells, in which water is available, but in amounts that are limiting to agricultural production. MAgPIE assigns a shadow price for irrigation water to all grid cells where water availability constrains agricultural production. The value of the

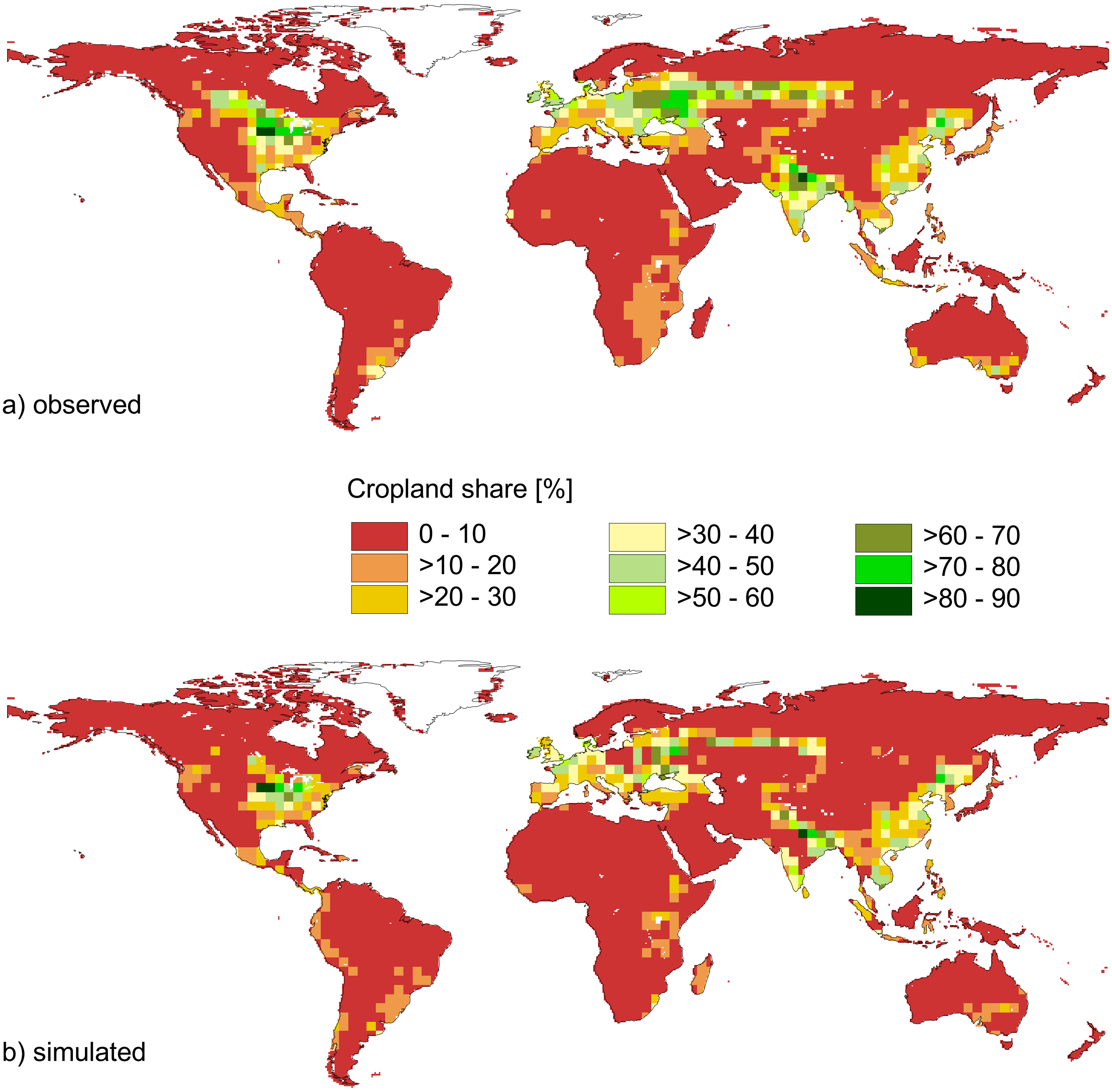

Figure 6.10: Observed (a) and simulated (b) cropland shares [%] for 1970.

shadow price is equivalent to the overall reductions in production costs that would be possible if water availability within this cell would increase by 1 m^3.

6.7 Discussion and Conclusions

We here present a globally applicable land-use model that computes spatially explicit land-use patterns by processing data on population, demand, and production costs with spatially explicit environmental data on crop yields and water availability for irrigation. By reproducing the historical land-use pattern of 1970, we could demonstrate that the overall performance of MAgPIE is satisfactory, although only data that would be also available for future projections have been used.

The structure of MAgPIE facilitates a harmonization of the differences in thematic, temporal,

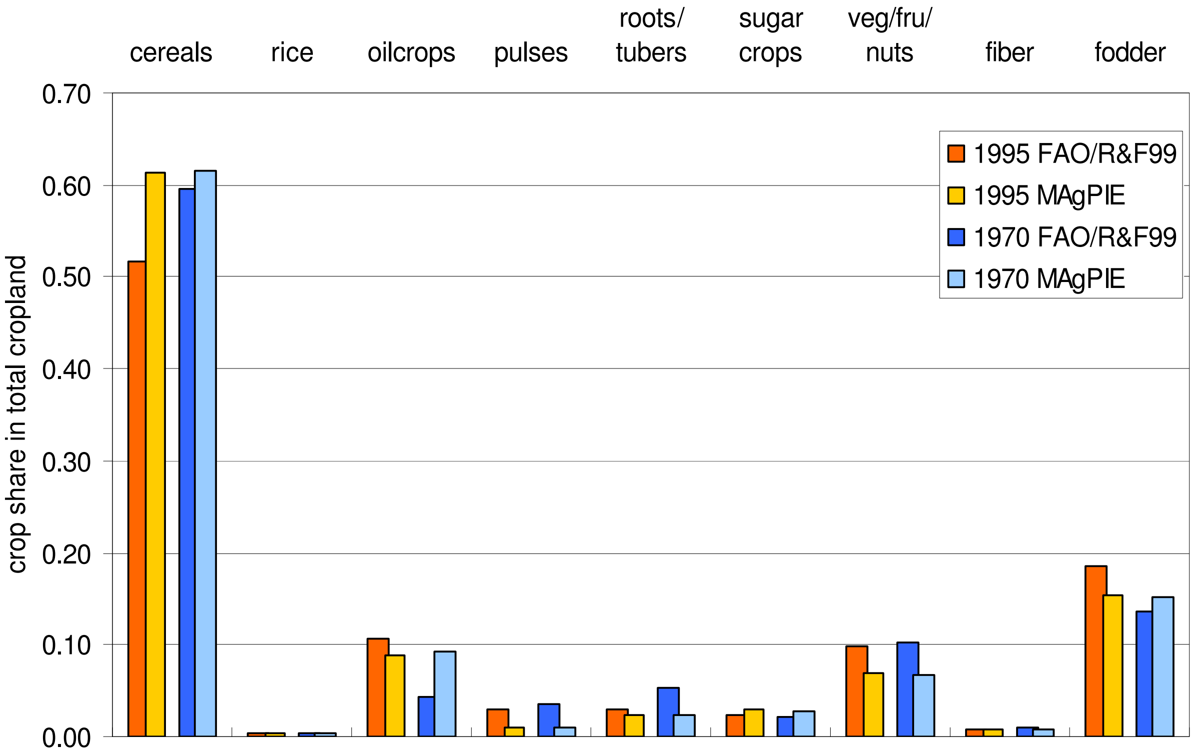

Figure 6.11: Crop shares in total cropland (EUR) as observed (red 1995/orange 1970) and simulated by MAgPIE (dark blue 1995/light blue 1970).

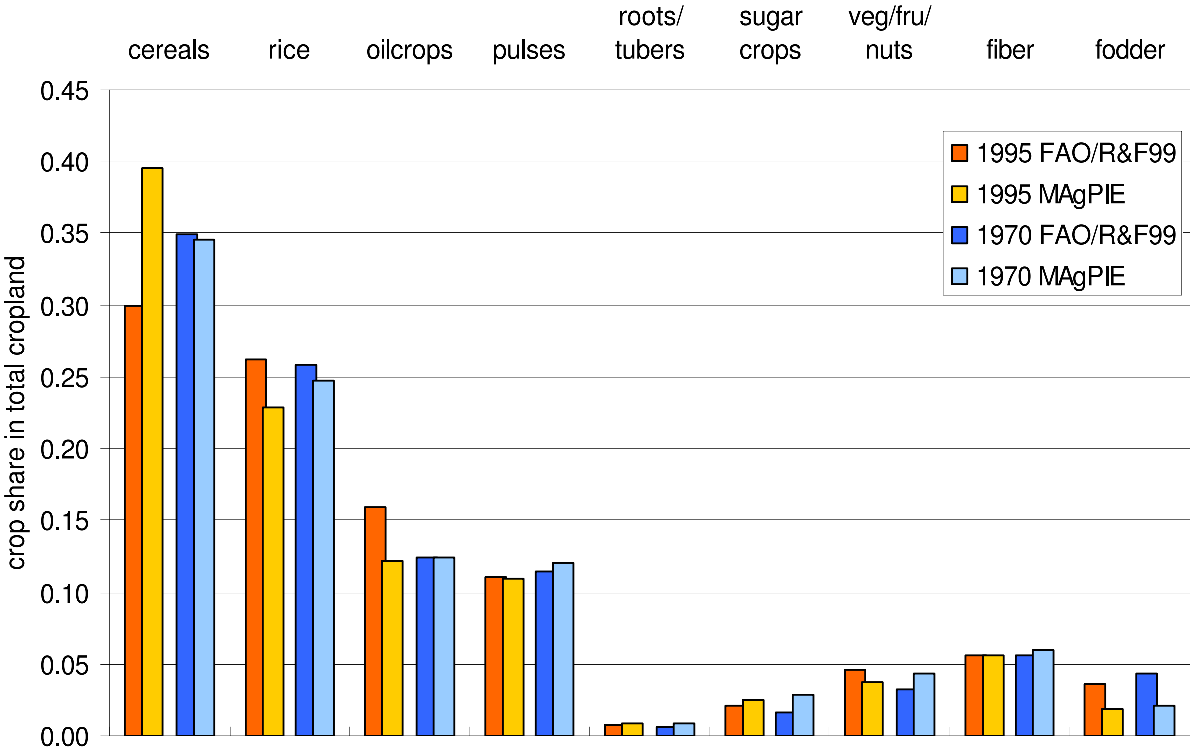

Figure 6.12: Crop shares in total cropland (SAS) as observed (red 1995/orange 1970) and simulated by MAgPIE (dark blue 1995/light blue 1970).

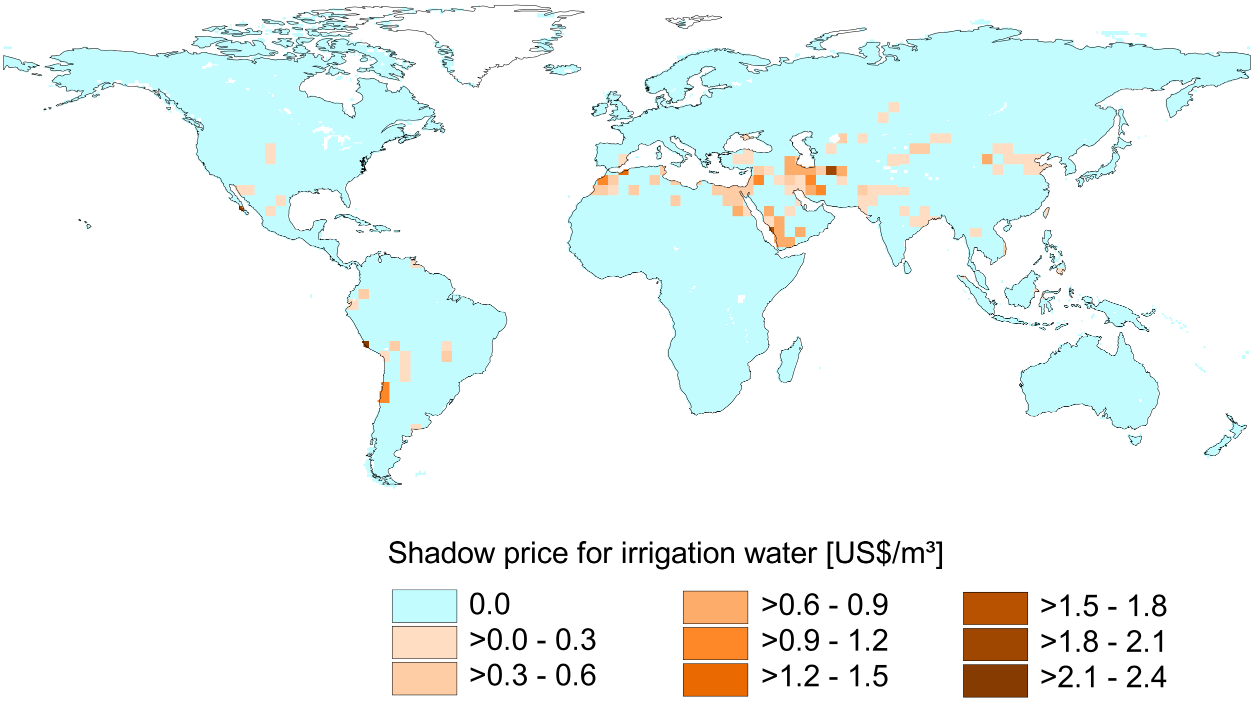

Figure 6.13: Shadow price for irrigation water [US$/m^3] in 1995 as simulated by MAgPIE. Shadow prices are shown only in grid cells where irrigation water is available but in limited amounts only. If sufficient irrigation water is available, the shadow price is zero by definition.

and spatial scales of economic and environmental sciences. Environmental data are supplied by the Lund-Potsdam-Jena DGVM for managed Lands (LPJ/mL). LPJ/mL has implemented a concept of crop functional types that represent groups of crop types that are similar in their physiological behavior and does not differentiate single crops such as rye, barley and wheat, which are jointly represented as ”temperate cereals”. This helps to bridge the gap between aggregated economic data and simulated yields, but does not resolve all thematic problems such as in the case of oil crops. Since MAgPIE is a linear optimization model, it automatically chooses the most efficient CFT in the most productive grid cells in order to satisfy a demand that can be supplied by several CFTs. The most efficient CFT in terms of production costs does not reflect all factors that influence the crop choice. It can be assumed, however, that field crops that strongly differ physiologically, as oil palms differ from sunflowers, also strongly differ in their environmental requirements and their potential acreage does not largely overlap.

MAgPIE computes spatially explicit land-use data on a geographic grid of 3.0x3.0° resolution. This is a trade-off between computational feasibility and accounting for sub-regional spatial heterogeneity of land suitability. DGVM simulations of terrestrial biogeochemical budgets are robust against reductions in spatial resolution, as shown by Müller and Lucht [2007, see Chapter 5], but information on spatial heterogeneity is lost when the spatial resolution is reduced. Computational requirements of the optimizer currently prevent finer spatial resolutions. Nonetheless, this is a straightforward approach to generate spatially explicit land-use patterns as a result of economic considerations.

However, the simulation of the historical land-use pattern of 1970 also revealed some drawbacks of the modeling concept: As an optimization model, MAgPIE tends to underestimate area demand because of overspecialization. This is partially prevented by several constraints on the production side, such as rotational constraints and constraints on the maximal land-conversion rate. However, under decreasing area demand, the optimizer is free to rearrange the spatial pattern of agricultural production within the initial, larger, land budget. This favors overspecialization as the production is less constrained, which may also be the case in future projections but was not the case in the historical development from 1970 to 1995, where total cropland actually increased instead of the decrease in our backcast validation.

Trade patterns and the relationship of caloric intake per available income have not been adopted to the situation of 1970 because the validation was carried out under strict utilization of data that are available for long-term future projections as well. This leads to an underestimation of the size of cropland area in AFR, FSU, LAM, MEA, and SAS, demonstrating the importance of these factors. However, as long as there are no long-term projections of detailed economic data on trade, demand and production patterns, land-use patterns will generally have to cope with these limitations.

Essential socio-economic inputs for MAgPIE are data on population and GDP per capita only. Demand is derived from population and the empirical relationship of income and food consumption. Both population growth and GDP development are available as long-term projections. So far, data on regional patterns of production costs [US$/ha] are kept constant. This is certainly unrealistic, however, long term projections of detailed data on agricultural demand, supply and production are not available and production cost structures are of secondary importance only: The crop mix is only largely affected by production costs if several crops that satisfy the same demand category are comparable in yields. Trade patterns are also constrained by minimum self-sufficiency ratios; however, regional differences in production costs will likely determine what regions will be net exporters. It may be a promising approach to investigate the relationship between agricultural production costs and GDP development in order to make production costs more consistent with the economic development of a region.

The model structure of MAgPIE harmonizes the differences between biospheric and economic models. Offline coupling to the biospheric model LPJ/mL has been achieved in an offline mode already and yields the potential to directly compute biospheric limitations such as freshwater availability that is affected by land-use in upstream cells. On the economic side, coupling has not been tested yet, but is supported by the model structure. If coupled to economic growth models, such as the MIND model [Edenhofer et al., 2005], coupling can only be achieved via iterative computations. Since the model needs to be quickly computable for iterations, the coupling to these models may require further reductions in the complexity of MAgPIE or prevent the inclusion of additional aspects.

MAgPIE in its present form accounts for several driving processes of land-use change. Furthermore, the model structure supports the inclusion of additional processes that have not been implemented yet: So far, the agricultural land equipped for irrigation is distributed proportionally to the crops produced there. This is not realistic since crops are usually irrigated balancing the crop specific requirements and environmental conditions. The model structure of MAgPIE allows for a separation of rain-fed and irrigated production as well as other management options in different production activities. However, economic data to parameterize these management separations are not available as these are provided in aggregate form only. Consequently, this inclusion of more detail also increases parameter uncertainty of the model.

Other land-intensive goods such as wood and timber but also biofuels can be included in the model without additional structural changes. This requires a parameterization of these production activities and additional demand categories. If these sectors are included as well, MAgPIE internally computes their competition with food production for fertile land.

The linear-programming technique is powerful, flexible, and computationally very efficient. However, some of the driving processes are not included because they are not supported by the linear model structure. A non-linear programming approach is required to enable more complex structures of biophysical constraints: In the case of water it would be useful to include stocks of natural resources to be managed over time.

Overall, MAgPIE performs satisfactorily well and can be applied to project future land-use patterns based on projections of trade, population and environmental conditions. This allows for long-term future projections under changing environmental and socio-economic conditions. By generating spatially explicit land-use data, MAgPIE can provide essential inputs for assessing the effects of land-use change on the terrestrial biosphere. The valuation of binding constraints allows for an economic analysis of biospheric constraints on agricultural production. This is unique in globally applicable land-use models, especially as MAgPIE explicitly considers water as an essential input to agricultural production. However, the simplifying assumptions on trade, demand and production costs have been shown to affect the regional performance of MAgPIE. Economic and environmental data are processed consistently. If coupled dynamically to an economic model that computes agricultural demand, MAgPIE directly establishes the linkage between supply side constraints and demand. So far, the general applicability of the model has been demonstrated. Inherent potentials to account for additional driving processes of land-use change have not been fully exploited yet and deserve further attention.

Appendix: MAgPIE model description

Variables

x	level of activity (21 crop activities [ha], 3 livestock acitivities [ton], 2 land conversion activities [ha], 3 input purchase activities [US$])

Parameters

c	production costs per activity unit [US$]
d_food	demand for food energy [GJ]
y_food	food energy delivery (from crops and livestock) [GJ]
y_feed	feed energy delivery (from crops and residues) [GJ]
y_fodd	green fodder energy delivery (from crops) [GJ]
y_land	land delivery (i.e. from conversion acitivites) [ha]
y_wat	water delivery (i.e. from irrigation activities) [m^3]
y_input	variable input delivery (i.e. labour, chemicals, capital) [US$]
req_feed	feed energy requirements (i.e. per ton of livestock output) [GJ]
req_food	green fodder energy requirements (i.e. per ton of livestock output) [GJ]
req_land	land requirements (i.e. cropland, pasture) [ha]
req_wat	water requirements [m^3]
req_input	variable input requirements (i.e. labor, chemicals, capital) [US$]
req_share	area to be considered for rotational constraints [ha]
land_const	available land (cropland, pasture, non-agricultural land) [ha]
wat_const	available water discharge for irrigation [m^3]
max_share	maximum crop share in average rotation [%]
self_sufficiency	minimum share of regional demand that needs to be satisfied by regional production [%]

Indices

i	number of economic regions (10)
j	number of grid cells per region (total 2178 grid cells (3.0x3.0°))
k	number of all acitivites (21 crop (kcr), 3 livestock (kli), 2 land conversion (klc), 3 input purchase (kin) activities)
l	number of food energy demand categories (10)
m	number of agricultural land types (3; cropland, pasture, non-agricultural land)
n	number of rotational constraints (10)

Goal function

Goal function of MAgPIE is the minimization of total costs of production, C, summed over all regions:

$$C = \sum_i \sum_j \sum_k x_{i,j,k} * c_{i,k} \tag{6.1}$$

subject to

Global constraints

Food energy demand (minimum constraint; for all l demand types):

$$\sum_i \sum_j \sum_k x_{i,j,k,l} * y\_food_{i,j,k,l} \geq d\_food_{i,l} \tag{6.2}$$

(similar for fiber and bioenergy)

Regional constraints (for all i regions)

(Note: all k activities are included in all constraints in order to reduce the number of indices; however, many of the parameter values may be zero.)

Minimum trade balance (regional supply ≥ regional demand * self-sufficiency rate):

$$\sum_j \sum_k x_{i,j,k} * y\_food : i, k, k \geq d\_food_{i,l} * self\_sufficiency_{i,l} \tag{6.3}$$

(similar for fiber and bioenergy)

Feed energy balance (regional demand ≤ regional supply):

$$\sum_j \sum_k x_{i,j,k} * (req\_feed_{i,k} - y\_feed_{i,j,k}) \leq 0 \tag{6.4}$$

Green fodder balance (regional demand ≤ regional supply):

$$\sum_j \sum_k x_{i,j,k} * (req\_fodd_{i,k} - y\_fodd_{i,j,k}) \leq 0 \tag{6.5}$$

Input purchase balance (regional demand ≤ regional supply; for all kin inputs):

$$\sum_j \sum_k x_{i,j,k} * (req\_input_{i,k,kin} - y\_input_{i,j,k,kin}) \leq 0 \tag{6.6}$$

Cellular constraints (for all j cells):

Land constraints (for all m land types):

$$\sum_k x_{i,j,k} * (req\_land_{i,k,m} - y\_land_{i,j,m}) \leq land\_const_{i,j,m} \tag{6.7}$$

Land conversion constraint:

$$\sum_k x_{i,j,k} * y\_land_{i,j,m} \leq land\_const_{i,j,"non-agri."} \tag{6.8}$$

Rotational constraints (for all n constraint types):

$$\sum_k x_{i,j,k} * req\_share_{i,k,n} \leq max\_share_{i,n} * land\_const_{i,j,"cropland"} \tag{6.9}$$

Water constraints:

$$\sum_k x_{i,j,k} * (req\_wat_{i,k} - y\_wat_{i,j}) \leq wat\_const_{i,j} \tag{6.10}$$

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Abbreviations and Units

Abbreviations

AEZ	Agro-Ecological Zones
AFR	Sub-Saharan Africa
CC	Simulations with changes in Climate and atmospheric Carbon dioxide concentrations, but static land-use patterns
CCL	Simulations with changes in Climate, atmospheric Carbon dioxide concentrations, and land-use patterns
CFT	Crop functional type
CGE	General Equilibrium Model
CPA	Centrally-planned Asia including China
CRU	Climate Research Unit of the University of East Anglia, UK
DGVM	Dynamic Global Vegetation Model
EUR	Europe including Turkey
FSU	Newly Independent States of the Former Soviet Union
GCM	General Circulation Model
GDP	Gross Domestic Product
GWP	Gridded Population of the World
HC	Harvested Carbon flux
IAM	Integrated Assessment Model
IMAGE	Integrated Model to Assess the Global Envrionment
IMPRS-ESM	International Max Planck Research School on Earth System Modelling
LAM	Latin America
LPJ	Lund-Potsdam-Jena Dynamic Global Vegetation Model
LPJ/mL	Lund-Potsdam-Jena Dynamic Global Vegetation Model for managed Lands
MAgPIE	Management model of Agricultural Production and its Impact on the Envrionment
MEA	Middle East/North Africa
MF	Management Factor
NAM	North America
NEE	Net Ecosystem Exchange
NPP	Net Primary Production
NUTS2	Nomenclature of Statistical Territorial Units, level 2
PAO	Pacific OECD including Japan, Australia, New Zealand
PAS	Pacific (or Southeast) Asia
PEM	Partial Equilibrium Model
PFT	Plant functional type
$\mathbf{R_h}$	Heterotrophic respiration (soil respiration)
SAS	South Asia including India
SRES	Special Report on Emission Scenarios

Important Units

GJ	Giga Joule (10^9 Joule)
ha	hectare (100x100m)
km	kilometer (10^3 m)
m	meter
Pg	Peta-gram (10^{15} grams)
PgC	Peta-grams Carbon
t	metric ton (10^6 grams)
US$	Dollars of the United States of America

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Berichte zur Erdsystemforschung Nr.3 Juli 2004	**A Multi-Actor Dynamic Integrated Assessment Model (MADIAM)** Michael Weber
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