

Earth System Dynamics in the Anthropocene

Modelling Key Processes of Climate-Human Interactions
in the Terrestrial Biosphere

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Silke, Jonas and Mattis - Without you I'm nothing ...

Abstract

Human activities, primarily the combustion of fossil fuels and the global modification of the land surface, are transforming the Earth System at unprecedented scale. Climate change and the overexploitation of natural resources may soon overwhelm the adaptive capacities of many ecosystems and societies, which could lead to substantial losses in human well-being and political destabilization. Science has a responsibility to provide society with the scientific basis for the social and political discourse about a possible transition towards global sustainability. This requires, *inter alia*, fundamental knowledge about mechanisms and feedbacks in the Earth System that may lead to significant large-scale changes in environmental conditions and which are therefore of crucial importance for the future development of nature and society. In this context, it is the goal of this thesis to contribute to a better understanding of the most important global drivers that will determine the future of the land biosphere during this century: climate change and human land use.

Based on a Dynamic Global Vegetation Model (DGVM), the first part of this thesis examines two large climatic disturbances of the terrestrial carbon cycle that were observed during the last three decades. These analyses focus on the effects of changes in temperature, precipitation and radiation after the eruption of Mount Pinatubo in 1992/93 and during the strong 1997-1998 El Niño event on plant productivity and soil decomposition. Results indicate that increased carbon storage in the land biosphere explains the most part of the atmospheric CO₂ anomaly. The strengthening of the terrestrial carbon sink results from a very heterogeneous spatial pattern of changes in carbon uptake and release by vegetation and soils.

The second part of this thesis addresses the worldwide increasing demand for bioenergy that may become the most important driver of future land use change due to the large area requirements of biomass cultivation. A combination of vegetation modeling and spatial data analyses is used to assess global bioenergy potentials that consider various sustainability requirements for food security, biodiversity protection and the reduction of greenhouse gas emissions and to evaluate the environmental impacts of large-scale energy crop cultivation. The results indicate that bioenergy may provide between 15 and 25% of the global energy demand in 2050. Exploiting these potentials, however, requires the conversion of another 140-450 Mha of natural vegetation into agricultural land, affecting a large number of ecosystems that have already been fragmented and degraded and provide habitat for many threatened and endemic species.

Zusammenfassung

In nie dagewesener Größenordnung greift der Mensch durch die stetig zunehmende Verbrennung fossiler Energieträger und der weiträumigen Umgestaltung der Landoberfläche in die globale Umwelt ein. Klimawandel und Übernutzung natürlicher Ressourcen könnten schon in diesem Jahrhundert die Anpassungsfähigkeiten vieler ökologischer und sozialer Systeme übersteigen und somit zu gesellschaftlichen Konflikten und politischer Destabilisierung führen. Die Wissenschaft steht daher in der Pflicht, eine Informationsbasis für den politischen und gesellschaftlichen Diskurs über einen möglichen Übergang in eine nachhaltige Zukunft zu schaffen. Notwendig dafür ist unter anderem ein grundlegendes Verständnis der Mechanismen und Wechselwirkungen im Erdsystem, die zu großräumigen und bedeutsamen Veränderungen der Umweltbedingungen führen können und damit für die zukünftige Entwicklung von Natur und Gesellschaft von entscheidender Bedeutung sind. Vor diesem Hintergrund soll diese Studie zu einem besseren Verständnis der wichtigsten globalen Triebkräfte beitragen, die die Entwicklung der terrestrischen Biosphäre in diesem Jahrhundert prägen werden: Klimawandel und menschliche Landnutzung.

Auf der Basis eines Dynamischen Globalen Vegetationsmodells werden im ersten Teil der vorliegenden Arbeit zwei große klimatische Störungen des globalen Kohlenstoffkreislaufs untersucht, die innerhalb der letzten drei Jahrzehnte beobachtet wurden. Im Fordergrund steht die Frage, wie sich die veränderten Temperatur-, Niederschlags- und Strahlungsbedingungen nach dem Ausbruch des Pinatubo 1992/93 und während des starken El Niño Ereignisses von 1997/98 auf pflanzliche Produktivität und Zersetzungsprozesse im Boden auswirkten. Es zeigt sich, dass vermehrte Kohlenstoffspeicherung in der Landbiosphäre den überwiegenden Teil der atmosphärischen CO₂ Anomalien erklärt. Die Stärkung der terrestrischen Kohlenstoffsänke ergibt sich aus einem räumlich äußerst heterogenem Muster von veränderter Kohlenstoffaufnahme und -abgabe durch Vegetation und Böden.

Der zweite Teil dieser Arbeit beschäftigt sich mit der weltweit steigenden Nachfrage nach Bioenergie, die aufgrund des flächenintensiven Anbaus von Biomasse zur wichtigsten Triebkraft für zukünftige Landnutzungsänderungen werden könnte. Aus der Kombination von Vegetationsmodellierung und räumlichen Datenanalysen werden globale Bioenergiepotentiale unter Berücksichtigung verschiedener Nachhaltigkeitsanforderungen für Ernährungssicherheit, Schutz von Biodiversität und Reduktion von Treibhausgasemissionen bestimmt und mögliche ökologische Auswirkungen des großräumigen Anbaus von Energiepflanzen abgeschätzt. Für das Jahr 2050 könnten demnach 15 bis 25% des weltweiten Energiebedarfs durch Bioenergie abgedeckt werden. Dafür müssten allerdings weitere 140-450 Millionen Hektar natürliche Vegetation in Agrarland umgewandelt werden. Diese Landnutzungsänderungen würden zahlreiche Ökosysteme betreffen, die bereits heute degradiert und fragmentiert sind und vielfach wichtige Habitats für eine große Zahl bedrohter und endemischer Arten darstellen.

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1 General Introduction

1.1 Unsustainable interactions of humanity with their environment

The earth has reached a crossroads. With massive emissions of greenhouse gases and the unsustainable exploitation of natural resources on land and in the oceans, human activities are modifying the global environment in manifold ways, pushing parts of the Earth System beyond their range of natural variability. If these trends continue unabated, human well-being may deteriorate significantly during the coming decades, because many ecologic and socio-economic systems will be overwhelmed by the expected magnitude and rate of changes in climate and other environmental conditions.

Humans have always altered their local environments, but driven by the growing needs of a rapidly expanding and increasingly affluent world population, human impacts on the Earth's ecosystems since the mid 20th century have become unprecedented in magnitude and scale. Present atmospheric CO₂ levels are nearly 40% above preindustrial values [Canadell et al., 2007], as illustrated by the iconic 'Keeling curve' (Fig. 1.1). About 35% of the total historic CO₂ is directly linked to changes in land use [Houghton, 1999].

More than 75% of the earth's ice-free land surface has already been directly modified by human action [Ellis and Ramankutty, 2008, Sanderson et al., 2002] and about a quarter of the terrestrial primary production is harvested for food and fibre [Haberl et al., 2007]. Intensive land use practices led to a doubling of reactive nitrogen at the land surface [Schlesinger, 2009], significantly altered the global water cycle [Gedney et al., 2006, Piao et al., 2007, Rost et al., 2008a] and escalating biodiversity loss is driving the 6th major extinction event [Sala et al., 2000, Thomas et al., 2004]. From an Earth System perspective these processes are worrying, because atmosphere, terrestrial ecosystems and the oceans form a tightly coupled system with numerous feedback mechanisms and teleconnections. Once critical thresholds are surpassed, which may already have happened in some cases [Hansen et al., 2008], the Earth System can switch into a qualitatively different state with extreme events and rates of change that would surmount the resilience of many human and environmental systems, overwhelming any well-planned adaptation measures [Lenton et al., 2008, WBGU, 2007]. Increasing global disparity in terms of wealth, security, fundamental rights, and future prospects add to the uneven distribution of vulnerability and risk.

At the beginning of the 21st century, humanity has evolved into a geologic force with global extent that is reshaping the entire planet. This epoch of largely unregulated rapid expansion and resource exploitation is therefore called the Anthropocene [Crutzen, 2002]. Against this background, it is clear that climate stabilization, energy security,

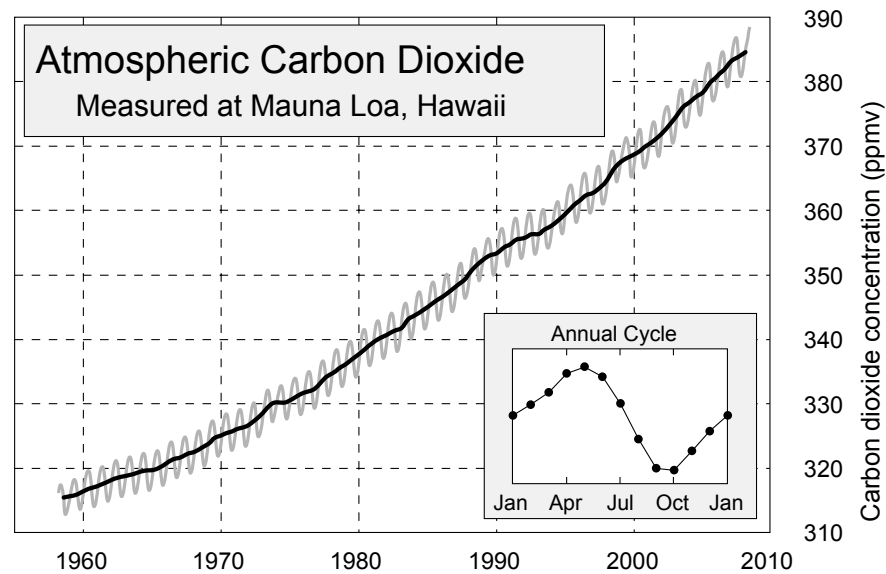


Figure 1.1: The 'Keeling curve' shows the historic rise of atmospheric carbon dioxide concentrations as directly measured at Mauna Loa, Hawaii. Annual fluctuations are caused by seasonal variations in plant photosynthesis with more carbon dioxide being removed from the atmosphere during the Northern Hemisphere summer. The average annual cycle is shown in the inset figure. Source: http://en.wikipedia.org/wiki/Keeling_curve.

the conservation of biological diversity and thus long-term human well-being can only be achieved with a radical transformation of the entire industrial metabolism, aimed at a low-carbon energy infrastructure and intelligent global environmental management. But the time left to reduce emissions drastically in order to confine global temperature rise to 2°C above pre-industrial levels and thus prevent unmanageable changes in climate is rapidly running out [Allen et al., 2009, Meinshausen et al., 2009, Schneider, 2009, Smith et al., 2009, Solomon et al., 2009].

1.2 Earth System Analysis

It is an open question if societal and political will, socioeconomic and institutional capacities and the speed of technological innovation will be sufficient for a conscious transition towards a sustainable use of the Earth and its limited resources. Ultimately it is society as a whole that must take responsibility and make a clear decision about the norms and values that shall guide the future development of planet Earth. Science plays an important role in this process, because it can support decision making by delivering sound information regarding the complex processes and interactions within the earth system [Kates et al., 2001, Schellnhuber et al., 2005]. We need to understand what kind of changes in the earth system may occur over the next decades due to human activities and which accessible pathways towards global sustainability exist.

Science has responded to this challenge by proposing a new contract with society [Lubchenco, 1998] that involves the emergence of novel research strategies known as Earth System Science [Schellnhuber, 1999], Sustainability Science [Kates et al., 2001] or Land Change Science [Turner et al., 2007] as essential elements of global environmental change and sustainability research. In 2001, the Global Analysis, Interpretation and Modeling Task Force (GAIM) formulated 23 overarching questions [Sahagian and Schellnhuber, 2002] that define the overall context for systems-level research of the complex Earth system. Because of the wide variety of analytical, operational, normative and strategic components of global sustainability that will determine the long-term viability of socially shaped relationship between humans and nature, Earth System Analysis deploys an entire toolkit of existing and developing techniques to study the functioning of the coupled Earth system.

1.2.1 Tools and Methods in Earth System Science

Earth System Science is problem-driven, integrative, interdisciplinary and uses a multitude of scientific methodologies to study the complex interactions of nature and societies within the earth system, covering a wide range from fine detailed studies of small scale processes within the Earth' physical, biological and human systems to the holistic view of macro scaled features at the planetary scale. All of these methodologies have specific strengths and weaknesses regarding measurable quantities, accuracy, as well as spatial and temporal resolution. With respect to terrestrial ecosystems, which are the main subject of this thesis, the most important approaches are paleo-science, ground-based measurements, remote sensing, laboratory experiments and computer modeling.

Most of our current knowledge and concepts about major transitions and the long-term dynamics of the Earth, such as the origin of oxygenic photosynthesis [Canfield, 2005], great oxidation [Kump, 2008] or the Paleocene-Eocene Thermal Maximum [Kennett and Stott, 1991, Zachos et al., 2003], is based on paleoscientific reconstructions of past environments that used records from sediments, fossils and ice cores. These analyses are, however, based on relationship between estimated quantities and proxy data from ocean and lake sediments, tree rings, ice cores, fossil pollen, corals and historical records with very heterogeneous coverage in time and space, so that especially very old proxy variables are subject to large uncertainties and scientific dispute.

Comprehensive and reliable data from contemporary earth observation (EO) and monitoring is regarded as a key component of sustainable development [UNEP, 2007], because it provides a wide array of information and measurements of natural and artificial phenomena required in environmental planning, disaster monitoring and resource management. Sources of EO data include satellite and airborne remote sensing, in-situ monitoring stations and specific measurement campaigns. Ground-based observations, such as flux measurements, biomass inventories or community descriptions are generally very accurate, but are restricted to single sites or networks that do not provide global coverage in most cases. Satellite remote sensing is able to produce repeated synoptic views of large areas at frequent intervals, a major prerequisite for detecting and monitoring changes, including areas inaccessible for ground-based methods due to physical

Analytical Questions

2. What are the major dynamical patterns, teleconnections and feedback loops in the planetary machinery?
3. What are the critical elements (thresholds, bottlenecks, switches) in the Earth System?
5. What are the anthropogenic disturbance regimes and teleperturbations that matter at the Earth System level?
7. Which are the most vulnerable regions under global change?

Operational Questions

10. What levels of complexity and resolution have to be achieved in Earth System modelling?
12. What might be the most effective global strategy for generating, processing and integrating relevant Earth System data sets?
14. What are the most appropriate methodologies for integrating natural-science and social-science knowledge?

Normative Questions

15. What are the general criteria and principles for distinguishing non-sustainable and sustainable futures?
16. What is the carrying capacity of the Earth?
17. What are the accessible but intolerable domains in the co-evolution space of nature and humanity?
18. What kind of nature do modern societies want?

Strategic Questions

21. What is the optimal decomposition of the planetary surface into nature reserves and managed areas?
22. What are the options and caveats for technological fixes like geoengineering and genetic modification?

Figure 1.2: Subset of the GAIM Earth System Questions [Sahagian and Schellnhuber, 2002].

or political constraints.

Important applications include monitoring of human land use, deforestation activities and vegetation dynamics. On the other hand, many sensors cannot image Earth through clouds and under low solar angles, which limits data availability over tropical and high latitude regions. Satellite images are also contaminated by the effects of atmospheric absorption and scattering, that need to be removed in order to retrieve surface reflectances needed to correctly quantify surface properties. Empirical and radiative transfer modeling approaches used for atmospheric correction depend on information about actual atmospheric conditions that are generally not available at sufficient spatial and temporal accuracy, so that surface quantities derived from remote sensing data are subject to uncertainty. A recent attempt to overcome remaining limitations of EO data concerning their availability, quantity, quality, accuracy or geographical coverage is the GEOSS [GEO, 2009] initiative, that aims to proactively link producers and consumers of EO data and stimulate the development of new systems to close remaining gaps. The Global Earth Observation System of Systems will provide crucial information for societies in nine areas directly related to human well-being (natural and human-induced disasters, environmental sources of health hazards, energy resources, climate change and its impacts, water resources, weather forecasts, ecosystems management, sustainable agriculture and conservation of biodiversity).

Laboratory experiments are used to characterize and quantify biotic and abiotic processes that occur in natural and anthropogenic ecosystems. These include microbial, physico-chemical and plant physiological mechanisms that control the cycling of carbon, nitrogen and water within and between vegetation, soil and atmosphere, their spatial and temporal variability and the impacts of global change on these processes and their interactions. An important related question is the response of soil heterotrophic respiration (R_h) to warming temperatures that might act as a positive feedback to climate change. Laboratory soil incubation experiments are conducted to estimate the temperature sensitivity of decomposition. These studies, however, rely on curve fitting techniques [Davidson and Janssens, 2006] based on certain assumptions that are not well constrained. Similar studies therefore have therefore produced contradictory results in the past [Knorr et al., 2005, Andren et al., 2005]. In general, results from laboratory experiments are not readily transferable to the real world, because it is never possible to reproduce environmental conditions and constraints exactly.

Computer models are an essential and inseparable part of Earth System Analysis that provide a coherent frameworks to link available information from paleo studies, EO, laboratory experiments and emerging scientific concepts, a prerequisite for integrated assessment for environment and sustainability. Simulation modeling is a unique tool to illustrate the “multitude of potential planetary futures” [Schellnhuber, 1999] that result from the uncertainties in political decisions, economic development, climate change and the response of the World’s ecosystems to changes in climatic conditions, for example. In the field of global change research, a large variety of models have been developed, that range from simple stylized models to study major processes and their interactions to highly sophisticated Earth System models, that couple Dynamic Global Vegetation Models (DGVMs, see 1.2.1) with Atmosphere-Ocean General Circulation Models (AOGCMs).

1 General Introduction

Simulation experiments play a key role in global change research and thus also in political decision-making processes, as they are the basis of climate prediction, climate impact assessments and many “what if” scenarios that analyze the implications of different policy options. It is therefore very important to consider specific characteristics and uncertainties when interpreting any model results. In any case, the use of comprehensive models should support and not substitute critical thinking. Uncertainties in the simulations can arise from incomplete understanding of the modeled system or parts thereof and thus incorrect and incomplete descriptions of processes and poorly understood assumptions in a model. Further uncertainty can result from flawed and incomplete data used to parameterize a model’s process formulations, define boundary conditions and drive the model [Frigg and Hartmann, 2006, Zaehle et al., 2005]. Introducing a large number of additional constraints to attain higher empirical adequacy (i.e., agreement with observations and measurements), may obscure insufficient understanding of the underlying mechanisms or even the total lack of significant processes in a model. This study is based on a state-of-the-art DGVM called LPJmL, that is described in more detail in the following section.

Dynamic Global Vegetation Modeling in Earth System Science

Dynamic global vegetation models were originally developed to study the role of vegetation and soils in the Earth system, in particular with respect to their influence on the global cycles of carbon and water, biosphere-atmosphere interactions [Field et al., 2007] and the effects of global environmental modification due to human activities, such as land use change [Bondeau et al., 2007] and emissions of greenhouse gases [Cramer et al., 2001, Schaphoff et al., 2006]. State-of-the-art DGVMs build upon the most important processes and principles of plant geography, physiology, biogeochemistry and biophysics to represent both natural and human modified ecosystems. Most of these models are rather similar in terms of structural organization and modularity.

The world’s diversity of plants is usually represented in the form of only a few functional types, that differ in structure (trees versus herbaceous plants), photosynthetic pathway (C_3 or C_4), leaf type (broad-leaved or coniferous) and phenology (evergreen versus deciduous) and other physiological and structural characteristics. The spatial resolution of the simulations depends on the resolution of available climate, soil and land use that drive are used to drive DGVMs. The potential range of PFTs is constrained by a set of bioclimatic limits, that are based on the dependence of physiological processes related to plant growth and reproduction on climatic conditions. Multiple PFTs may co-exist and compete for resources within a single grid cell. At the heart of most of these models, the calculation of photosynthesis follows either the process-based biogeochemical approach by Farquhar [Farquhar et al., 1980] and Collatz [Collatz et al., 1992], or uses the statistical relationship between net primary productivity (NPP) and absorbed photosynthetically active radiation (APAR) in a so-called light use efficiency algorithm. NPP is the balance between carbon uptake (photosynthesis) and release (autotrophic respiration) and describes actual plant growth. Fixed carbon is the allocated to different biomass compartments (leaves, sapwood, hardwood, roots) following a set of fixed co-

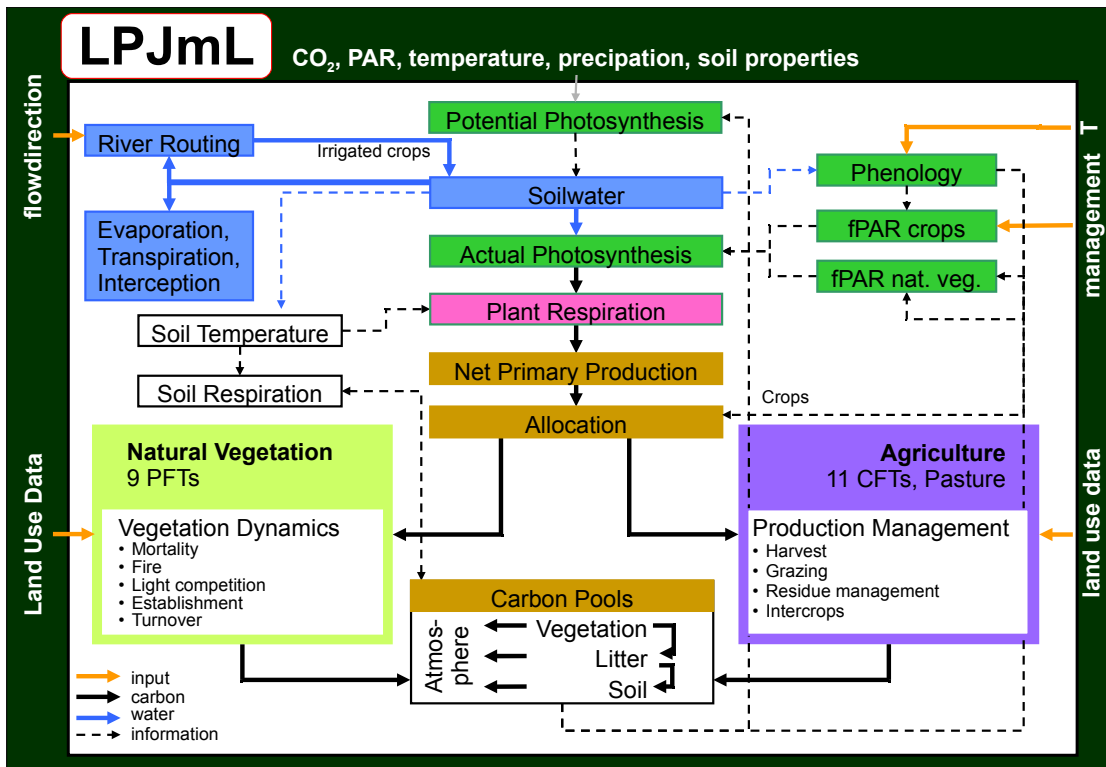


Figure 1.3: Typical structure of a DGVM. Various input data are used to drive the different ecophysiological processes considered in the model which are connected via nested loops in space and time. From Prentice et al.

efficients. Compartment specific rates of tissue turnover and plant mortality determine the flux of dead biomass into the litter pool from where it is ultimately transferred into the soil carbon pool. Fire is the most important disturbance factor on the global scale and therefore also simulated by current vegetation models. Biomass burning changes vegetation structure and distribution and is responsible for annual CO_2 emissions that are half the size of those related to fossil-fuel combustion [Bowman et al., 2009]. Most DGVMs also feature a macro scale representation of the global water cycle, including interception, soil evaporation, the influence of snow and permafrost on the seasonality of runoff [Gerten et al., 2004] and lateral water transport between grid cells [Rost et al., 2008a]. Soil organisms consume dead biomass that enters the soil, and respire CO_2 in this process. Several soil pools are generally defined for each grid cell with different decomposition rates to account for labile and more resistant soil carbon pools.

Space and time loops connect the various ecosystem processes, such as vegetation physiology, plant growth, competition and population dynamics that occur on different time scales. Fast processes like photosynthesis and transpiration are usually calculated on daily or even sub-daily time steps. Intermediate processes varying throughout the season include phenology, carbon allocation, soil respiration and are represented with a

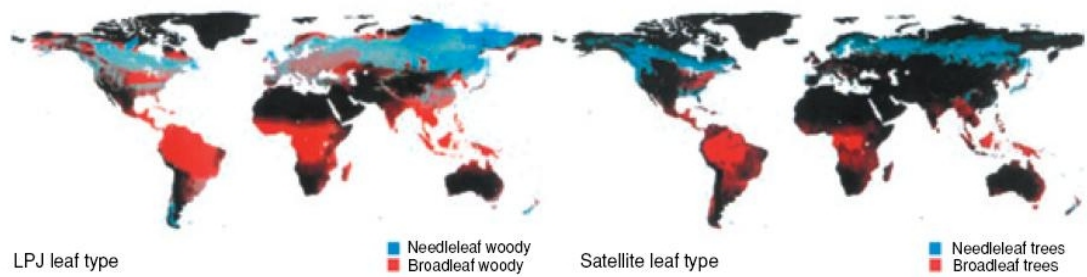


Figure 1.4: Comparison of simulated and observed distribution of woody vegetation based on LPJ data and satellite observations [Sitch et al., 2003].

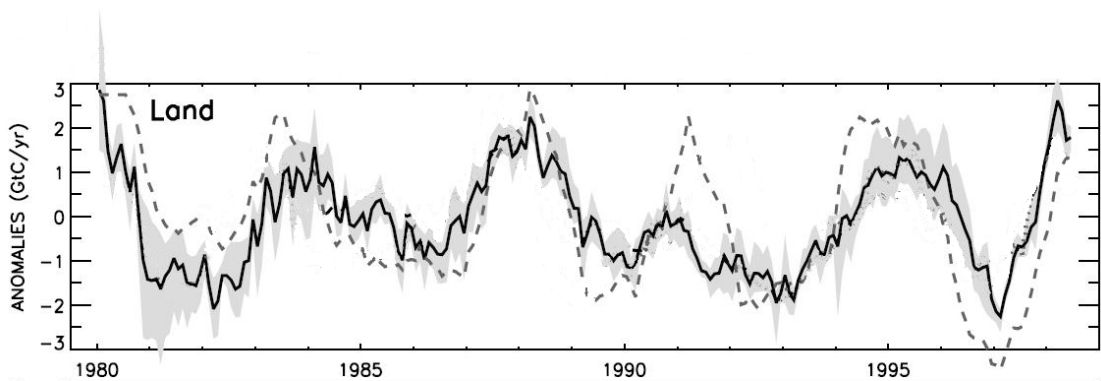


Figure 1.5: Mean anomalies of global land carbon flux anomalies during 1980 and 1998 from LPJ (dashed grey line) and atmospheric CO₂ inversions (solid black line) (modified from Peylin et al. [2005]).

time step of one month in most cases. The slowest processes represented in DGVMs, such as biomass burning, land use change and vegetation dynamics usually occur on an annual time step.

A large number of publications have been produced that test the adequacy and accuracy of DGVM simulations against various contemporary observations. The LPJ model, for example, has been compared extensively with eddy covariance measurements, atmospheric CO₂ concentration measurements, satellite remote sensing data and ground observations. Global structure and distribution of natural vegetation as simulated by LPJ largely corresponds to remote sensing based land cover maps (Fig. 1.4) and satellite measurements of LAI and FPAR were used to prove the accuracy of modeled vegetation dynamics (Fig. 1.5, Fig. 1.6, chapter 2, chapter 3).

The simulation of the terrestrial carbon cycle has been validated using flux measurements, results from inverse modeling and atmospheric measurements. It was shown that LPJ can reproduce the carbon exchange between vegetation and atmosphere and its seasonal variability [Dargaville et al., 2002, Lucht et al., 2002, McGuire et al., 2001, Peylin et al., 2005, Sitch et al., 2003]. Integral components of the global water cycle

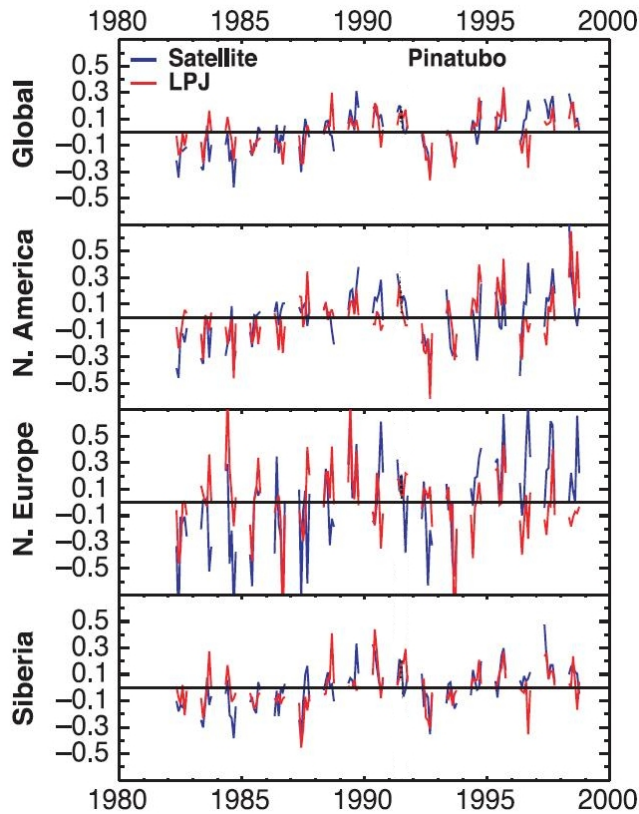


Figure 1.6: Comparison of simulated and observed anomalies of LAI from LPJ and long-term remote sensing for the boreal zone. No satellite data is available during winter, because of insufficient light conditions and snow cover (modified from Lucht et al. [2002]).

are also well reproduced by LPJ. Transpiration, evaporation, interception, soil moisture and surface runoff, including its intra- and interannual variability, match estimates from state-of-the-art hydrological models and radar remote sensing data Gerten et al., 2004, Sitch et al., 2003, Wagner, 2003.

DGVMs are continually developed following the progresses made in relevant scientific disciplines. For example, current research is concentrating on the implementation of process-based nutrient cycles, especially with respect to nitrogen constraints on NPP and the postulated future limitation of CO₂ fertilization due to N deficiency [Xu-Ri and Prentice, 2008]. More realistic simulation of plant dispersal and migration are needed to study the impact of rapid climate change and human land use on the future development of natural ecosystems. Although the first DGVMs are now capable of simulating crop productivity and yields based on generic representations of CFTs, a number of unresolved issues still remain. Many processes and management strategies required for a valid assessment of climate change impacts on agriculture, are only treated simplistically in the models or lack completely. Forest management and dedicated biomass plantations

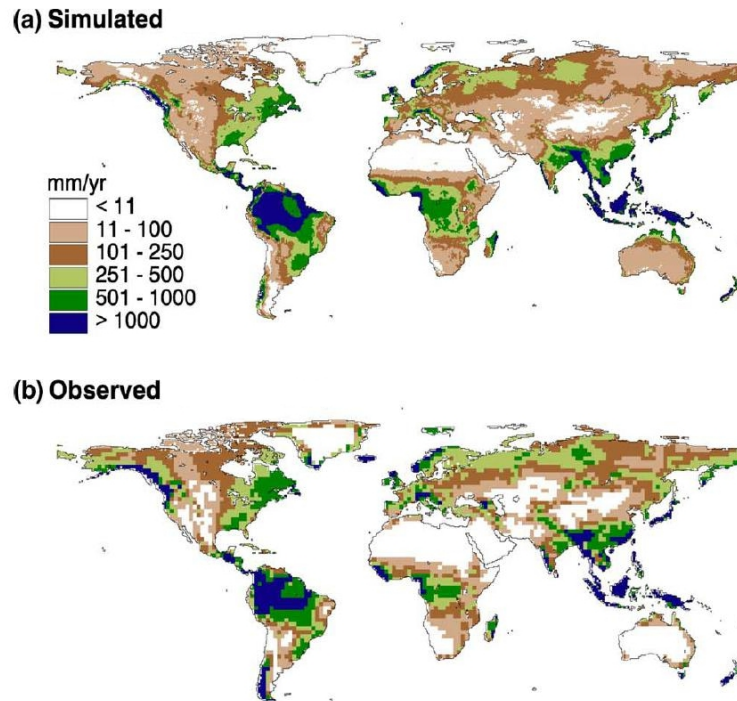


Figure 1.7: Comparison of long-term mean values for annual runoff (mm). LPJ simulations (a) show the 1969-1990 period. Average data from observations (b) were calculated from diverse time periods (Modified from Gerten et al. [2004].)

and other new types of land use are also missing entirely in most of the present generation DGVMs [Prentice et al., 2007].

1.3 The terrestrial biosphere in the Anthropocene

The land biosphere is under the dual threat of accelerating climate change and increasing human land use, that will both have large impacts on the structure and functioning of terrestrial ecosystems. This would effect key ecosystem services such as plant productivity and the flows of carbon and water with far-reaching consequences for human well-being. While higher growing season temperatures and reduced water availability may damage food systems [Battisti and Naylor, 2009], land use change is already the primary cause for species extinction and loss of biodiversity [Chapin et al., 2000].

1.3.1 Terrestrial carbon cycle

Life on earth is based on carbon. The chemical element makes up about 50% of the Earth's biomass, most biotic processes depend on chemical energy contained in organic carbon compounds, and atmospheric carbon dioxide contributes to the natural greenhouse effect that is vitally important for most living organisms. Carbon dioxide is

constantly being exchanged between the atmosphere, oceans, land biosphere and the lithosphere in the so-called global carbon cycle. Although 99% of the world's carbon is stored in rocks and sediments of the crust, this pool is controlled by slow geologic processes, primarily the carbonate-silicate cycle, that operate over millions of years [Berner, 2003]. On time scales ranging from seconds to centuries and hence relevant to humanity, atmospheric CO₂ is controlled by biological and physicochemical processes in the terrestrial biosphere and the oceans. Humans have significantly modified the global carbon cycle through emissions of greenhouse gases caused by the excessive combustion of fossil fuels and large scale changes in land cover [Falkowski et al., 2000]. This is very important, because the “fast” part of the global carbon cycle is centrally involved in many of the feedbacks and nonlinearities that may accelerate global warming and impacts far beyond what can be expected from human emissions alone [Zimov et al., 2006].

Terrestrial ecosystems remove CO₂ from the atmosphere through photosynthesis and store it in new organic matter. It is primarily returned to the atmosphere when organisms oxidize organic molecules in the process of respiration to yield energy for metabolism and growth. Landscape fires constitute another major respiratory pathway of carbon into the atmosphere that amounts to 50% of anthropogenic carbon dioxide emissions from fossil-fuel combustion [Bowman et al., 2009]. Gross primary production (GPP), i.e. the annual uptake of CO₂ by the world's vegetation, is about 120 GtC/yr. Autotrophic respiration (R_a) by the plants releases about 60 GtC/yr, so that the annual net primary production (NPP) amounts to 60GtC. Over longer time scales the balance between carbon gains and losses determines the accumulation of carbon in the biosphere called net ecosystem production (NEP). Net biome productivity (NBP) integrates the spatially varying patterns of NEP over larger regions, combining different stand ages and disturbance regimes [Chapin, Matson, and Mooney, 2002].

Human activities involve massive emissions of carbon dioxide, methane and nitrous oxide and other greenhouse gases. Levels of carbon dioxide in the atmosphere, for example, are now higher than anytime in the past 800000 years [Lüthi et al., 2008, Siegenthaler et al., 2005, Petit et al., 1999] and may even exceed the range of natural variability during the previous 23 million years [Pearson and Palmer, 2000, Pagani et al., 2005]. Deforestation and agricultural conversion also release substantial amounts of carbon adding to a significant perturbation of biogeochemical cycles. But although annual emissions of carbon now exceed 9 Gt [Canadell et al., 2007], only about 45 % remain in the atmosphere. Measurements of O₂/N₂ in air samples and the abundance of $\delta^{13}\text{C}$ in atmospheric CO₂ have been used to show increased carbon uptake on land and in the oceans amounts to up to about half of the emitted anthropogenic carbon [Keeling et al., 1996].

Four mechanisms are responsible for increased carbon storage in terrestrial ecosystems: historic land use change, CO₂ fertilization, nitrogen deposition, and climate change. Large parts of the world have seen extensive deforestation until the middle of the last century. More and more land was needed to feed the growing world population and before the intensive exploitation of fossil fuels, biomass was also humanity's primary source of energy. In those areas where human activities have ceased, forests and other natural vegetation types regrow, increasing carbon stocks over time. Measures in some

Outlook Chapter 2

Terrestrial carbon uptake is currently limiting the extent of climate change, because the land biosphere absorbs about 30% of the anthropogenic CO₂ emissions each year [Canadell et al., 2007]. However, the response of the land carbon sink to changes in climate is not yet fully understood. Large scale climatic disturbances of the recent past provide good opportunities to test and improve our understanding of biosphere-climate interactions and to evaluate the capabilities of DGVMs.

The scope of chapter 2 is to

1. quantify the relative contributions of NPP and Rh to the observed variations in atmospheric CO₂ growth rate.
2. differentiate the effects of temperature and precipitation anomalies on carbon uptake and release.

This chapter has been published in Carbon Balance and Management [Erbrecht and Lucht, 2006] (verbatim quote, but with references merged in the thesis bibliography; same for the following chapters).

world regions to suppress wildfires contribute to this trend. Gains in photosynthesis and possible biomass production are expected from rising atmospheric CO₂ levels because carbon assimilation in C₃ plants is not saturated under current conditions [Long et al., 2004]. Magnitude and temporal development of the so-called CO₂ fertilization effect at the ecosystem level remains uncertain, however, because constraints in resource availability [Reich et al., 2006], photosynthesis acclimation [Ainsworth and Long, 2005] and competition with other species [Malhi, 2002] may reduce growth enhancement. Outside of the tropics, vegetation is generally nitrogen limited. Atmospheric deposition of reactive nitrogen increased 3-5 fold during the last century and it is believed that vegetation responded with additional carbon uptake [Reay et al., 2008]. In the future, a higher nutrient availability may partly counteract progressive nitrogen limitation [Luo et al., 2004]. Finally, changes in climatic conditions stimulate photosynthesis and respiration and so control both carbon uptake and release. As a consequence of rising temperatures most mid- and high-latitude regions are also experiencing a lengthening of the growing season [Walther et al., 2002]. By slowing the growth of atmospheric CO₂, carbon sinks have effectively reduced the speed of human induced climate change. Future changes in climate and land use are likely to degrade some of the mechanisms responsible for the recent carbon sinks, so that carbon uptake may be reduced or even reversed towards the end of the century [Chapin et al., 2008, Field et al., 2007, Schaphoff et al., 2006].

Backed up by inverse modeling and mass balance computations based on atmospheric CO₂ data, the net carbon sink in the land biosphere is estimated to have been about 1 GtC/yr between 1990 and 2005 IPCC [2007]. However, current observations do not allow the separation of land use change emissions and the actual carbon uptake by terrestrial ecosystems, i.e., what is observed is only the 'residual land sink'. Using estimated values of the land use source term, a mean land sink of -1.7 (-3.4 to 0.2) and -2.6 (-4.3 to -0.9)

Outlook Chapter 3

Reduced growth in the atmospheric CO₂ concentration after the eruption of Mount Pinatubo in 1991 was mainly driven by the terrestrial biosphere, but the processes involved and their relative importance remain disputed. Based on an extended version of LPJ, chapter 3 investigates the

1. contribution of the land biota and other components of the global carbon cycle to the global CO₂ anomalies.
2. influence of diffuse radiation on terrestrial carbon uptake during 1992 and 1993.
3. impacts of post-Pinatubo climate conditions on regional patterns of carbon sources and sinks.

This chapter is currently being prepared for submission.

GtC/yr for the 1980s and 1990s respectively can be assumed. Terrestrial carbon uptake is characterized by a strong seasonal and latitudinal variability, as depicted by the see-saw pattern of the iconic Keeling curve from Mauna Loa. During the summer of the northern hemisphere, photosynthesis exceeds respiration, reducing the amount CO₂ in the atmosphere, while during winter, carbon release from vegetation and soils dominates and atmospheric CO₂ increases again. Although the basic mechanisms involved in the “breathing of the biosphere” [Fung et al., 1987] are well known, the location, magnitude and temporal variability of carbon sinks and sources remains uncertain [Erbrecht and Lucht, 2006, Myneni et al., 2001, Nemani et al., 2003, Peylin et al., 2005, Potter et al., 2003b, Schimel et al., 2001, Zeng et al., 2005]. Top-down and bottom up studies agree that substantial net carbon uptake occurs in the the forests of the northern extra-tropics. Large uncertainties still remain for tropical lands, which according to atmospheric inversions are either carbon neutral or sinks [Gurney et al., 2002, Luyssaert et al., 2008]. However, recent findings from long-term monitoring of tropical forests indicate significant carbon uptake during recent decades as a pan-tropical phenomenon [Lewis et al., 2009].

Ecosystems and the climate system are closely coupled through a multitude of pathways, including fluxes of greenhouse gases, radiation, heat and surface roughness. Plant distribution and productivity depends on local climate conditions and at the same time physical properties of the land surface affect climate on the local, regional and global scale [Chapin et al., 2008, Heimann and Reichstein, 2008].

1.3.2 Human land use

Unprecedented population growth, economic development and the globalization of markets have led to a rapidly growing demand for natural resources and products that is met by an accelerating conversion of natural ecosystems into more or less intensively used patches of agricultural land [Foley et al., 2005]. At the local scale, land use activities are

Outlook Chapter 4

An exploding demand for biomass as a feedstock for biofuels, electricity, heat and biomaterials may take the "human domination of Earth's ecosystems" [Vitousek et al., 1997] to a next level. In chapter 4, the potentials and risks of global biomass cultivation under consideration of various sustainability criteria are assessed. The main goals are:

1. To estimate the availability of land for biomass plantations constrained by future requirements for food security, nature conservation and climate mitigation.
2. To narrow down the range of realistic global bioenergy potentials.
3. To illustrate the potential consequences for agricultural water and fertilizer demand.
4. To explore regional environmental consequences entailed by land use change for bioenergy plantations.

This chapter has been published in *Global Change Biology Bioenergy* [Beringer et al., 2011].

driven by individual economic opportunities closely linked to social, political and infrastructural factors, rather than poverty and population [Lambin et al., 2001]. Immediate effects of changes in land cover and use include habitat loss, degradation and fragmentation, eutrophication, alteration of nutrient cycles, increased GHG emissions because of reduced carbon storage capacities in soils and vegetation, accelerated soil erosion, as well as changes in regional climate through altered albedo and fluxes of latent and sensible heat [Feddema et al., 2005, Foley et al., 2005]. The continuing over-exploitation and destruction of natural ecosystems, environmental toxification with heavy metals, artificial organic compounds and other persistent pollutants and the introduction of invasive species also constitute a major threat for biodiversity [Ehrlich and Pringle, 2008].

During the previous 40 years, the world's agricultural land expanded by nearly 500 Mha and now about 1600 Mha are used as croplands, and 3410 Mha as pastures. [FAO-STAT, 2010]. Land use change and agricultural land use are responsible for a significant part of the global increases in the atmospheric concentrations of carbon dioxide, nitrous oxide and methane. About 20% of current human GHG emissions are associated with deforestation and agricultural development [Denman et al., 2007]. Current hot-spots of land cover change include tropical forests in the Amazon basin and Southeast Asia where large scale deforestation destroys the world's most diverse and productive terrestrial ecosystems. Wooded wetlands, for example, contain about 540 GtC, equivalent to 25-30% of all carbon in vegetation and soils (MA, 2005), which is rapidly lost from the soils when the land is drained for cultivation.

Pressure on global land use will increase significantly during this century as a consequence of three main factors: a continuously growing world population with changing

dietary habits towards more land-intensive commodities, increasing demand for biomass products and accelerating climate change that will change the suitability of land for the cultivation of crops [WBGU, 2009]. Already now, more than a billion people are suffering from hunger [FAO, 2009a], mainly in sub-Saharan Africa. And although in purely statistical terms, there is sufficient food available on the world markets today, and regional shortages in supply are primarily a problem of food distribution and access [WBGU, 2009], it will become more and more difficult to satisfy the nutritional requirements of a growing and increasingly affluent world population in the future. Further intensification of existing agricultural areas is therefore very likely and the agricultural land base is expected to grow by up to 500 Mha until 2050, at the expense of natural ecosystems [FAO, 2003, Rockström et al., 2007, Tilman et al., 2001, WBGU, 2009]. Depending on the development of a global bioenergy market, a strong increase in competition for land resources may arise between food and biomass production [WBGU, 2009], that might compromise regional food security and increase the risk of poverty and conflict WBGU [2007]. In addition, changes in average climate and extreme events will have an increasingly substantial impact on global food security during this century [Battisti and Naylor, 2009, Lobell et al., 2008].

1.4 Objectives

The general scope of this thesis is to develop the overall understanding of the Earth system with regard to the main driving forces of future terrestrial biosphere dynamics: climate change and land use activities. Terrestrial ecosystems play a central role in the climate system and the Earth' biogeochemistry, because they regulate fluxes of energy, water, carbon, nitrogen and other elements between the land surface and the atmosphere. Soils and plants are the foundation of human nutrition and there are numerous other direct and indirect societal benefits that depend on biodiversity and ecosystem services. Given the great risks for human well-being associated with continuing ecosystem degradation [Millenium Ecosystem Assessment, 2005], a better understanding of key drivers and impacts is therefore key to sustainable economic, environmental and social development.

As described in 1.2.1, a wide range of methodologies are available to study the Earth system. This study deals with past and future global scale phenomena that involve above- and below ground biophysical and biogeochemical processes, climatic and anthropogenic driving forces and that require the integration of heterogeneous data. Modeling techniques are therefore most appropriate and form the basis of this work. Due to it's broad spectrum of topics, this study contributes to several of the overarching GAIM questions (Fig. 1.2 on page 4). Substantial model development extends the available methodological toolkit for Earth System Science [Steffen et al., 2004] and allows a spatially explicit analysis of major dynamical patterns of the terrestrial carbon cycle in chapters 2 and 3. Contemplating the future of global land use and "anthropogenic disturbance regimes" in chapter 4 helps to identify accessible trajectories in the co-evolution of nature and society, highlights potential key regions vulnerable to further degradation

1 General Introduction

of natural ecosystems and is one steps towards the identification of “non-sustainable and sustainable futures”.

Specific research questions dealt with in the following chapters are listed separately in text boxes on pages 12 (chapter 2), 13 (chapter 3) and 14 (chapter 4).

1.4.1 Structure of the thesis

This thesis consists of three main sections (chapter 2, chapter 3, and chapter 4) that explore different examples of global scale phenomena

1. Major climate disturbances to study the effects on the terrestrial biogeochemistry *Examples chosen*

- a) Post-Pinatubo strengthening of the global carbon sink during 1992 and 1993 (chapter 2)
- b) Acceleration of atmospheric CO₂ growth during the strong El Niño event in 1997/1998 (chapter 3)

To be studied

- Effects of temperature, precipitation and diffuse radiation anomalies on biosphere-atmosphere carbon exchange
- Relative contribution between canopy photosynthesis, plant respiration and soil respiration to changes in carbon sinks and sources
- Spatial patterns of and regional differences in NPP and Rh anomalies

2. Major land use disturbances to study the effects on natural ecosystems, water use and GHG emissions *Example chosen*

- a) Massive future expansion of dedicated biomass plantations for the production of bioenergy (chapter 4)

To be studied

- Global potentials of bioenergy from cellulosic energy crops
- Spatial patterns of land availability for biomass plantations
- Trade-offs between food production, nature conservation and biomass cultivation

1.4.2 Author’s contribution to individual chapters of this thesis

Paper 1 (Chapter 2)

Wolfgang Lucht suggested the scope of the study. I reviewed the relevant literature, aquired and prepared the additional datasets required, extended the LPJ model, performed the simulations, interpreted and visualized the results and wrote several versions of the manuscript with helpful comments from my co-author Wolfgang Lucht.

Paper 2 (Chapter 3)

On the basis of Wolfgang Lucht's previous study on biosphere dynamics in the boreal zone after the eruption of Mount Pinatubo, we jointly developed the idea of expanding this kind of analysis to the global scale. I prepared the relevant review of the literature, compiled and preprocessed additional datasets, designed and performed the simulations, and interpreted the results. I also prepared several versions of this manuscript that were greatly improved by valuable comments from Dieter Gerten and Wolfgang Lucht, who also guided the whole process.

Paper 3 (Chapter 4)

Wolfgang Lucht developed the idea to perform sustainability oriented analysis of global biomass cultivation for bioenergy as a new form of potentially large scale human land use based on the LPJmL framework. I did the relevant software development and implementation and realized the model validation. I also designed the scenarios in close collaboration with the German Advisory Council on Global Change (WBGU) and Wolfgang Lucht. All LPJmL simulations and post-processing as well as the interpretation of results were performed by myself. I drafted several versions of the manuscript based on many fruitful discussions with Wolfgang Lucht.

2 Impacts of large scale climatic disturbances on the terrestrial carbon cycle

1

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Abstract

Background

The amount of carbon dioxide in the atmosphere steadily increases as a consequence of anthropogenic emissions but with large interannual variability caused by the terrestrial biosphere. These variations in the CO₂ growth rate are caused by large scale climate anomalies but the relative contributions of vegetation growth and soil decomposition is uncertain. We use a biogeochemical model of the terrestrial biosphere to differentiate the effects of temperature and precipitation on net primary production (NPP) and heterotrophic respiration (Rh) during the two largest anomalies in atmospheric CO₂ increase during the last 25 years. One of these, the smallest atmospheric year-to-year increase (largest land carbon uptake) in that period, was caused by global cooling in 1992/93 after the Pinatubo volcanic eruption. The other, the largest atmospheric increase on record (largest land carbon release), was caused by the strong El Niño event of 1997/98.

Results

We find that the LPJ model correctly simulates the magnitude of terrestrial modulation of atmospheric carbon anomalies for these two extreme disturbances. The response of soil respiration to changes in temperature and precipitation explains most of the modelled anomalous CO₂ flux.

¹An edited version of this chapter was published in *Carbon Balance and Management*: Beringer T, Lucht W: Impacts of large scale climatic disturbances on the terrestrial carbon cycle, *Carbon Balance and Management*, 20, GB4015, doi: 10.1029/2006gb002742.

Conclusions

Observed and modelled NEE anomalies are in good agreement, therefore we suggest that the temporal variability of heterotrophic respiration produced by our model is reasonably realistic. We therefore conclude that during the last 25 years the two largest disturbances of the global carbon cycle were strongly controlled by soil processes rather than the response of vegetation to these large scale climatic events.

2.1 Background

Anthropogenic emissions continuously add about 7000-8000 million metric tons of carbon to the atmosphere per annum [Marland et al., 2003]. Atmospheric carbon dioxide measurements show that the rate of increase of atmospheric CO₂ varies substantially from year to year [Peylin et al., 2005]. It is widely accepted that these variations are caused by the terrestrial biosphere through the processes of carbon uptake during photosynthesis and carbon release during soil respiration [Prentice et al., 2001]. Additionally, strong disturbances such as large scale fires can significantly alter the exchange of carbon between terrestrial ecosystems and the atmosphere. For example, up to 65 % of the observed CO₂ growth rate in 1998 was attributed to burnt biomass in tropical and boreal regions [van der Werf et al., 2004]. In comparison, variations in the oceans [Le Quere et al., 2003], deforestation, and land use change are much smaller [Houghton and Hackler, 2002].

Uncertainty remains, however, regarding the relative influence of the driving climatic anomalies (temperature and precipitation anomalies) on the most prominent terrestrial carbon processes, namely vegetation growth (NPP) and soil decomposition (Rh). Numerical models of the land carbon cycle allow investigations of these relationships.

The two largest anomalies of atmospheric CO₂ growth rate during the last 25 years are related to two large climatic disturbances – the increased planetary albedo after the eruption of Mount Pinatubo in 1991 and the strong El Niño event of 1997/98. The Pinatubo eruption was an extraordinary event because of the large amount of aerosols that were injected into the lower stratosphere where they were distributed around the globe, leading to a world-wide cooling of about 0.5°C [Hansen et al., 1996]. The 1997/98 El Niño event was unusual in that it was extremely strong [McPhaden, 1999].

We use the LPJ model of terrestrial carbon and water cycles Gerten et al. 2004, Sitch et al. 2003 to explore the covariability of climatic forcings and physiological responses (namely NPP and Rh) of the terrestrial biosphere on a global scale as well as for selected latitudinal regions. Results show that a large fraction of the observed CO₂ growth rate variability is controlled by varying soil organic matter decomposition rather than changing plant productivity. This sheds additional light on previous studies that highlighted connections between the interannual variability of atmospheric CO₂ growth and net primary productivity Hicke et al. 2002, Nemani et al. 2003, Potter et al. 2003a.

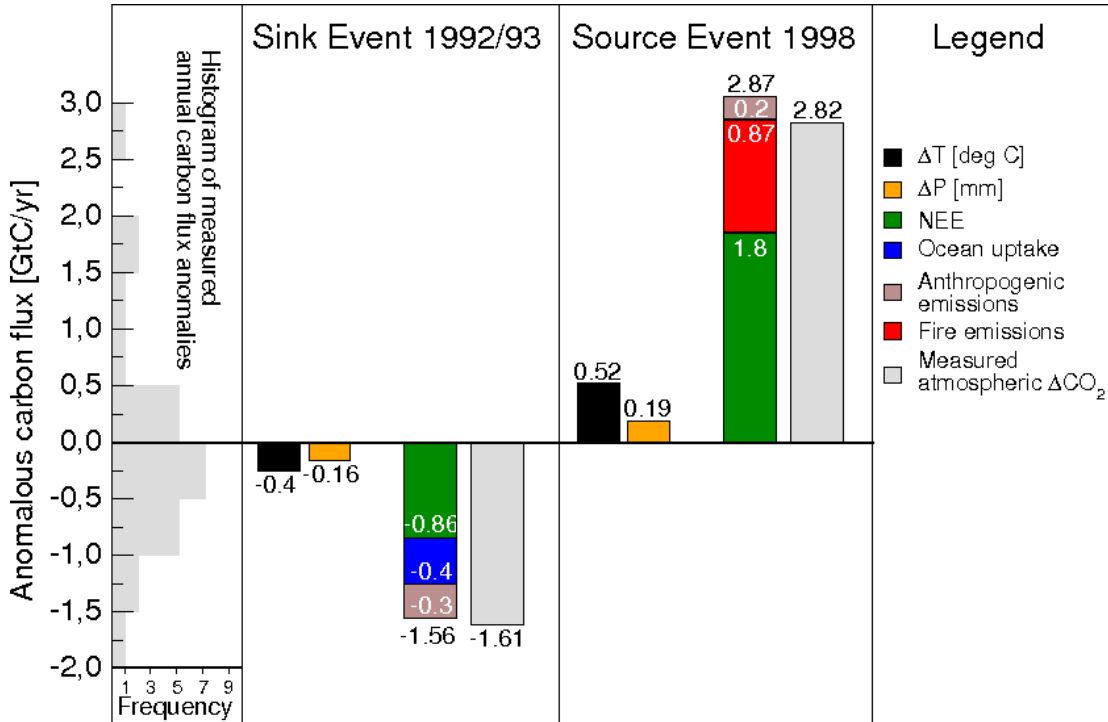


Figure 2.1: Global carbon balance during 1992/93 and 1998 using modelled and measured data of carbon sources and sinks and atmospheric reference data. Negative fluxes denote carbon uptake. Negative values of measured atmospheric ΔCO_2 denote a reduction it's rate of increase. Temperature and precipitation anomalies are calculated from the climate data set [Österle et al., 2003]. The histogram on the left is computed from measured carbon flux anomalies of last 25 years to illustrate the exceptional perturbation of the global carbon cycle in the two periods under investigation [Marland et al., 2003].

2.2 Results

The 1992/93 sink event

In order to calculate the share of observed CO_2 variability controlled by terrestrial ecosystem physiology we used state-of-the-art estimates of carbon flux anomalies from oceans, land-use change, anthropogenic emissions, and fires and reduced the measured atmospheric CO_2 growth rate anomalies accordingly (see figure 2.1).

An amount of -0.91 GtC/yr of the observed anomaly of -1.61 GtC/yr is found to have been caused by changes in NPP and Rh. The LPJ model computes -0.86 GtC/yr (fig. 2.2): it is in quantitative agreement with the observations.

Higher than normal oceanic carbon uptake and reduced anthropogenic emissions contributed to the anomalous carbon flux in addition to vegetation productivity and soil respiration (fig. 2.1). There are no indications that wild fires contributed significantly to the observed post-Pinatubo flux anomalies [Goldammer and Mutch, 2001].

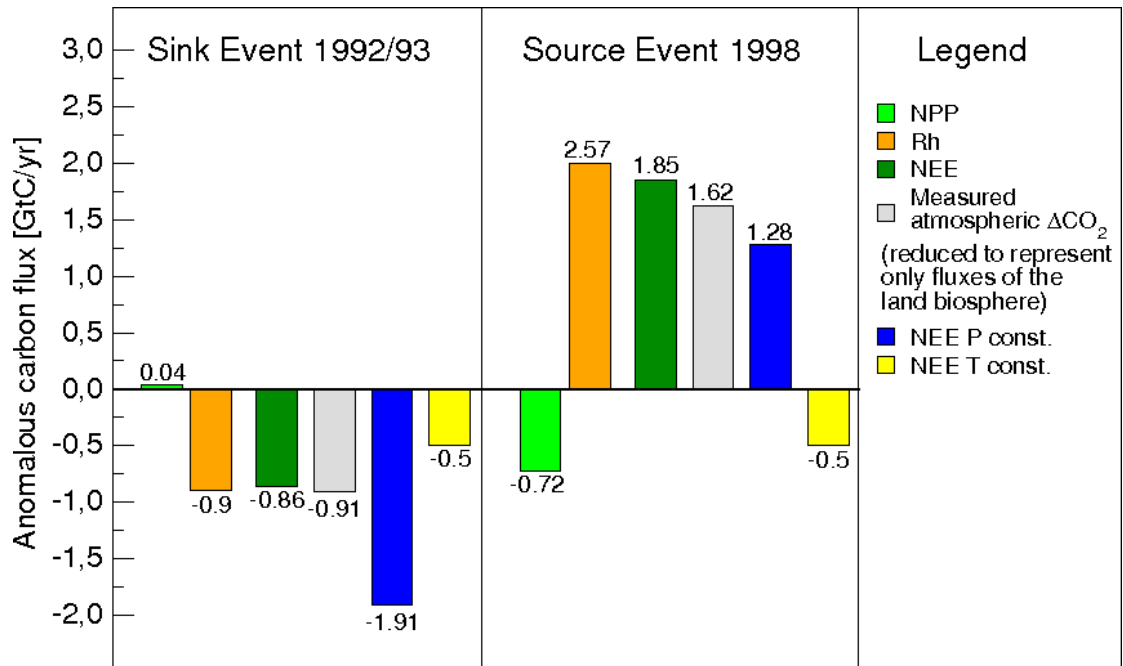


Figure 2.2: Global modelling results (NPP, Rh, NEE) and atmospheric reference data representing changes in ecosystem physiology. Negative values of NEE, NPP and Rh denote carbon uptake by the land biosphere. Negative values of measured atmospheric ΔCO_2 denote a reduction in its rate of increase.

What was the cause for this large anomalous sink – changes in NPP or Rh? The model shows that the pronounced reduction of atmospheric CO_2 increase results from reduced soil respiration whereas NPP did not change (cf. Angert et al., 2004, Gu et al., 2003, Lucht et al., 2002).

The 1998 source event

The physiological response of the land biosphere during the strong 1997/98 El Niño event was diametrically opposite to that of the 1992/93 period. A large anomalous flux of 2.82 GtC into the atmosphere was measured in 1998 of which 1.62 GtC can be assigned to vegetation growth and soil decomposition processes of the terrestrial biosphere (fig. 2.1). LPJ simulates a value of 1.85 GtC due to stronger soil respiration that was partly counteracted by increased photosynthetic activity (fig. 2.2). The remaining 1.2 GtC of the anomalous land source consists of a small contribution from anthropogenic emissions (about 0.2 GtC) while the rest is attributable to carbon emissions from extensive fires in tropical, subtropical and boreal regions [Randerson et al., 2005, van der Werf et al., 2004] (fig. 2.1).

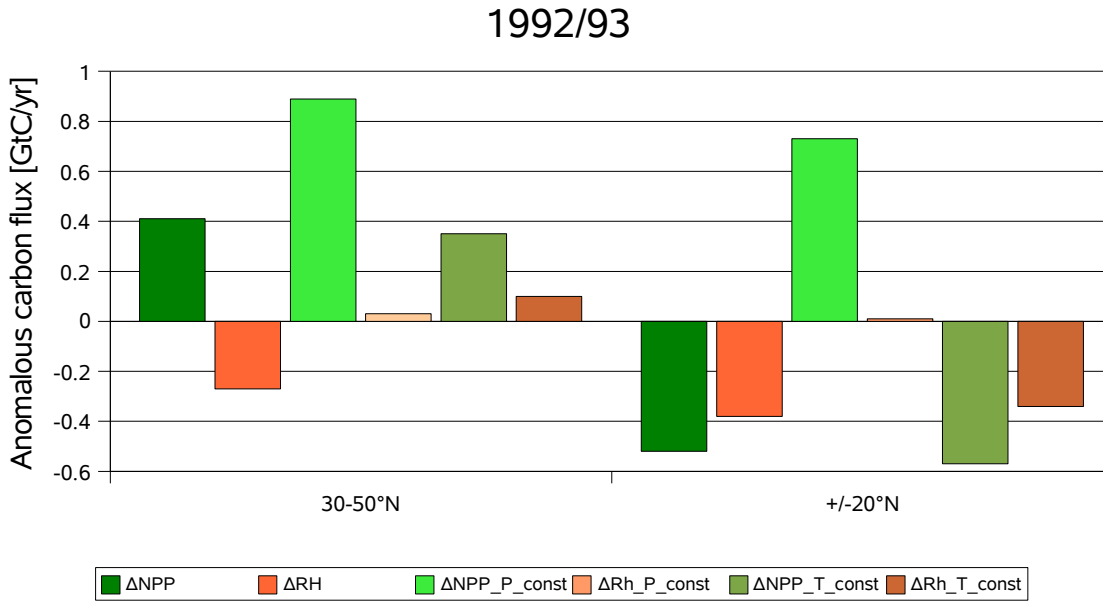


Figure 2.3: Simulated anomalies of NPP and Rh in 1992/93 for temperate and tropical latitudes. P_const represents the simulations where the precipitation anomalies were removed. T_const represents the simulations where the temperature anomalies were removed. Positive values of NPP denote carbon uptake by vegetation. Positive values of Rh denote carbon release from soils.

2.3 Discussion

The 1992/93 sink event

The quality of modelled soil carbon decomposition is less certain than that of NPP. Studies show, however, that the temporal variability of modelled vegetation activity is in good agreement with independent satellite data [Hickler et al., 2006, Lucht et al., 2002], indicating that the temporal variations of the associated simulated NPP are likely reliable. Because measured and modelled NEE, i.e. the difference of Rh and NPP, are found to be very similar in magnitude, we suggest that our simulation of the magnitude of anomalous soil respiration is plausible.

While the results show that soil processes controlled the increased land sink it remains unclear why NPP did not react to the climatic anomalies and what the relative importance of changes in temperature and precipitation were. We carried out a factorial experiment where either post-Pinatubo temperature or precipitation anomalies (that is, only the 1992-94 anomalies) were removed in the simulations, i.e. monthly values of temperature and precipitation were replaced by their corresponding 1979-2003 averages. These simulations help to clarify how relevant the changes in temperature and precipitation were for the carbon budgets of vegetation and soils. We find that if the global cooling after the Pinatubo eruption is removed (NEE T const.) the terrestrial carbon sink declines together with Rh, and higher values of NPP are achieved (fig. 2.3).

2 Impacts of large scale climatic disturbances on the terrestrial carbon cycle

When the observed precipitation anomalies, associated with a weak El Niño event that occurred during the same time period, are eliminated, negative temperature anomalies alone trigger a much larger sink than observed (fig. 2.3, P const). The increased net flux of carbon from the atmosphere into the biosphere results from enhanced NPP whereas Rh remains unchanged. In summary, it appears that the anomalously large sink post-Pinatubo was caused mainly by the dampening effects of lower temperatures on soil microbial activity (fig. 2.2), but that post-Pinatubo water-limitation of NPP weakened the strength of the sink.

The 1998 source event

Warmer and wetter than usual conditions during 1998 stimulated both NPP and Rh in the wake of the large El Niño, with a particularly pronounced effect on soil respiration (fig. 2.2). The small anomalous increase in precipitation in the climate data deviates from the general assumption that El Niño episodes in the Amazon basin are characterized by extended dry seasons, lower wet season precipitation and shifts in spatial rainfall distribution [Prentice et al., 2001]. The strong sensitivity of heterotrophic respiration to soil moisture content has also been observed in eddy covariance measurements [Saleska et al., 2003]. Due to teleconnections El Niño periods also affect climatic conditions in the extratropics. For example, vegetation activity in the northern temperate regions is positively correlated with ENSO during the northern summer [Buermann et al., 2003]. A pattern of negative NPP anomalies in the tropics and positive anomalies in the temperate zones is also produced by the LPJ model. However, the simulated global carbon balance is mainly determined by the differential response of tropical NPP and Rh. In the northern mid-latitudes, higher CO₂ uptake by vegetation is counterbalanced by increased respiration due to higher temperatures (fig. 2.4).

The dominant contribution of tropical ecosystems to the large land-atmosphere flux during El Niño conditions due to the opposite variation of NPP and Rh has been noted in other modelling studies as well [Potter et al., 2003a, Zeng et al., 2005].

Removing precipitation anomalies from the climate data results in a small terrestrial carbon sink that is triggered by increasing NPP in the tropics while reducing the carbon flux from soils (fig. 2.4, P const). The influence of the temperature anomalies is more important outside the low latitudes. Eliminating the positive temperature anomaly of 1998 reduces Rh significantly in the mid-latitudes whereas the carbon fluxes in and out of tropical ecosystems become balanced (fig. 2.4, T const). Thus the 1998 carbon source resulted from two mechanisms, a limitation of vegetation activity and a stimulation of soil decomposition in the tropics as well as temperature-driven acceleration (possibly via teleconnections) of heterotrophic respiration relative to NPP in northern temperate regions.

2.4 Conclusions

We conclude that the two largest variations of the global carbon cycle observed during the last 25 years were predominantly controlled by soil processes rather than by vegeta-

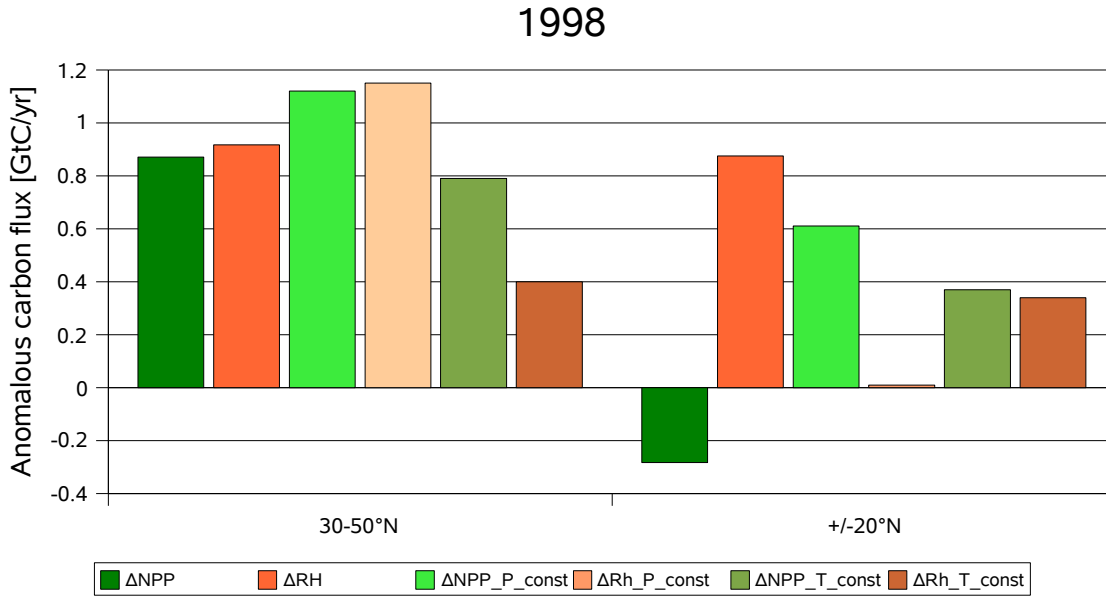


Figure 2.4: Simulated anomalies of NPP and R_h in 1998 for temperate and tropical latitudes. P_const represents the simulations where the precipitation anomalies were removed. Positive values of NPP denote carbon uptake by vegetation. Positive values of R_h denote carbon release from soils.

tion activity. This adds a different perspective to previous analysis [Hicke et al., 2002, Nemani et al., 2003, Potter et al., 2003a] that concentrated on contributions of global NPP anomalies to atmospheric CO_2 growth rate anomalies. While NPP indeed plays an important role, analysis shows that in some periods changes in NPP alone do not explain the observed excursions of atmospheric carbon dioxide accumulation. This applies particularly to the two large events analysed in this paper, and in both cases changes in soil respiration explain the observed variability. Considering only the relationship between climate and NPP underestimates the true variability of the global carbon cycle. Vegetation growth and soil decomposition react differentially to anomalies in temperature and precipitation.

Observed and modelled NEE anomalies agree surprisingly well, suggesting that the LPJ model simulates the temporal variability of soil organic matter decomposition sufficiently. The model can hence be applied to the analysis of the land biosphere's modulation of atmospheric CO_2 concentration and the biogeochemical effects of large scale climate variations.

There are several implication for policy. First, long-term climate protection strategies aimed at full accounting of terrestrial carbon sources and sinks should focus on soil and vegetation processes equally. Currently, much more is known about vegetation responses to climate change than about soil processes [Davidson and Janssens, 2006]. Second, the terrestrial carbon cycle varies strongly in space and time. A monitoring regime therefore should take into account the characteristics of the dynamics observed and modelled for

different global regions and temporal periods. Climatic events may strongly alter the short-term balance, rendering them untypical of the average behaviour.

2.5 Methods

LPJ DGVM

The LPJ Dynamic Global Vegetation Model [Gerten et al., 2004, Sitch et al., 2003] is a biogeochemical model of fluxes of carbon and water in terrestrial vegetation and soils. Carbon uptake during photosynthesis is estimated using the Farquhar-Collatz scheme which is coupled to two soil layers [Farquhar et al., 1980, Collatz et al., 1992]. Assimilated carbon is allocated to four pools (leaves, sapwood, heartwood and fine roots) following allometric and functional relationships [Sitch et al., 2003]. Carbon from dead biomass enters above- and belowground litter pools and is then transferred to a fast and slow decomposing soil carbon pool. Soil organic matter decomposition is calculated using a modified Arrhenius formulation [Lloyd and Taylor, 1994] which implies a decline in apparent Q_{10} with temperature, as well as an empirical soil moisture relationship [Foley, 1995]. We performed simulations with 0.5 degrees spatial resolution (59199 grid cells) using an interpolated climatology of monthly values of temperature, precipitation and radiation [New et al., 2000, Österle et al., 2003]. A land cover data set produced at the University of Maryland provided a realistic distribution of global crop lands [Hansen et al., 2000]. The LPJ-DGVM has been extensively validated using various data from atmospheric measurements, active and passive remote sensing data, and flux measurements. It was shown that the model is capable of simulating large scale structure, distribution and phenology of global vegetation [Lucht et al., 2002, Sitch et al., 2003] as well as the inferred seasonal cycles of soil moisture [Wagner, 2003], evapotranspiration and runoff [Gerten et al., 2004].

Acknowledgements

We acknowledge project funding from the State of Brandenburg (TE) and the International Max Planck Research School on Earth System Modelling. We thank Sibyll Schaphoff, Dieter Gerten, and Wolfgang Cramer for valuable contributions and continued support. We would like to express our thanks to Will Steffen for having been the Handling Editor and to three anonymous reviewers for their very helpful comments.

3 Regional response patterns of the terrestrial biosphere to Pinatubo eruption

1

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Abstract

After Mount Pinatubo erupted in 1991 the rate of atmospheric CO₂ increase decelerated exceptionally over a period of two years. While it is generally accepted that the strengthening of the global carbon sink was mainly driven by the terrestrial biosphere, the processes involved and the magnitudes of their respective contribution remain disputed. Effects of changes in temperature, precipitation, drought, the occurrence of fires and the effect of diffuse radiation anisotropy of solar irradiation upon vegetation and soils are regarded as possible explanations. We used a biogeochemical model of the terrestrial biosphere to simulate the spatio-temporal responses of net primary production (NPP) and heterotrophic soil respiration (Rh) to the post-Pinatubo climate conditions during 1992 and 1993. The simulations show that anomalous variations in temperature and precipitation explained most of the observed higher carbon uptake over land, which resulted from a complex regional response pattern of NPP and Rh. Increased carbon uptake is simulated for boreal ecosystems, where soil respiration reacted stronger than photosynthesis to summer cooling, and the mid-latitudes, where a combination of positive rainfall anomalies and lower temperatures is responsible for enhanced plant productivity and reduced soil respiration. Gains in canopy radiation use efficiency as a consequence of increased diffuse radiation at the land surface may have contributed to the strengthening of the global carbon sink, but only to a minor extent due to the strong reduction in total irradiance under cloudy skies [Alton, 2008]. These modeling results are supported by independent data from atmospheric measurements and remote sensing.

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3.1 Introduction

Annual emissions of carbon dioxide from fossil fuel consumption and changes in land use currently exceed the actual accumulation of carbon dioxide in the atmosphere, which implies surplus assimilation of CO₂ over land and in the oceans in the so called global carbon sink. Land surface processes play a key role in the global carbon source–sink behavior as they control the large year-to-year variability that characterizes the observed rise in atmospheric CO₂ concentration [Prentice et al., 2001]. Seasonally fluctuating imbalances of terrestrial carbon uptake and release control the net exchange of carbon between the land biosphere and the atmosphere, yet their spatial and temporal dynamics still remain disputed [Gurney et al., 2002, Keeling et al., 1996, Peylin et al., 2005, Stephens et al., 2007]. Plants fix atmospheric CO₂ during photosynthesis and allocate about 50% of the synthesized carbohydrates to new tissues. The remainder is rapidly consumed for maintenance and growth respiration and transferred back into the atmosphere. The amount of carbon gained after these autotrophic respiratory losses is the net primary productivity (NPP). Dead biomass enters the soil organic matter pool where it is respired by bacteria and fungi. The resulting efflux of CO₂ is referred to as heterotrophic respiration (Rh). Besides, through ecosystem respiration significant amounts of carbon are returned to the atmosphere through natural and man-made burning of biomass [van der Werf et al., 2004]. Deforestation and other activities related to land-use change and land management are also contributing to rising atmospheric greenhouse gas concentrations [Houghton and Hackler, 2002]. Net ecosystem exchange (NEE) measures the actual flux of CO₂ between ecosystems and the atmosphere. NEE varies seasonally due to the fluctuating imbalance between net photosynthesis and ecosystem respiration. While measurements of atmospheric oxygen and nitrogen revealed the biological regulation of the land carbon sink [Keeling et al., 1996], the processes involved, their relative quantitative importance, and their dynamic responses to changing atmospheric conditions are still debated. Additionally, a number of emergent feedback mechanisms have been identified that result from the fundamental coupling of the earths’ atmosphere and land ecosystems [Doney and Schimel, 2007, Moorcroft, 2006]. Changes in local climate conditions can ultimately lead to the redistribution of major vegetation types. Reduced carbon storage in soils and vegetation [Friedlingstein et al., 2006] or a complete breakdown of the terrestrial carbon sink [Cramer et al., 2001, Dutta et al., 2006, Schaphoff et al., 2006] would further accelerate anthropogenic climate change. Large perturbations of the atmosphere provide excellent opportunities to test and expand our understanding of the couplings between biogeochemical and climatological processes, especially since global earth observation systems are now providing comprehensive data on terrestrial ecosystems and the physical climate at various spatial and temporal resolutions [GEO, 2009]. The most significant stratospheric perturbation of the 20th century was caused by the eruption of Mount Pinatubo in June 1991. About 20 megatons of gaseous sulfur dioxide were injected into the lower stratosphere during the eruption and subsequently converted into aerosol particles that encircled the globe within three weeks [Gillet et al., 2004, Newhall et al., 2002, Olmo et al., 1999]. The volcanic aerosol layer affected the chemical and radiative properties of the atmosphere in various ways. Enhanced backscat-

tering of incoming solar radiation led to a net loss of insolation by about 3 Wm^{-2} in 1992 and 1 W m^{-2} in 1993 [McCormick et al., 1995]. At the same time, the fraction of diffuse radiation was up to 10% higher in 1992 and 1993 due to increased scattering of solar radiation by the volcanic aerosols. These changes in earth's energy balance led to a reduction of global mean surface temperatures by about 0.5°C in 1992 compared to the long-term mean. In 1993, negative temperature anomalies were smaller and negligible afterwards [Hansen et al., 1996]. However, on a regional scale temperature anomalies varied substantially in time and space. Continental surface temperatures over North America were up to 2°C lower than normal in the northern hemispheric summer of 1992, while positive temperature anomalies dominated over Siberia, Western Europe, and Australia [Kelly et al., 1996, Kirchner et al., 1999]. During the northern hemispheric winters of 1992 and 1993, however, near-ground temperatures increased up to 3°C compared to the long-term mean over North America, Western Europe and Siberia [Fischer et al., 2007, Robock, 2002]. There is also evidence that the volcanic radiative forcing had a significant effect on terrestrial precipitation Broccoli et al. [2003], Lambert et al. [2004]. According to Gillet et al. [2004] global rainfall over land was reduced after the eruption. But just as for temperatures, rainfall anomalies were extremely variable in space and time. Additionally, the 1991/92 ENSO event and a phase change of the quasi-biennial oscillation coincided with the eruption that also affected surface temperatures and rainfall patterns [Broccoli et al., 2003, Buermann et al., 2003, Santer et al., 2001, Yang and Schlesinger, 2001, 2002]. Atmospheric measurements revealed that the accumulation of CO_2 in the atmosphere decelerated notably to about 0.8 ppm/yr in 1992 and 1993 compared to a mean value of about 1.6 ppm/yr between 1979 and 2003, despite continuously increasing anthropogenic emissions [Keeling et al., 1995, Marland et al., 2005]. There is general agreement that the strengthening of the global carbon sink in 1992 and 1993 was primarily driven by the land biosphere, while the oceanic carbon balance changed only marginally [Jones and Cox, 2001, Peylin et al., 2005]. Two different hypotheses have been proposed that relate the strengthening of the land sink to post-Pinatubo climate anomalies. One hypothesis is based on the differential response of NPP and Rh to the reduced surface temperatures during the growing periods and to the precipitation changes [Angert et al., 2004, Jones and Cox, 2001, Lucht et al., 2002]. Low temperatures inhibit enzymatic activity and thus photosynthesis and the microbial decomposition of soil organic matter. Both processes exhibit different temperature sensitivities that are additionally modulated by soil moisture and vapor pressure deficit (VPD). Results from different modeling studies suggest that after the Pinatubo eruption Rh was reduced stronger than NPP, leading to reduced flux of CO_2 into the atmosphere. The other hypothesis rests upon the fact that increased diffuse radiation can boost the radiation use efficiency (RUE) of vegetation canopies [Gu et al., 2003, Mercado et al., 2009, Roderick et al., 2001]. Anisotropic irradiance is distributed more homogeneously among the leaves, exposing a larger share of photosynthetic tissue to intermediate levels of illumination and thus reducing light saturation effects [Gu et al., 2002]. In this case enhanced NPP causes additional carbon storage in plant tissues. The aim of this study is to quantify, spatially explicitly, the dominant mechanisms that were involved in the perturbation of the global carbon cycle after the eruption of Mount Pinatubo, and to

investigate the relative roles of the processes proposed by the two above hypotheses. We used the LPJ Dynamic Global Vegetation Model [Sitch et al., 2003, Gerten et al., 2004] including a simple representation of agricultural land [Schröder, 2008] to simulate the influence of temperature, precipitation and diffuse radiation anomalies on photosynthesis and soil microbial activity in 1992 and 1993. By integrating different observational data sets documenting the post-Pinatubo dynamics of other carbon cycle components not modeled explicitly here, we attempt to fully reconstruct the observed reduction in atmospheric CO₂ increase as induced by the increased land sink. Satellite-based measurements of photosynthetic activity [Myneni et al., 1997] were used to validate the LPJ model.

3.2 Methods

3.2.1 LPJ DGVM

The LPJ-DGVM is a global model of the terrestrial biosphere that combines process-based representations of large scale vegetation dynamics, biogeochemistry and biogeography to simulate carbon and water fluxes between land and atmosphere [Gerten et al., 2004, Sitch et al., 2003]. Nine plant functional types (PFTs) defined by photosynthetic pathway (C₃, C₄), phenology (deciduous, evergreen), physiognomy (woody, herbaceous) and life cycle (annual, perennial) represent the structural and functional diversity of terrestrial vegetation. Vegetation dynamics and composition are driven by competition for light and water as well as climatic conditions within a grid cell. Carbon assimilation is calculated using the coupled Farquhar-Collatz approach [Farquhar et al., 1980, Collatz et al., 1992] and a two-layer water balance scheme [Gerten et al., 2004] enabling a realistic estimation of gross primary productivity (GPP) and plant respiration including the effects of drought stress on assimilation and evapotranspiration [Gerten et al., 2007]. Net primary production (NPP), the difference between GPP and autotrophic respiration, is allocated annually to four carbon pools, representing leaves, sapwood, heartwood and fine roots, following a set of allometric and functional rules [Sitch et al., 2003]. Dead biomass enters separate above- and below-ground litter pools and is ultimately transferred to a slow and fast soil carbon pool. Decomposition rates of litter carbon and soil organic matter is calculated as a function of soil temperature [Lloyd and Taylor, 1994] and moisture using a modified Arrhenius formulation that uses a realistic decline in Q₁₀ values with temperature [Foley, 1995]. Fire disturbances are simulated as a function of fuel load and litter moisture [Thonicke et al., 2001]. LPJ has been comprehensively validated using various data from atmospheric measurements, active and passive remote sensing, and carbon flux measurements. It was shown that the model is capable of simulating the large scale structure, distribution and phenology of global vegetation correctly [Erbrecht and Lucht, 2006, Hickler et al., 2004, Lucht et al., 2002, Sitch et al., 2003]. Modeling results are also in good agreement with the observed seasonal cycles of soil moisture [Wagner, 2003], as well as evapotranspiration and runoff [Gerten et al., 2004].

3.2.2 Modification of the original model formulation

Effects of diffuse radiation on canopy RUE

Three climatic factors were likely responsible for the modification of the land carbon sink after the eruption of Mount Pinatubo: changes in the diffuse component of light, a reduction in total PAR and reduced surface temperatures, especially during the growing season. Anomalies in temperature and precipitation are already considered in the standard version of the LPJ model code. However, LPJ uses a big-leaf approach to calculate canopy photosynthesis [Sitch et al., 2003] which does not separate direct and diffuse light and thus does not include changes in LUE with variations in the diffuse share of incoming solar radiation. For this study, we thus modified the model in such a way that light extinction in plant canopies is reduced when the diffuse component of PAR increases. Anomalies in the diffuse fraction of light for the years 1992 and 1993 relative to the 1985-1990 period were calculated from the Global Energy and Water-Cycle Experiment (GEWEX) Surface Radiation Budget (SRB) Project Release 2 data set [NASA, 2006]. In the simulations model parameters were then adjusted according to Roderick et al. [2001], so that the largest anomalous increases in diffuse light that occurred during 1992-1993 lead to a 10% increase in canopy RUE. We also used the size of the diffuse radiation anomalies to scale the concurrent reductions in total available light energy by up to 3% as a consequence of enhanced light scattering by the volcanic aerosols [Roderick et al., 2001]. It has been observed that the strong decrease in total irradiance under cloud leads to decrease in primary productivity and daily carbon sequestration that is not counterbalanced by the effects of higher diffuse sky radiance and cooling-induced reductions in heterotrophic respiration [Alton, 2008, Cohan et al., 2002]. Therefore, we reduced the positive effect of diffuse light anomalies on photosynthesis with increasing cloud cover. Under clear sky conditions potential gains in canopy RUE remain diminished and decline linearly to zero when cloud covering reaches 100%. This is a conservative assumption given that observations indicate decreasing productivity on overcast days, due to the strong attenuation of shortwave radiation [Alton, 2008].

Land use

Since a model-based analysis of contemporary atmospheric CO₂ variability must include a correct representation of the actual land cover, and because the original LPJ model only considered potential natural vegetation, we implemented a simple modeling scheme for managed agricultural areas discerning cropland and pasture [Schröder, 2008]. Maps of land use for the years 1992 and 1993 were derived from the MODIS land cover classification [Friedl et al., 2002, Strahler et al., 1999] and the HYDE data set of cropland and pasture distribution [Klein Goldewijk, 2001]. The physiognomy of crops was emulated by allowing establishment of only C₃ and C₄ grass-type PFTs on farmed areas. Crops were assumed to be harvested annually removing 75% of the aboveground biomass, the remainder being transferred into the litter pool. Within managed lands the occurrence of vegetation fires was restricted to grazing lands (pastures).

3.2.3 Modeling protocol

We forced the LPJ model with 0.5 degree resolution monthly fields of temperature, precipitation and cloud cover for the period 1901-2003 [Mitchell et al., 2004, Österle et al., 2003]; the monthly values were disaggregated to daily values as described in Gerten et al. [2004]. Global CO₂ concentrations and soil texture data were used as input data (see Sitch et al. [2003] for a detailed description). The transient modeling period was preceded by a 1000-yr spinup to get the carbon pools and vegetation distribution into equilibrium. We conducted four different simulations (S1 through S4) to evaluate the relative contributions of the three mechanisms (1) increasing diffuse radiation, (2) reduced total PAR, and (3) cloudiness on terrestrial carbon sequestration in the years 1992 and 1993. Table 1 provides an overview of the four simulation setups, or rather which of the different mechanisms are included in the different simulations. S1 is the baseline simulation that considers only the effects of changes in temperature and precipitation on the terrestrial carbon balance. Simulations S2 through S4 account for those processes and their combinations related to the larger proportion of diffuse radiation.

Table 3.1: Setup of LPJ simulations S1 through S4. Plus sign indicates that the corresponding mechanism was included in the simulation.

Mechanism	Scenario			
	S1	S2	S3	S4
<i>RUE increase</i> due to higher diffuse PAR	-	+	+	+
<i>Lower total PAR</i> due to increased scattering	-	-	+	+
Effects of <i>cloud cover</i> on diffuse radiation effect	-	-	-	+

For each of these simulations, we calculated the anomalies of carbon fluxes related to NPP, Rh and wildfires spatially explicitly for each grid cell, as well as their global averages for years 1992 and 1993 relative to the 1979-2003 period. The annual carbon balance NEP is calculated as the difference between NPP, Rh and the fire flux, so that negative values indicate a carbon sink in the particular year.

Carbon flux data

To complement our model-based analyses of carbon fluxes from terrestrial ecosystems, we additionally considered observational data that report carbon flux anomalies from the oceans [Le Quere et al., 2003], from land use change [Houghton and Hackler, 2002], and from anthropogenic emissions [Marland et al., 2005]. Global averages for these data sets were available for the 1979-2003 period.

3.3 Results

3.3.1 Global CO₂ anomalies in 1992/1993

Anomalies of anthropogenic carbon emissions into the atmosphere (-0.29 PgC/yr), the uptake of carbon into the oceans (-0.4 PgC/yr) and changes in the rate of deforestation (+0.17 PgC/yr) were found to be too small to explain the observed slowdown of atmospheric CO₂ accumulation of 1.61 PgC/yr in 1992 and 1993 (Figure 1). In contrast, we found the magnitude of the modeled land carbon sink in simulation S1 to have been -0.87 PgC/yr (value corrected for the positive deforestation flux anomaly). This NEE reduction was caused by both reduced NPP and Rh, the former being only -0.15 PgC/yr smaller than the average over 1979-2003, whereas Rh dropped by -1.17 PgC/yr. Temperate regions were responsible for about 65% of the simulated strengthening of the land carbon sink, with a five-fold higher carbon uptake in the northern mid-latitudes, while boreal ecosystems contributed the remaining 35%. Above-average emissions from natural fire disturbances in tropical ecosystems, likely a consequence of ENSO-related drought, attenuated the land sink by 0.29 PgC/yr. Taken together, these estimates indicate that the global carbon sink grew by -1.56 PgC/yr during 1992/93 relative to the long-term mean, which is in line with the observed -1.61 PgC/yr.

When including the beneficial effect of aerosol light scattering on canopy RUE in simulation S2, NPP rises significantly as compared to S1, thus amplifying anomalous terrestrial carbon uptake by about 50% to -1.29 PgC/yr. However, the global sink is then overestimated by 30% compared to the expected value based on atmospheric measurements. As the volcanic aerosol layer increased the planetary albedo, less solar radiation available for photosynthesis reached the Earth's surface. Consequently, the calculated terrestrial carbon sink in S3 is smaller than in S2, though only slightly, such that the aggregate biospheric and anthropogenic flux anomaly during 1992 and 1993 still exceeds the measured value by about 0.3 PgC/yr. Considering additionally the modulating effect of cloud cover on atmospheric radiation transfer and canopy photosynthesis (S4) further reduces the inferred anomalous biospheric carbon sink to -1.53 PgC/yr, a value that corresponds to the result of simulation S1. Notably, the modeled zonal anomalies of NPP and Rh during 1992 and 1993 are also largely in accordance with the results from S1. The strengthening of the terrestrial carbon sink is overestimated in simulations S2 and S3 indicating that the positive effect of diffuse radiation on NPP was not effective on the global scale after the eruption of Pinatubo, because of the contemporary decline of total PAR at the surface. We therefore assume that the response of the terrestrial biosphere to the climatic forcing during 1992 and 1993 eruption is correctly represented in simulation S1 and constrain further spatially explicit analyses to these results.

3.3.2 Regional patterns of terrestrial carbon sources and sinks in 1992/93

We applied a simple classification scheme for the modeled anomalies of NPP, Rh and the resultant carbon balance of simulation S1 in order to visualize the spatially variable response of vegetation and soil carbon fluxes (Figure 2) to the climatic perturbations (Figure 3).

Table 3.2: Global anomalies of NPP and Rh during 1992/93 in GtC/yr. Figures in parenthesis show regional anomalies for the boreal, temperate and tropical zone, respectively.

Process	Scenario			
	S1	S2	S3	S4
Δ NPP	-0.15 (-0.14, 0.63, -0.61)	0.45 (0.18, 0.70, -0.41)	0.22 (0.05, 0.67, -0.49)	-0.06 (-0.16, 0.74, -0.66)
Δ Rh	-1.17 (-0.43, -0.25, -0.46)	-1.13 (-0.46, -0.24, -0.40)	-1.15 (-0.45, -0.25, -0.42)	-1.06 (-0.46, 0.11, -0.50)

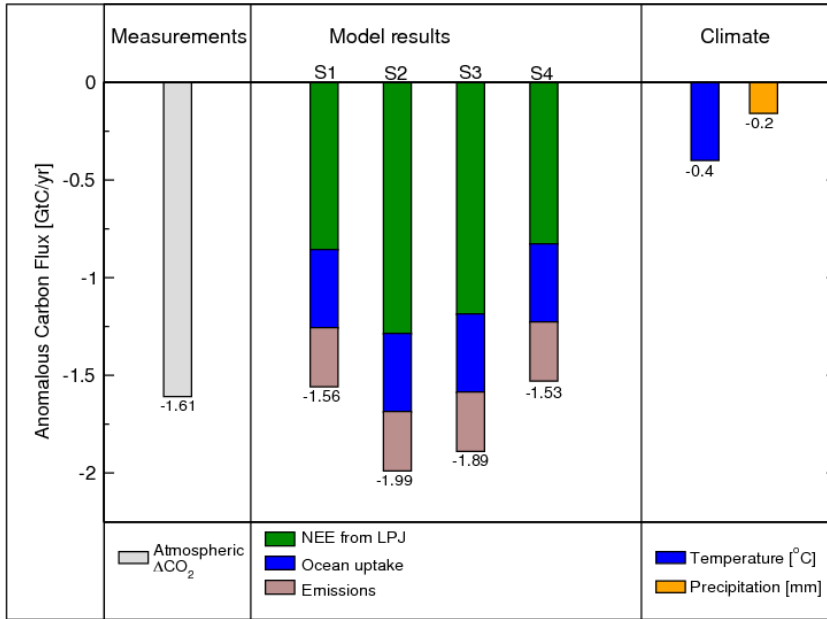


Figure 3.1: Comparison of measured and LPJ-modeled global post-Pinatubo carbon flux anomalies averaged over the years 1992 and 1993 relative to the period 1980-2000. Negative values indicate an decreased carbon flux into the atmosphere relative to the base period. Data on ocean uptake are from LeQuéré et al. [2003]; emissions from fossil fuels are from Marland et al. [2005]; and emissions from land use change from Houghton et al. [2002]. Temperature and precipitation anomalies are calculated from Österle et al. [2003].

The analysis suggests that two different modes of climate-biosphere interaction underlay the observed increase of the terrestrial carbon sink during 1992/1993 in the northern hemisphere. Large parts of the high northern latitudes experienced positive temperature anomalies of up to 3°C together with reduced annual precipitation [Kirchner et al., 1999]. These conditions triggered a reduction in both NPP and Rh, the response of the latter having been stronger. Ecosystems in the mid-latitudes responded predominantly positive to lower temperatures and increased rainfall with an overall rise in NPP. The response of Rh to the climatic forcings was less homogeneous. While Rh was simulated to be above average in some regions it was found to be lower than normal in others. Drier conditions prevailed in tropical regions that constrained both plant productivity and heterotrophic respiration.

Carbon sinks were located predominantly in northern mid-latitudes (-0.67 PgC/yr) and boreal regions (-0.27 PgC/yr) as a result of differential changes in NPP and Rh. While NPP was higher in temperate regions leading to enhanced carbon sequestration in new biomass, NPP declined in high northern latitudes, but this reduction in vegetation activity was counterbalanced by a stronger decrease in Rh. Both processes strengthened the global carbon sink. Carbon was released from tropical ecosystems in this simulation due to a relatively stronger decline of NPP than Rh and more frequent

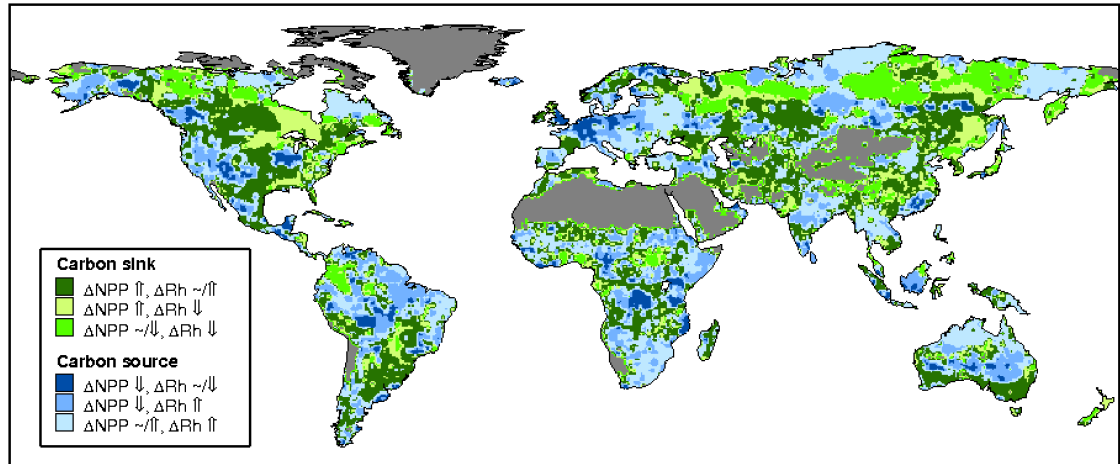


Figure 3.2: Classification of LPJ-simulated NPP and Rh anomalies in 1992/93 relative to 1979-2003. Upward and downward arrows indicate positive and negative anomalies, respectively. Small values within $\pm 15\%$ around zero are marked with a tilde. Grey areas showed no changes.

fire events. Anomalous release of carbon is also modeled over eastern North America, western Europe, central Siberia, northern South America as well as large parts of the African continent. Again, carbon loss is not related to a single mechanism but results from shifts in the regional balances between NPP and Rh.

3.4 Discussion

The LPJ model is able to accurately simulate the observed strengthening of the land carbon sink after the eruption of Mount Pinatubo during 1992 and 1993 (Figure 1). According to LPJ, enhanced carbon uptake occurred predominantly in the northern hemispheric extratropics, due to regional changes in temperature and precipitation. The smaller contribution of tropical and southern hemispheric ecosystems to the slowdown of atmospheric carbon dioxide growth during this period, as simulated by the model, has also been inferred from regional atmospheric CO_2 inversions [Peylin et al., 2005, Schimel et al., 2001]. Within the broader zones of increased carbon storage or release, underlying biogeochemical processes varied substantially among regions (Figure 2). According to our simulations, the observed strengthening of the global carbon sink was not related to a single “Pinatubo effect”, but was driven by the differential response of vegetation productivity and soil respiration to regional changes in temperature and precipitation [Raich et al., 2006].

This is to be expected given that natural variations in temperature, water availability and radiation impose varied limitations on ecosystem productivity and heterotrophic respiration in different parts of the world [Churkina and Running, 1998, Nemani et al., 2003, Gerten et al., 2005]. NPP generally increases with higher temperature and precipitation. Microbial activity and hence heterotrophic respiration is also promoted by warm

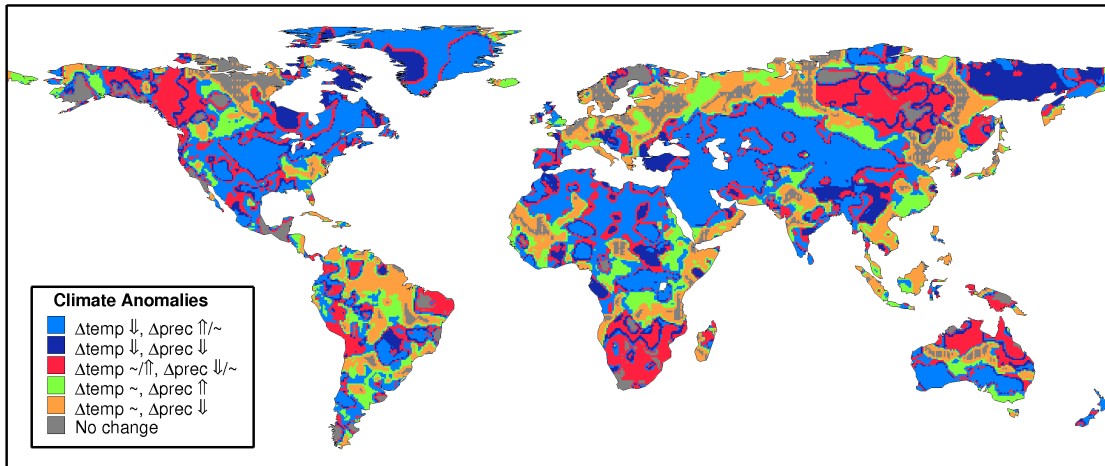


Figure 3.3: Classification of positive (upward arrow) and negative (downward arrow) temperature and precipitation anomalies in 1992/93 compared to 1979-2003. Upward and downward arrows indicate positive and negative anomalies, respectively. Small values within $\pm 15\%$ around zero are marked with a tilde.

moist conditions if sufficient oxygen is available. At the same time, higher temperatures may reduce soil moisture by increasing evapotranspiration and hence also decomposition. NPP and soil respiration react differently to changes in soil water content. While decomposition is more restricted by high soil moisture than NPP, plant productivity is more constrained by low soil moisture [Chapin et al., 2002]. Clouds reduce the total amount of solar radiation available at the land surface due to increased absorption and scattering in the atmosphere, while the share of diffuse radiation increases. Observations and model experiments have shown that the strong decline in primary productivity due to reduced irradiance is generally not compensated for by higher LUE and cooling-induced reductions in respiration under clouds [Alton, 2008].

In the high northern latitudes vegetation is generally temperature limited [Nemani et al., 2003]. Changes in the carbon balance of boreal ecosystems were mainly driven by summer cooling and winter warming [Kirchner et al., 1999]. Heterotrophic respiration responded stronger to temperature changes than photosynthesis [Chapin et al., 2002], so that carbon release from soils declined further than plant growth during the summer month. Cold winter temperatures are a limiting factor for vegetation productivity in the high latitudes [Nemani et al., 2003] so that winter warming promotes photosynthesis due to longer growing periods. Both processes lead to stronger carbon sinks. Lucht et al. [2002] showed that the modeled decrease in boreal vegetation activity during summer is in accordance with satellite measurements of leaf area index. The mid-latitudes exhibit a heterogeneous pattern of carbon sources and sinks during the 1992-1993 period. Increased vegetation activity exceeded accelerated decomposition in central and eastern North America, central and eastern Asia and southern South America, where positive rainfall anomalies [Trenberth and Dai, 2007] reduced the water limitation of vegetation productivity typical for these regions [Nemani et al., 2003]. Similar changes in

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temperature as observed in the higher latitudes with cooler summers and warmer winters further contributed to these trends. Drier conditions prevailed over Western Europe, large parts of Sub-Saharan Africa and Australia, which were responsible for widespread reductions in vegetation productivity and the development of carbon sources. Similar climatic conditions as observed during the 2003 summer heatwave prevailed over Western Europe with summer warming and drying, albeit smaller in magnitude [Ciais et al., 2005]. Both photosynthesis and soil respiration were reduced, but the stronger decline in plant productivity determines the overall carbon balance. The observed decrease in global precipitation over land following the eruption of Pinatubo has been attributed to both the volcanic activity and the contemporaneous 1991-1994 ENSO events [Gillet et al., 2004, Trenberth and Dai, 2007, Lambert et al., 2004]. Drier conditions in large areas of equatorial South America and Africa led to the simulated weakening of carbon sinks mainly due to reduced NPP. This is a characteristic response of tropical ecosystems to drier El Niño conditions that inhibit plant productivity [Asner et al., 2000, Foley et al., 2002]. We analyzed the relative importance of the different climatic factors for the terrestrial carbon cycle after the Pinatubo eruption with two additional simulations based on the S1 setup, in which either temperature or precipitation anomalies were removed from the 1992 and 1993 climate data. Variations in both precipitation and temperature were responsible for decreasing NPP and Rh in high-latitude ecosystems, but the response to the latter was stronger [Lucht et al., 2002]. In the mid-latitudes, drier conditions also limited photosynthesis. Lower temperatures partly attenuate this effect and on average a positive NPP anomaly remains for this region during 1992 and 1993. Decreasing NPP and Rh in tropical regions were almost exclusively related to reduced precipitation in our simulation.

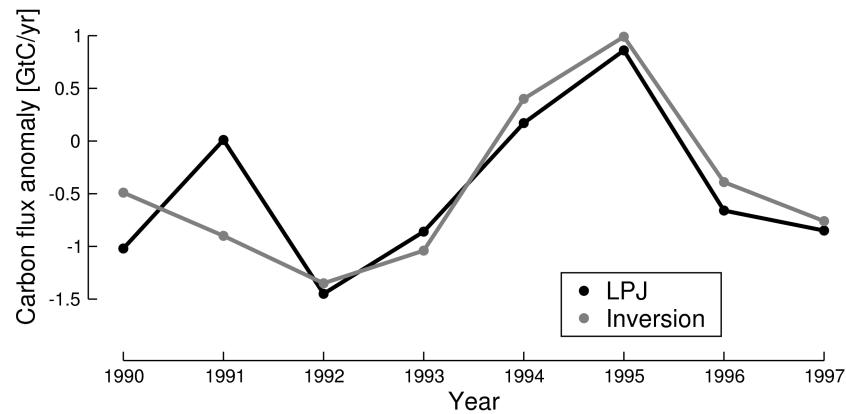


Figure 3.4: Estimates of carbon flux anomalies in the period 1990-1997 from LPJ and from atmospheric inversions relative to 1980-1998 [Peylin et al., 2005].

It has been suggested that the increase in diffuse shortwave radiation caused by the volcanic aerosol layer stimulated canopy photosynthesis globally, and hence increased primary production was the reason for the observed strengthening of the terrestrial carbon sink [Gu et al., 2003, Roderick et al., 2001]. Our results based on a temporally

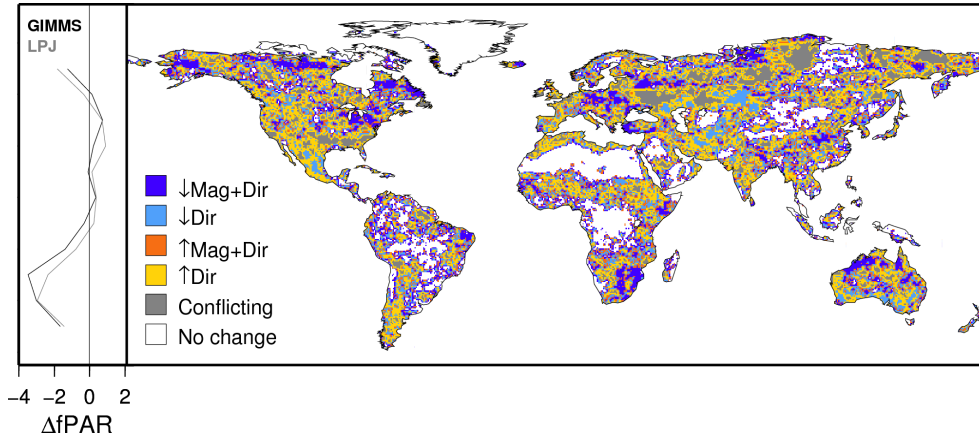


Figure 3.5: Comparison of LPJ-simulated and observed fPAR anomalies over land during 1992/93 relative to 1982-2002, demonstrating whether both data sets show consistent direction of change (Dir) and whether the magnitude of change differed by a maximum of 5% (Mag) between observations and simulations. Pixels for which the data sets show opposing trends are marked as Conflicting. The graph on the left side shows a comparison of latitudinal averages from the same data. fPAR is derived from the Global Inventory Modeling and Mapping Studies (GIMMS) version 3 NDVI data set [Myneni et al., 1997, Schröder, 2008].

and spatially comprehensive modeling analysis including the combined effects of changes in temperature, precipitation, direct and diffuse radiation on the carbon balance of terrestrial ecosystems suggest, however, that potential gains in canopy RUE related to higher proportions of diffuse light were largely counterbalanced by the declining total solar energy available at the surface due to the shortwave attenuation by clouds and volcanic aerosols. It is possible that a small positive effect from the stimulation of photosynthesis by increases in diffuse radiation is present but it was found here to be overwhelmed by a much larger temperature and precipitation effect, that sufficiently explains the measured deceleration of atmospheric CO₂ growth. For example, Gu et al. [2003] showed that Harvard Forest NEE was on average 16.5% higher between 1992 and 1993 relative to the 1995-2001 period as a consequence of enhanced photosynthesis. The corresponding eddy-flux measurements, however, were collected under clear-sky conditions around noontime only – a situation when the positive effect of increased diffuse radiation is greatest [Alton, 2008, Cohan et al., 2002]. In simulation S1, LPJ also shows NPP growth for the Harvard Forest region even though the positive effect of diffuse light on canopy RUE are not accounted for, and variations in plant productivity are only related post-Pinatubo climate anomalies. On average, simulated NEE in this region increased by about 10 % during 1992 and 1993 relative to the 1995-2001. Other studies based on vegetation modeling [Angert et al., 2004], tree ring analyses [Krakauer and Randerson, 2003] and remote sensing [Lucht et al., 2002, Nemani et al., 2003, Piao et al., 2007] also conflict with the thesis of a global rise in NPP.

Our findings are further supported by a high level of agreement between modeled

3 Regional response patterns of the terrestrial biosphere to Pinatubo eruption

and observed changes in the land carbon balance after the volcanic eruption inferred from atmospheric measurements (figure 3.4) and remote sensing data (figure 3.5), both in magnitude and spatial patterns. Previous analyses revealed a close consistency of observed and simulated leaf area index anomalies for the boreal zone [Lucht et al., 2002]. The anomalous changes in fPAR simulated by our model are also in good agreement with remote sensing data (Figure 5) from the AVHRR sensor [Myneni et al., 1997]. Both data sets indicate that larger areas of reduced vegetation activity are predominantly located in the higher latitudes, a trend towards enhanced productivity is visible in the mid-latitudes and larger patches of relatively stable NPP are found in the tropics. The consistency between simulations and observations which are completely independent of each other suggests that the satellite-observed variability is not an artifact of aerosol contamination of the satellite signal. The spatial pattern of carbon flux anomalies for Europe also corresponds well with typical climate anomalies for tropical eruptions, mainly driven by reduced continental precipitation [Fischer et al., 2007].

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4 Global bioenergy scenarios

1

Abstract

Humans have always changed their local environment in their search for food and shelter, but as a consequence of massive population growth, technological progress and increasing affluence that occurred since the industrial revolution, the combined actions of humanity are now transforming face and functioning of the entire planet at unprecedented speed. The material turnover of modern industrial and post-industrial societies is already causing worldwide environmental degradation. If current trends in human-environment interactions are not halted or reversed, humanity may face dramatic threats from accelerating climate change, collapsing ecosystem services, fading fossil fuel resources and continuing population growth already in the coming decades.

Bioenergy is a prime example for the complex challenges involved in managing a great transformation towards a sustainable, low-carbon society. While supporters of increased biomass use highlight the prospects of fossil fuel substitution and rural development in developing countries, there are rising concerns about the manifold consequences of massively expanding human land use activities for natural ecosystems and their functioning. At the same time some economic models project significantly higher mitigation costs if less than expected amounts of biomass become available for electricity production with CCS.

Providing substantial amounts of bioenergy will require the large scale cultivation of energy crops at the expense of either existing cropland or natural ecosystems. Bioenergy may thus become another major driving force within the agriculture-environment nexus that is already posing controversial challenges for policy and research with respect to food security, soil degradation and water depletion. As long no global integrated land policy is established, the future development of the bioenergy sector will be directly or indirectly depend on decisions made in the realms of energy, security, development, environmental, trade and agricultural policy.

It is therefore all the more important that science produces “analytical, diagnostic and prognostic” knowledge of the Earth system [Lucht, 2010] under different development scenarios by taking a comprehensive but necessarily “Crude Look at the Whole” [Gell-Mann, 2010] as a fundamental requirement for political and social discourse (see also 1.2).

¹The second part 4.2 of this chapter was published in *Global Change Biology Bioenergy* [Beringer et al., 2011]

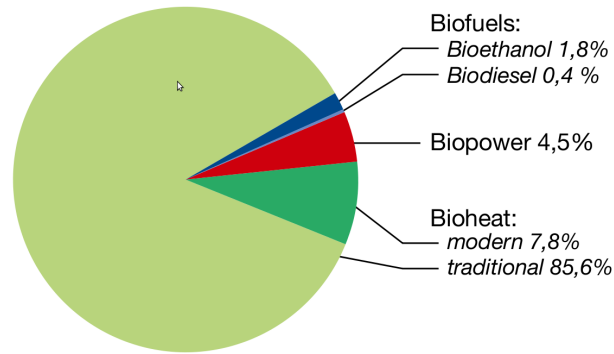


Figure 4.1: Current biomass use for liquid fuels, electricity and heat. Assuming a global bioenergy supply of 50.3 EJ [taken from WBGU [2009]]

Against this background, the second part of this thesis is concerned with the increasing use of biomass as a renewable energy source that may become an important driver of changes in ecosystem services, climate mitigation and food security in the coming decades. Chapter 4.1 provides a comprehensive introduction to the topic as well as the methodological approach used in this thesis to simulate the large scale cultivation of cellulosic energy crops, assess the availability of land under different scenarios of climate protection and nature conservation, estimate global bioenergy potentials and characterize the associated impacts on natural resources. The detailed description of the technical approach is necessary because the modern energy crops (fast-growing trees and grasses) had not been implemented in global vegetation models before. It was therefore necessary to extend an existing model of the terrestrial biosphere. Chapter 4.2 describes and discusses the results of the different bioenergy scenarios. This part has been published in *Global Change Biology Bioenergy*.

4.1 Simulating the large scale cultivation of 2nd generation energy crops: methods and motivation

Firewood was the primary source of energy for most of human history and has been replaced by coal, oil and natural gas only during the last 150 years. Biomass is still the world's largest renewable contributor to global primary energy supply (fig. 4.1).

Current bioenergy production, however, is almost exclusively based on the non-commercial use of wood for cooking and heating in developing countries. Only in recent years, growing concerns about climate change, energy security and rural impoverishment have sparked renewed interest in modern forms of bioenergy use.

One of the reasons is that biomass is regarded as a carbon-neutral source of energy (i.e. carbon released in combustion has been fixed during photosynthesis) and has therefore been embraced by developed countries as one strategy to fulfill their Kyoto commitments and to contribute to the transformation towards a low-carbon economy. Recent price rises and the foreseeable scarcity of natural resources (e.g. 'peak oil') have also made developing countries acknowledge the economical and political risks involved in depending

4.1 *Simulating large scale energy crop cultivation: motivation and methods*

to a great extent on fossil energy carriers that are mostly imported from a small number of politically unstable regions and stimulated interest in increased domestic energy production on the basis of renewable energy crops.

As a consequence, a number of bioenergy promoting policies, such as the EU's Biofuels Directive (2003/30/EC) have already been developed. Strong promotion of biofuels has also been driven by interest of the automobile industry, because only minor technical modifications of existing combustion engines are required to use biofuels, avoiding considerable and expensive changes in technology, while promoting the use of biofuels gives companies an inexpensive way to show off their commitment to climate change mitigation and reducing required changes in consumer behavior to the choice of fuel at the gas station.

Substituting expensive imports of fossil energy is one of the most important motives for bioenergy programmes in emerging economies and developing countries alike. At the same time many of these countries are rich in agricultural land and have favorable climatic conditions and regard the emergence of a world market in biomass and biofuels as a great development opportunity not to be missed.

Initial euphoria, however, has gradually been replaced by controversial discussions about benefits and risks involved in a massively increasing demand for bioenergy and in particular biofuels. The effectiveness of biofuels in reducing GHG emissions is now seriously being questioned. Recent scientific analysis have shown that, for example, converting tropical forests into plantations of palm oil leads to carbon emissions from land use change that will outweigh carbon benefits from using biofuels for decades to centuries [Gibbs et al., 2008]. So from a climate mitigation and biodiversity protection perspective, a sustainable use of bioenergy will require a broad framework of policies and regulations that define fundamental sustainability standards and strengthen international environmental and development regimes, such as the Convention on Biological Diversity (CBD), the Convention to Combat Desertification (UNCCD), the World Heritage Convention (WHC) and the Ramsar Convention on Wetlands (Ramsar).

On the other hand, the use of biomass to produce energy is regarded as a necessary bridging technology that can help to reduce GHG emissions until growth and technological progress in solar and wind energy production are enough to provide a sufficient supply of electricity by mid century [WBGU, 2009].

Analyses of global potentials of biomass to produce liquid fuels, electricity, heat and materials are therefore urgently needed in order to evaluate the possible contribution of bioenergy to the transformation towards sustainable energy systems in a low-carbon society. Various sources of biomass exist that differ in quantity, accessibility and their effects on land use change and environmental conditions. Using waste materials and residues from households, industry, agriculture and forestry is probably the least problematic, because it entails fewer risks for land use and food prices. However, given the huge demand for biomass that is expected to develop when stringent climate protection goals are agreed upon and comprehensive pricing of greenhouse gas (GHG) emissions are established, dedicated biomass plantations are believed to become the most important contributor to the global bioenergy supply. Assuming significant further increases in productivity and efficiency, several studies have suggested that some surplus agricul-

tural land may be used for energy crops [Hoogwijk, 2005, Smeets et al., 2007]. It is unclear however, if this is a realistic scenario and given that changes in precipitation patterns and dynamics are expected with climate change, even more land than currently used may be required to feed a global population of 9 billion by 2050 [Rockström et al., 2007, 2009]. The large-scale cultivation of energy crops may therefore compete directly with food production on existing agricultural areas, or compete with nature conservation where natural or semi-natural ecosystems are converted into dedicated biomass plantations. In most cases, direct and indirect changes in land-use [Fargione et al., 2008, Melillo et al., 2009, Searchinger et al., 2008] will lead to losses in biological diversity [Fitzherbert et al., 2008] and greenhouse gas emissions from vegetation and soils.

Although results from life-cycle analyses of energy crops vary widely depending on the methodology use, there is general agreement that energy savings and GHG reductions achieved by current practices to produce non-fossil transportation fuels, heat and energy from food crops are low or even negative in many cases, and hardly ever perform as good as perennial crops even under the best circumstances [Adler et al., 2007, WBGU, 2009]. Very high expectations are therefore being placed on more efficient technologies based on dedicated second-generation lignocellulosic bioenergy crops that are exclusively grown in order to produce energy from their harvestable biomass. Advantages of growing perennial energy crops include less competition with food, higher energy savings, carbon sequestration, and GHG reductions, reduced fertilizer demand, biomass yield per area, and overall higher environmental sustainability.

The most intensively studied and most widely cultivated herbaceous energy crops are the perennial rhizomatous species *Miscanthus* and Switchgrass. Both utilize the C₄ photosynthetic pathway and are up to 60 % more water and nutrient use efficient compared to C₃ plants [Heaton et al., 2008]. Nitrogen and other nutrients are remobilized after the growing season and relocated from aboveground parts to rhizomes thus minimizing nutrient losses with harvest. This mechanism reduces the amount of fertilizers required to sustain high yield levels. *Miscanthus* originates from East Asia and different varieties and hybrids are already available that are adapted to different climatic conditions. Yield levels of up to 40 t/ha/a have been observed for this species [Clifton-Brown et al., 2004]. Switchgrass is native to the USA and exhibits high productivity under a wide range of environmental conditions.

Poplars (*Populus*) and willows (*Salix*) are two C₃ woody crops ideally suited to be grown under short rotation coppice in temperate latitudes. Harvesting intervals vary between 3 and 10 years and regrowth from stump is vigorous after cutting back the trees. About 10000 cuttings per hectare are typical for poplar plantations, while planting densities of willows may be twice as high for certain varieties [Karp and Shield, 2008]. In tropical and semitropical regions, *Eucalyptus* species are the most important woody crops with highest per area energy yields grown in short rotation woody crop systems (SRWC) [Moreira, 2006, Rockwood et al., 2004].

Against this background, there is great need for scientific analyses of opportunities and risks of a global scale biomass industry for energy and materials based on lignocellulosic crops. The wise use of biomass has the potential to contribute to the decarbonization of the world's energy system until other renewable sources, especially solar energy, are fully

4.1 Simulating large scale energy crop cultivation: motivation and methods

developed and available. Land-use conflicts on the other hand are very likely to increase significantly as the cultivation of food crops, biomass production and the protection of ecosystem services compete for land in a world that is under the rising pressures from climate change and population growth. The assessment of bioenergy potentials and consequences needs to be embedded in an interdisciplinary, global analysis of land use strategies and objectives. Ecological sustainability criteria, for example, are required to assure that

For example, standard economic rationale based on cost-benefit analysis would identify tropical and subtropical regions with high yield levels and low production costs as primary locations for large scale biomass plantations. This could lead to the replacement of food production on existing cultivated land with potential impacts on food prices and local availability. A rising demand for bioenergy and biofuels could also be met by establishing biomass plantations at the cost of natural vegetation involving large amounts of carbon emissions and biodiversity losses in most cases. Ecological sustainability criteria are therefore required to avoid unintended side effects on food security and ecosystem services.

The following sections describe the implementation of lignocellulosic energy crops in the LPJmL model (section 4.1.2) and the spatial data sets used to estimate available resources of land and the consequences of using these areas for dedicated biomass production (section 4.1.4).

4.1.1 Recent estimates of global bioenergy potentials

Recent estimates of global bioenergy potentials differ in underlying assumption about future land availability, environmental conditions, population growth and dietary habits, technological progress, sustainability constraints or socioeconomic development [Campbell et al., 2008, de Vries et al., 2007, Dornburg et al., 2008, Field et al., 2008, Hoogwijk et al., 2003, Hoogwijk, 2005, IEA Bioenergy, 2009, Reinhardt et al., 2007, Smeets et al., 2007, Tilman et al., 2006, van Vuuren et al., 2009, WBGU, 2003, 2009, Wise et al., 2009] and have thus produced a wide range of results. The calculation of global biomass availability is generally based on three main categories of biomass resources: dedicated energy crops, residues from food production and forestry as well as organic waste materials. In addition, the literature also distinguishes between theoretical, technical, economic and sustainable potentials. These terms are, however, not clearly defined and used differently by different authors so that mixtures of the different categories occur frequently. *Theoretical potentials* refer to the biophysical upper limits of worldwide biomass cultivation and residues extraction without further considering their environmental, social, political or economical viability. *Economic potentials* explore the amount of bioenergy that may be produced at economically profitable levels in a globalized biomass market. *Sustainable potentials* consider land use restrictions based on socioeconomic and environmental sustainability criteria that limit the amount of land available for the cultivation of energy crops. *Technical potentials* describe the influence of different conversion technologies and their efficiencies on the amount of bioenergy that can be produced from a certain amount of raw feedstock and are therefore derived from theoretical, economic or

4 Global bioenergy scenarios

sustainable potentials.

Differences in underlying assumptions about the main factors determining the long-term availability of biomass are responsible for a wide range of global bioenergy estimates ranging between 80 EJ/yr and 1100 EJ/yr, equivalent to between 15% and 230% of the present global primary energy demand. Table 4.1 shows a compilation of current estimates of the global biomass resource potentials for the different sources.

Table 4.1: Estimates of technical bioenergy potentials in 2050 for different biomass resources (based on Campbell et al. 2008, de Vries et al. 2007, Dornburg et al. 2008, Field et al. 2008, Hoogwijk et al. 2003, Hoogwijk 2005, IEA Bioenergy 2009, Reinhardt et al. 2007, Smeets et al. 2007, Tilman et al. 2006, van Vuuren et al. 2009, WBGU 2003, 2009, Wise et al. 2009).

Biomass source	Potentials in 2050 [EJ/yr]
Energy crops	30 - 700
Residues	
Food production	10 - 70
Forestry	30 - 150
Organic wastes	5 - 50
Surplus forestry	0 - 100
Combined total	75 - 1070

With an overall potential of 30-700 EJ/yr dedicated energy crops are generally believed to become the most important source of biomass. Very high annual supplies of bioenergy are only achievable if the intensification of existing croplands or a shift in dietary habits towards less meat consumption will reduce the demand for land required to produce food. Abandoned agricultural areas could then be used for the large scale cultivation of energy crops [Smeets et al., 2007]. Other more conservative studies [Campbell et al., 2008, Field et al., 2008] argue that sustainable biomass cultivation should only occur on land that was already used as cropland or pasture but has been taken out of production, implicitly ruling out any further destruction of natural ecosystems. Due to these strong restrictions the authors conclude that energy crops will supply less than 50 EJ per year. There is a general trend towards lower estimates of global bioenergy potentials in more recent scientific assessments when environmental and socioeconomic constraints for human land use are considered [WBGU, 2009, van Vuuren et al., 2009]. The largest source of uncertainty in these projections is the future availability of land for the cultivation of energy crops that will depend on the size of the world population, their dietary habits (esp. demand for animal proteins) and economic affluence, technological progress and rising yield levels in food production. The contribution of residues from agriculture and forestry may also be further reduced by environmental and economic consideration to around 25 EJ per year and increases in the global demand for wood products may exceed surplus production [WBGU, 2009].

4.1.2 Implementing lignocellulosic energy crops in LPJmL

LPJmL provides an integrated framework to study the effects of human land use on core ecosystem functions such as net primary production, carbon storage, yield potentials, and water availability [Bondeau et al., 2007, Gerten et al., 2004, Sitch et al., 2003].

LPJmL computes biomass production from NPP, i.e. the difference between chemical energy produced during photosynthesis and chemical energy used for maintenance and reproduction. The remaining woody biomass increment is allocated to different compartments within the plant according to four allometric relationships (in which k denotes a constant). The **pipe model** [Shinozaki et al., 1964, Waring et al., 1982] requires that a certain leaf area (LA) is supported by a corresponding area of transport tissue, the sapwood cross sectional area (SA).

$$LA = k_{la:sa} SA \quad (4.1)$$

Another relationship describes the connection between investments in fine root biomass (C_{root}) to investments in leave biomass (C_{leaf}). This forces plants in dry environments to invest more carbon in non-photosynthesizing tissues. lr_{max} is the maximum leaf-to-root mass ratio and ω is a measure of water availability ranging between 0 and 1 with decreasing water deficit on days with non-zero leaf cover [Haxeltine and Prentice, 1996].

$$C_{leaf} = lr_{max} \cdot \omega \cdot C_{root} \quad (4.2)$$

The relationship between vegetation height (H) and stem diameter (D) is prescribed by the third allometric rule [Huang et al., 1992].

$$H = k_{allom2} D^{k_{allom3}} \quad (4.3)$$

The fourth allometric relationship in the model relates crown area (CA) and stem diameter. This rule is derived from Reinecke’s rule [Zeide, 1993] which relates tree density and stem diameter under self-thinning conditions.

$$CA = k_{allom1} D^{k_{rp}} \quad (4.4)$$

The basic approach of LPJmL for simplifying floristic diversity is based on generic functional types, i.e. prototypes of plants representing groups of species with similar physiological and morphological traits. Up to now, LPJmL used 9 natural plant functional types (PFTs) and 13 crop functional types (CFTs) to simulate the variety of natural and agricultural ecosystems. In order to expand the model’s capacities for the scope of this thesis three additional biomass functional types (BFTs) were implemented. These BFTs represent the most widespread and promising types of lignocellulosic energy crops as described in section 4.1: fast-growing C_4 grasses, temperate and tropical trees.

The parametrization of the new BFTs is largely identical to their natural PFT equivalents “ C_4 perennial grass”, “temperate broadleaved summergreen tree” and “tropical broadleaved raingreen tree” [Sitch et al., 2003]. Table 4.2 shows the modified parameter

4 Global bioenergy scenarios

values. Increased transpiration rates (E_{max}) are based on recent measurements that report higher maximum rates of up to 8 mm per day during the growing season [Allen et al., 1999, Beale et al., 1999, Hall et al., 1998, Tricker et al., 2009]. The regular arrangement of crops on plantations improves the overall light availability for individual plants. Consequently, the relevant parameter α_a for CFTs in LPJmL is higher compared to PFTs in natural vegetation [Bondeau et al., 2007]. The same logic was applied to the newly implemented BFTs. Some varieties of C_4 grass species used as energy crops can maintain high rates of photosynthesis at low ambient temperatures [Naidu et al., 2003] and therefore the corresponding parameter ($T_{P,low}$) has been adjusted accordingly.

Table 4.2: BFT specific parameter values for r_{fire} (fire resistance), E_{max} (maximum transpiration rate), α_a (fraction of PAR assimilated at ecosystem level relative to leaf level) and $T_{P,low}$ (lower limit of temperature optimum for photosynthesis). Original values from corresponding PFTs C_4 perennial grass, temperate broadleaved summergreen tree and tropical broadleaved raingreen tree are given in parenthesis.

BFT	r_{fire} (-)	E_{max} (mm/day)	α_a (-)	$T_{P,low}$ (°C)
Temperate biomass tree	0.95 (0.12)	7.0 (5.0)	0.8 (0.5)	
Tropical biomass tree	0.95 (0.12)	7.0 (5.0)	0.9 (0.5)	
C_4 biomass grass	1.0 (0.01)	7.0 (5.0)	1.0 (0.5)	5.0 (20.0)

Table 4.3: Management parameters for woody and herbaceous BFTs in LPJmL.

BFT	Corresponding biomass crops	Harvest interval	Plant density per hectare
Temperate biomass tree	Poplar, Willow	7 years	15000
Tropical biomass tree	Eucalyptus	10 years	2000
C_4 biomass grass	<i>Miscanthus</i> , Switchgrass	1 year	n.a.

Parameters describing plantation management for woody and herbaceous BFTs are given in table 4.3. Woody energy crops are simulated as short rotation coppice (SRC) in which young tree stems are regularly cut down to near ground level at short intervals. An established root system at the time of harvest and nutrient storage in roots and stumps enables high yielding varieties of poplar, willow and eucalypts used for SRC to regrow vigorously in subsequent years (Forrest, 2008). Several harvest cycles are possible until plantations need to be replanted after 40 years. Mortality and fire occurrence on plantations were also reduced compared to natural vegetation, because it is assumed that effective pest and fire control will be established on modern biomass plantations as discussed here. Relative shares of food and energy crops, natural or abandoned vegetation within each grid cell are prescribed in the simulations allowing for transient analyses of future developments in global land use.

Relative shares of food and energy crops, natural or abandoned vegetation within

4.1 Simulating large scale energy crop cultivation: motivation and methods

each grid cell can be prescribed for each grid cell in the simulations allowing for transient analyses of future developments in global land use and the resulting changes in ecosystem services.

Validation

Biomass yield Simulated biomass yields of the different BFTs were compared to current yield levels observed at existing plantations and state-of-the-art estimates of yield levels expected for the coming decades.

Hybrid poplars are especially suitable for short-rotation forestry due to faster growth and higher productivity compared to parental species. The most productive clones are characterized by low canopy extinction coefficients which leads to high rates of canopy photosynthesis. Figure 4.2 compares the performance of poplar (*Populus*) clones grown as short rotation coppice at existing plantations with LPJmL simulations for these regions under current climatic conditions. Modeled biomass yields compare well with observations, although LPJmL shows less variability between the different regions.

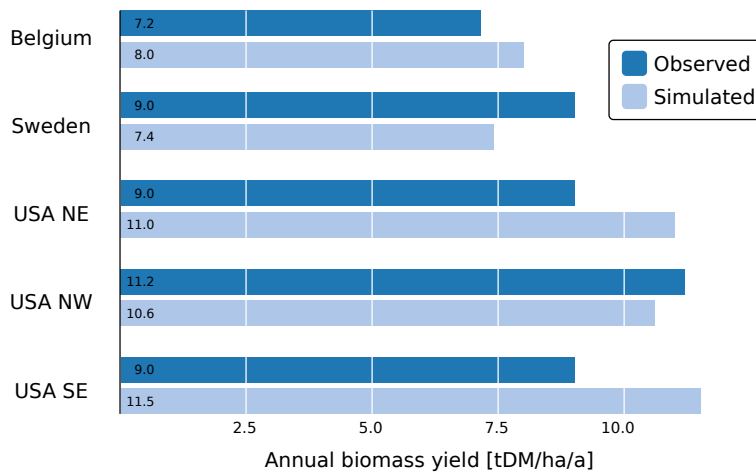


Figure 4.2: Comparison of current observed and simulated biomass yields from short-rotation poplars in Belgium [Pellis et al., 2004], Sweden [Nordh and Verwijst, 2004] and different regions of the US (NE: Northeast, NW: Northwest, SE: Southeast) [Baral and Guhab, 2004].

Eucalyptus is the dominant hardwood on forest plantations in tropical and warmer sub-tropical climates and *Eucalyptus* spp. also predominate as SRWCs [Campinhos Jr., 1999, Rockwood et al., 2004, Stape et al., 2004]. Stape et al. [2004] measured tree growth across a geographic gradient in north-eastern Brazil and derived mean annual biomass increment from stand-specific allometrics. Figure 4.3 shows that LPJmL is capable of reproducing the spatial variability in above-ground biomass productivity in rainfed plantations that is mainly controlled by rainfall. The range of MAI values is also representative for coppiced *Eucalyptus* plantations in tropical Africa [Zewdie et al., 2009].

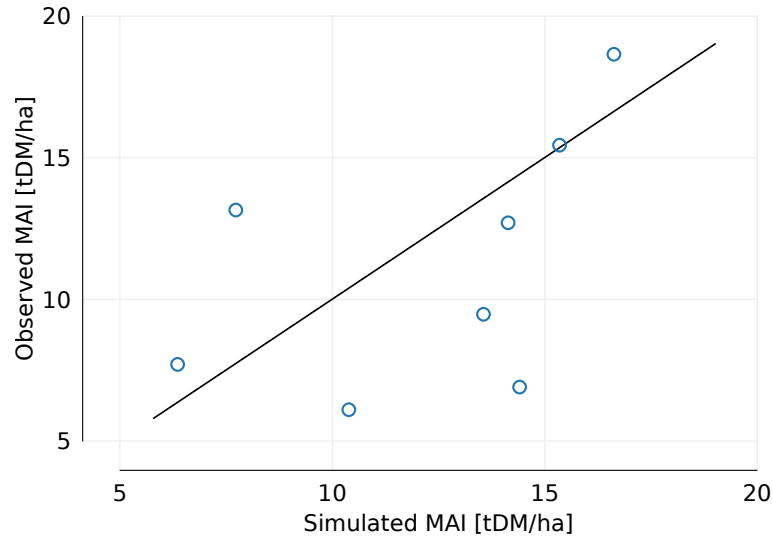


Figure 4.3: Observed and simulated mean annual biomass increment in *Eucalyptus* plantations across geographic gradient in Northeastern Brazil at a rotation age of 6 years [Stape et al., 2004].

Perennial rhizomatous grasses for bioenergy are increasingly grown worldwide, because they establish faster than woody energy crops and allow annual harvests, thus providing a regular yearly income for the farmers. If harvested in late winter or spring, the harvested biomass has a low moisture and mineral content which improves fuel quality. A number of *Miscanthus* trials have been established within the European Union that used *Miscanthus x giganteus*, a sterile triploid interspecific hybrid of *Miscanthus* [Karp and Shield, 2008], because it is highly productive under a wide range of climatic conditions. LPJmL simulations of potential yield levels in five European countries agree well with observations from 'European Miscanthus Improvement' sites (figure 4.4).

LPJmL simulations with the grass-type BFT were also compared to data from MIS-CANMOD, a specific *Miscanthus* productivity model [Clifton-Brown et al., 2004]. Figure 4.5 shows that LPJmL produces similar results for a range of sites that correspond to locations of European field trials.

Switchgrass is the most popular herbaceous biomass crop in the USA because it is a native species and can be used both for energy and forage production. It is expected that intensive breeding can increase average yields significantly by 2025 and even further by 2050 [NRDC, 2004]. Notably, these estimates do not account for the use of genetically modified plants. Current harvest levels and future gains are different for different regions of the USA. Average herbaceous biomass productivity as simulated by LPJmL for 2050 using an A2 scenario [Nakicenovic et al., 2000] from the HadCM3 model [Pope et al., 2000] in these regions is in the range of the 2025 predictions, with maximum values for certain sites reaching the 2050 levels. The general pattern of decreasing productivity between the best and the less suitable switchgrass lands is well reproduced in the simulations. Even though LPJmL overestimates current yield levels of switchgrass in the

4.1 Simulating large scale energy crop cultivation: motivation and methods

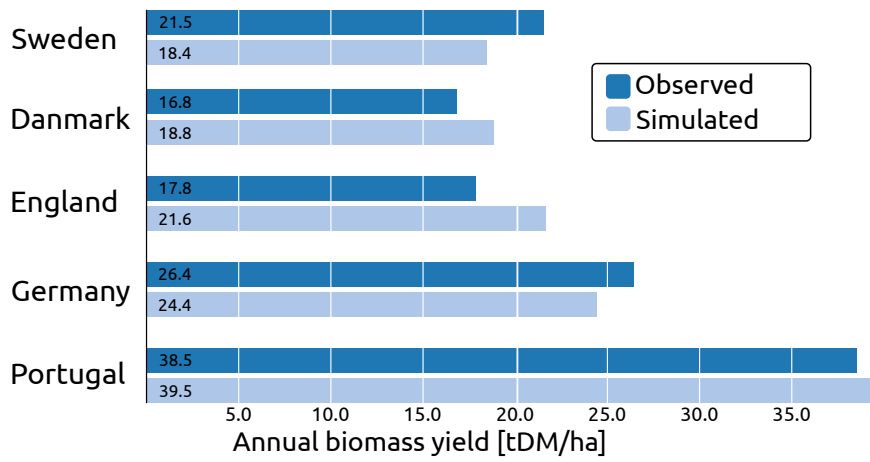


Figure 4.4: Simulated and observed autumn yields of *Miscanthus x giganteus* at some 'European *Miscanthus* Improvement' sites [Clifton-Brown et al., 2004].

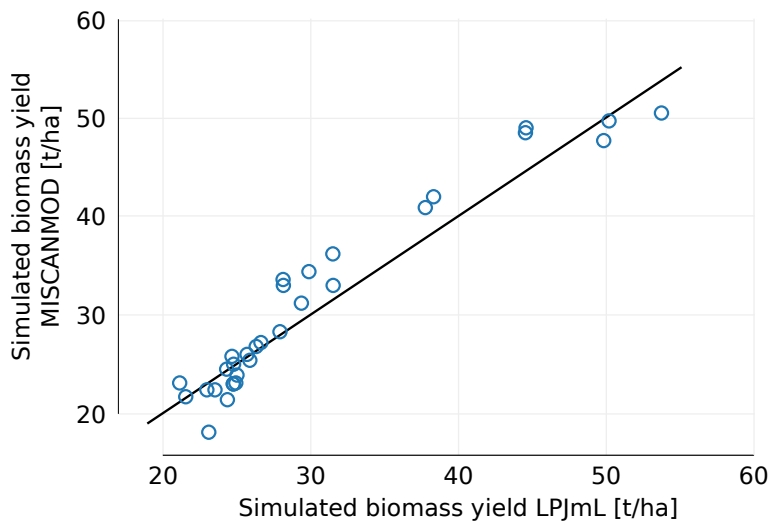


Figure 4.5: Comparison of simulated *Miscanthus* yields at different European sites from MISCANMOD and LPJmL.

4 Global bioenergy scenarios

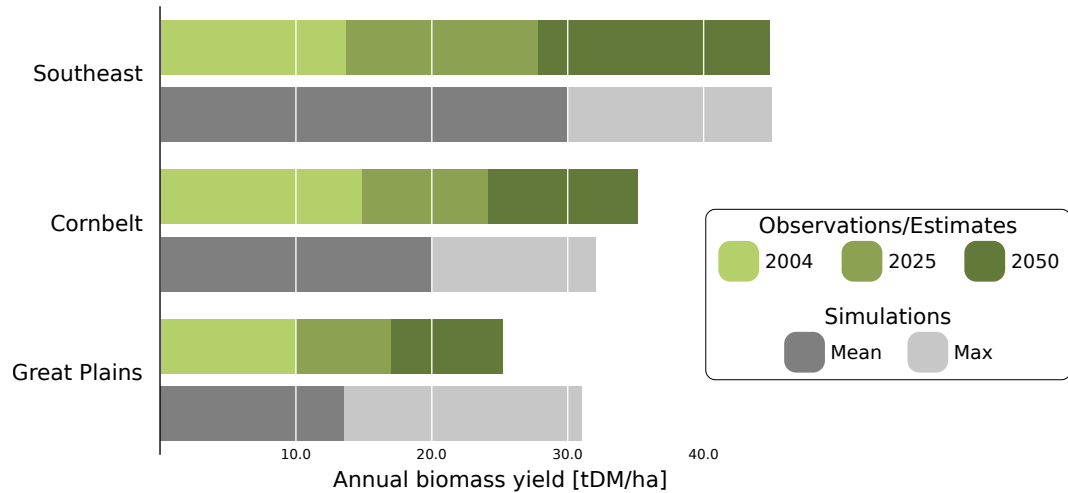


Figure 4.6: Regional averages and maximum simulated switchgrass yields for the year 2050 in different regions of the USA compared to current and projected harvest levels for 2025 and 2050 [NRDC, 2004].

USA, modeled biomass harvests stay within a reasonable range that may well be reached during the first half of this century.

It was shown that LPJmL simulations of biomass yields agree well with observations from existing field trials for a range of geographic locations. Spatial variations in plant productivity due to climatic conditions are also correctly reproduced. The beneficial effect of elevated atmospheric CO₂ on photosynthesis and plant productivity is in line with recent free air CO₂ enrichment experiments, indicating that modeled future increases in biomass harvest are not overestimated. This is also supported by the comparison of LPJmL simulations with anticipated yield potentials until 2050 that assume no genetic modification of energy crops.

4.1.3 Scenario construction

This thesis aims at contributing to a more comprehensive and balanced view of modern bioenergy as a new type of large scale human land use. The flow diagram in figure 4.7 summarizes the general approach used here. Climate scenario data from the IPCC fourth assessment report are used to drive a process based model of natural and agricultural vegetation (LPJmL) that calculates potential biomass yields for lignocellulosic energy crops with and without irrigation at a spatial resolution of 0.5 degrees. Simulated biomass yields are then combined with estimates of available land for dedicated energy crop plantations that are based on different ecological sustainability criteria. Sustainability constraints are chosen, for example, to prevent massive emissions of greenhouse gases due to land use change in ecosystems storing large amounts of carbon. The combination of simulated biomass yields and scenarios of available areas for biomass cultivation a range of potential global bioenergy supply. Land availability estimates are also combined with spatial data sets of terrestrial biogeography and biodiversity (ecosystem data)

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to evaluate the impacts of the estimated bioenergy scenarios on the remaining natural vegetation and wildlife.

The different biodiversity, wilderness and other environmental or land use datasets used in this study are briefly introduced in the following section. Their concrete application in the global bioenergy scenarios described in chapter 4.2 is explained in section 4.1.

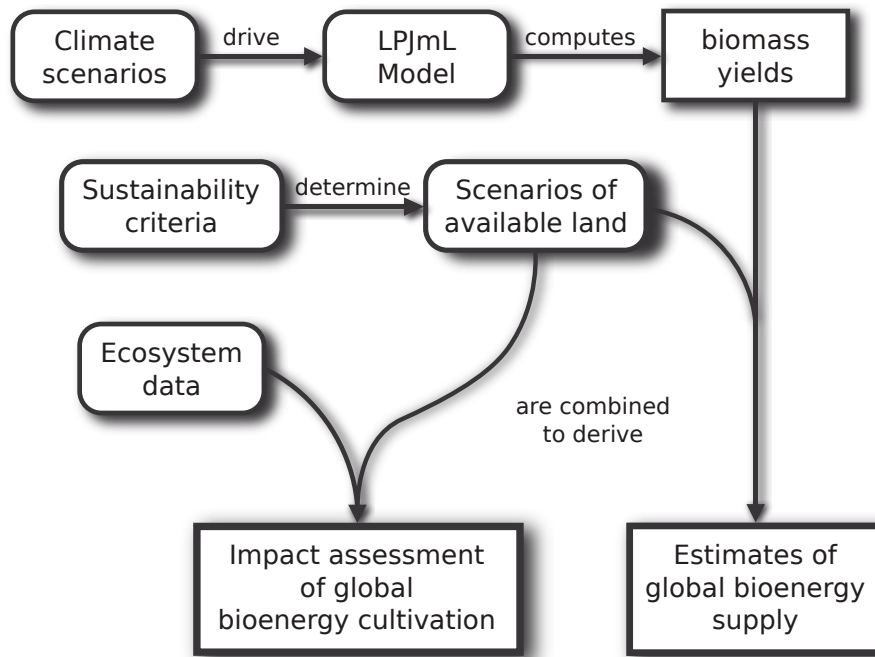


Figure 4.7: Overview of data sources and methods used here to derive estimates of global bioenergy potentials, required changes in land use and further analyses of potentially affected ecosystems.

4.1.4 Environmental data used in the scenarios

Human activities have already accelerated worldwide species extinction rates by a factor of 100-1000 compared to typical background rates that prevailed throughout most of Earth' history [Millenium Ecosystem Assessment, 2005]. Governments worldwide have reacted to this development by creating more than 100000 protected areas in 227 countries or territories that cover about 12 % of the terrestrial land surface (figure 4.8; UNEP-WCMC, 2009).

However, many parts of this global network are not well-managed and effectively protected. In addition, the protected-area system has not been developed strategically and therefore many threatened areas with high conservation value are not included, especially in the tropics [Rodrigues et al., 2004]. Existing protected areas will also be insufficient to prevent future habitat losses driven by climate change [Parmesan and Yohe, 2003] and

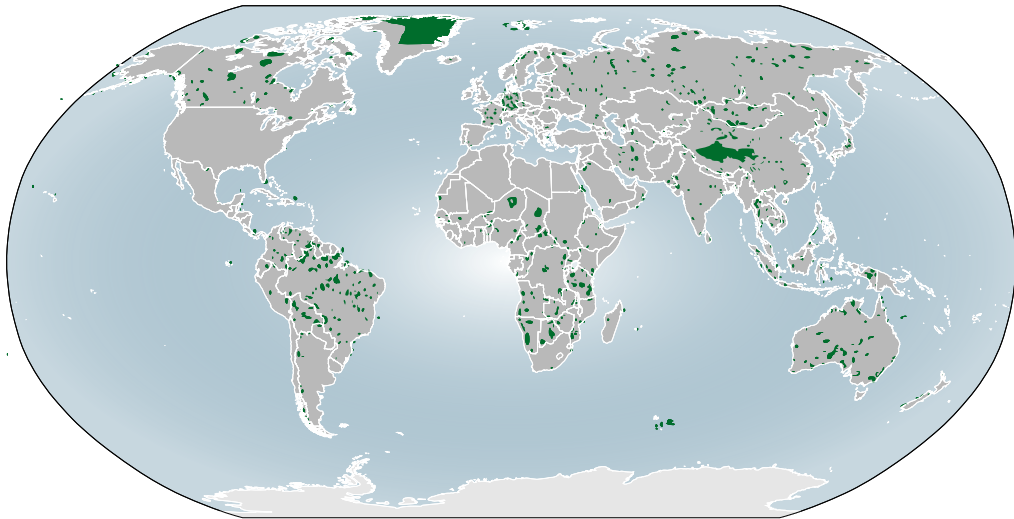


Figure 4.8: Global distribution of national and international protected areas from the World Database on Protected Areas [UNEP-WCMC, 2009].

expanding human activities. Additional land has to be placed under protection in the coming decades in order to solve the global biodiversity and ecosystem crisis [Ehrlich and Pringle, 2008]. The German biomass-electricity-sustainability ordinance (BioSt-NachV) adopted in 2009, for example, excludes biomass obtained from protected areas. In addition, former peatlands, wetlands, ecosystems with large carbon stocks and other land with high nature conservation value are also not accepted as cultivation areas for energy crops. The only exceptions are some traditional forms of human land use with cultural-ecologic value such as heathland.

Different global conservation templates mapping vulnerable and irreplaceable ecosystems have been developed to guide the selection of priority regions for future conservation efforts [Brooks et al., 2006, Naidoo et al., 2008]:

Biodiversity indicators

- Biodiversity hotspots [Myers et al., 2000]
- Centres of Plant Diversity [WWF and IUCN, 1994]
- Global 200 [Olson and Dinerstein, 2002]
- Endemic bird areas [Stattersfield et al., 1998]

Wilderness indicators

4.1 Simulating large scale energy crop cultivation: motivation and methods

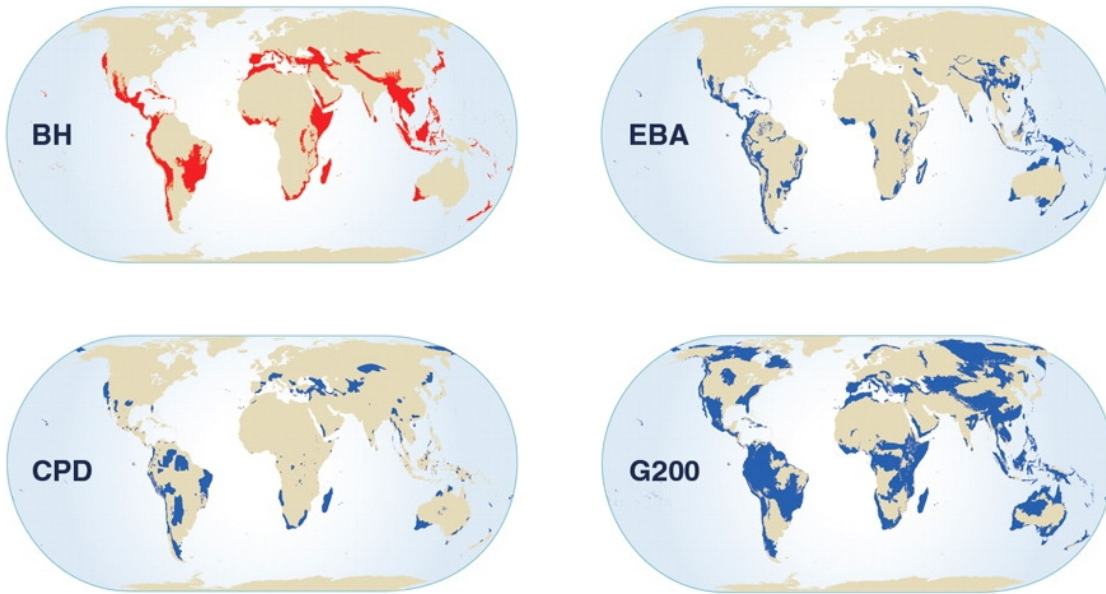


Figure 4.9: Spatial distribution of biodiversity indicators used here to constrain future land use change. BH: biodiversity hotspots [Myers et al., 2000], EBA: endemic bird areas [Stattersfield et al., 1998]; CPD: centers of plant diversity [WWF and IUCN, 1994], G200: global 200 [Olson and Dinerstein, 1998]. Modified from Brooks et al. [2006].

- High-biodiversity wilderness areas [Mittermeier et al., 2003]
- Frontier forests [Bryant et al., 1997]
- Last of the wild [Sanderson et al., 2002]

Based on these datasets, a two-step approach differentiating between biodiversity and wilderness indicators was developed that defines exclusion areas not available for bioenergy crop cultivation in a small set of scenarios. The varying degree of spatial agreement between the different datasets is used as an indicator for conservation value [Brooks et al., 2006, WBGU, 2009]. In this approach, a strong spatial association between many indicators implies a higher need for protection (figure 4.11). The spatial agreement between the biodiversity data sets is generally high. The biodiversity hotspots, for example, have an overlap of about 70% with the EBDs, 80% with the CPDs and 90% with the G200.

The most important shortcoming of this approach is the missing representation of large scale phenomena such as migration and global ecosystem dynamics such as the global carbon cycle. Integrating information about ecosystem fragmentation which ultimately determines the impact of habitat loss on species loss is also not possible at this time because appropriate data is not available on the global scale.

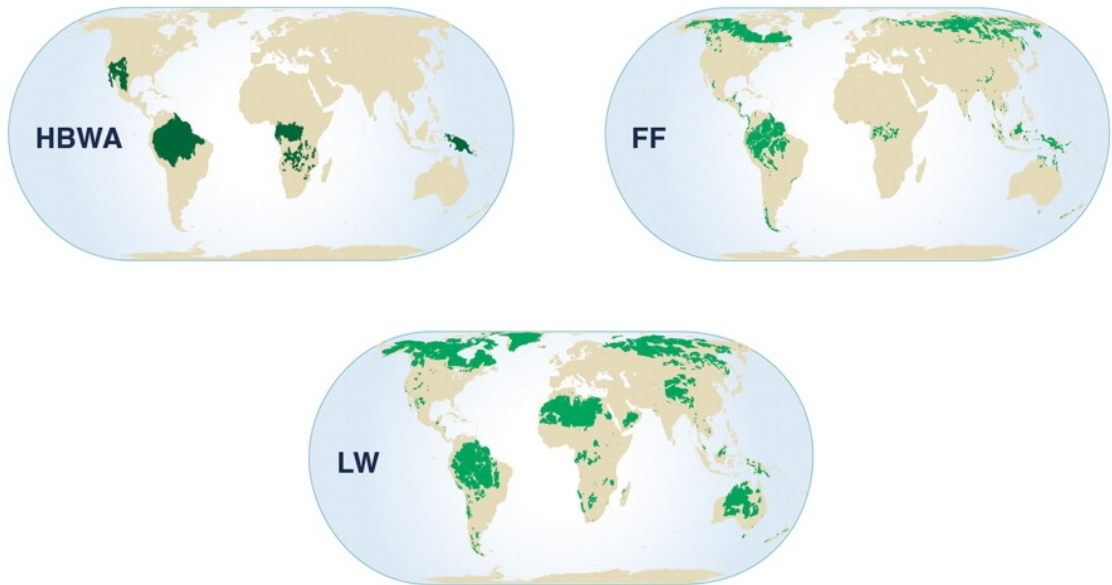


Figure 4.10: Spatial distribution of wilderness indicators used here to constrain future land use change. HBWA: high-biodiversity wilderness areas [Mittermeier et al., 2003], FF: frontier forests [Bryant et al., 1997], LW: last of the wild [Sanderson et al., 2002]. Modified from Brooks et al. [2006].

Biodiversity indicators

Only a few places in the world harbor large parts of animal and plant biodiversity. These regions are regarded as critical in order to prevent the mass loss of between one-third and two-thirds of all species that may go extinct if no further actions are taken to protect their habitats [Millenium Ecosystem Assessment, 2005].

Biodiversity Hotspots More than half of the World's animal and plant species occur in only 16% of the terrestrial land area. Accelerating human land use activities in these regions, even though affecting only a small additional amount land, would substantially increase the risks of large scale extinctions. This applies especially to tropical island states such as Madagascar, Indonesia or the Philippines. The biodiversity hotspots approach uses species diversity, the most accessible form of biodiversity, to identify 34 sites that are home to an extraordinary concentration of endemic species. Take together, these areas cover only about 2.1 million km² (2.3% of the land surface). Human activities have already destroyed more than 70% of the original habitat extent and land use change is continuing rapidly [Brooks and Mittermeier, 2002, Cincotta et al., 2000]. At least 1500 endemic plant species occur in each hotspot, most of them in tropical and Mediterranean ecosystems. Only about 40% the hotspot regions are currently protected.

Centres of Plant Diversity (CPD) More than 230 sites, with mainland regions hosting at least 1000 vascular plant species of which more than 10% are endemic and islands

4.1 Simulating large scale energy crop cultivation: motivation and methods

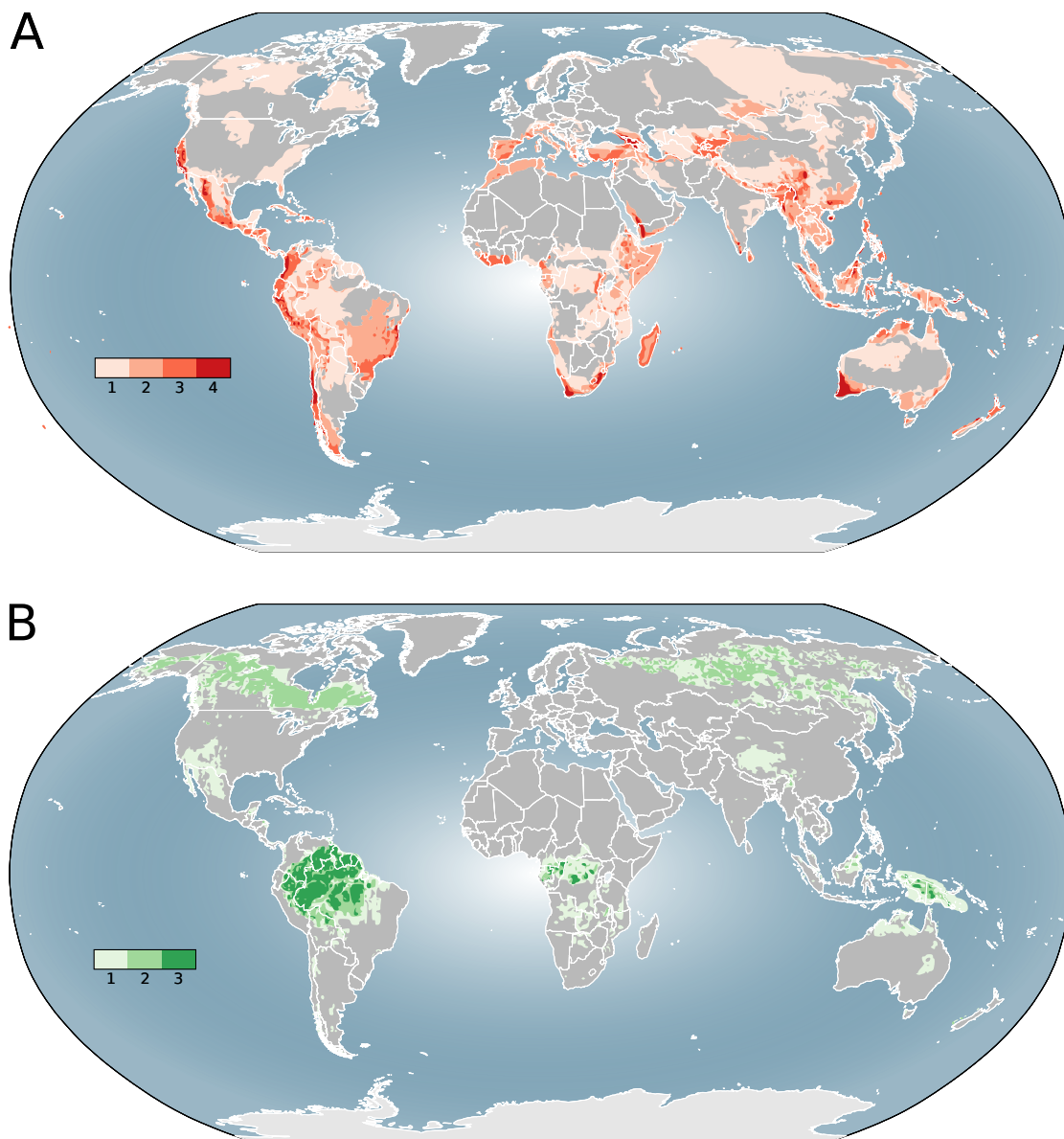


Figure 4.11: Spatial agreement between global conservation templates described in section 4.1.4. Figure 3A depicts the degree of overlap between the four biodiversity indicators (section 4.1.4). Figure 3B shows the spatial overlap between the wilderness indicators (section 4.1.4).

4 *Global bioenergy scenarios*

containing at least 50 endemic species or a minimum 10% share of endemics in the local flora, have been selected as Centres of Plant Diversity [WWF and IUCN, 1994]. Other selection criteria besides species-richness and a high degree of endemism were habitat diversity, value to humans, adaptation of a large number of species to local soil conditions and high risk of extinction. About four thirds of the CPDs are located in forests.

Global 200 (G200) Global 200 [Olson and Dinerstein, 1998] contains the most critical and endangered land, freshwater or marine ecoregions that are outstanding representatives of the Earth' diverse ecosystems and valuable in terms of biological diversity and ecosystem services. Ecoregions are larger units of land or water characterized by exceptional species richness, species endemism, taxonomic uniqueness and global rarity of habitat types.

Endemic Bird Areas (EBA) About 50% of all endemic bird species are now threatened or near-threatened with the other half being highly vulnerable to loss or degradation of habitat. The 218 Endemic Bird Areas [Stattersfield et al., 1998] are home to more than 90% of the World's endemic bird species and provide important habitat for widespread bird species as well. They are predominantly located in the tropical and moist montane forests of Indonesia, Mexico, Brazil, Peru and Colombia. With a total extent of 7.3 million km² (4.5% of the land surface) the EBAs also contain a large number of endemic plants.

Wilderness indicators

Ecosystem services are the benefits that humankind receives from a multitude of resources and processes performed by intact natural ecosystems. Beneficial functions include provisioning services such as food, water and timber, regulating services that control climate, floods, erosion and disease, and cultural services that include more abstract dimensions of human welfare such as recreational, aesthetic and spiritual benefits [Carpenter et al., 2008]. In recent years it has become increasingly clear that the progressive degradation and destruction of natural ecosystems due to human actions is threatening these economically, ecologically and socially important functions of wild nature [Balmford et al., 2002, Dobson et al., 2006, Srinivasan et al., 2008, TEEB, 2009]. The inextricable link between ecosystem destruction and persisting rural poverty are a major challenge for development policy, the livelihoods of half a billion people are threatened by the imminent loss of coral reefs due to rising temperatures and ocean acidification and the unsustainable overexploitation of global fish stocks is responsible for annual losses of about 50 billion US\$ in the fisheries industry [TEEB, 2009, Worldbank, 2010].

Wilderness areas play a key role in this context, because they provide valuable services, such as carbon sequestration and storage, even though they may not support the diverse communities of tropical ecosystems. Furthermore, costs for conserving these areas are comparatively low.

High-biodiversity wilderness areas (HBWA) Mittermeier et al. [2003] defined large contiguous areas of at least 10000 km² where at least 70% the historical habitat extent has largely remained in a natural state and human population density is less than five people per km² as high-biodiversity wilderness areas. The 24 HBWAs cover 65 million km² (44% of the terrestrial land surface) but are home to only 3 % of the human population. They harbor 18% of the World's vascular plants and 10 % of terrestrial vertebrate species, the majority of these species being concentrated into five HBWAs: Amazonia, the Congo forests of Central Africa, New Guinea, the Miombo-Mopane woodlands of Southern Africa and the North American desert complex. Only about 7% of the wilderness regions are currently protected as IUCN categories I-IV areas.

Frontier forests Almost 50% of the Earth' original forest cover has already been lost. Less than half of the remaining forests still exists in larger patches of mostly undisturbed and ecologically intact ecosystems. These frontier forests [Bryant et al., 1997] are predominantly located in Russia, Canada and Brazil and besides contributing a large portion of global ecosystem services, they are home to many groups of indigenous people. About 40% of all frontier forests are directly threatened by human activities such as logging or agricultural clearing. Outside the boreal regions where most most of these forests are located today, even more than three-quarters of these ecosystems are in danger.

Last of the Wild The last of the wild [Sanderson et al., 2002] are a global map of large contiguous areas within each biome that have experienced only very little human influence. Human influence was measured by human population densities, land transformation, accessibility and electrical power infrastructure. Apart from deserts and xeric shrublands, undisturbed tropical and boreal forests are the most important ecosystems depicted by the last of the wild.

Other datasets

GLASOD Land degradation and desertification due to overexploitation and inappropriate land use activities such as land clearance, overgrazing and poor irrigation practices can lead to a long-term decline in land quality and productivity. Land degradation occurs on all continents except Antarctica and is responsible for declining crop yields that erode local and regional food security, biodiversity loss and water pollution [Kaiser, 2004, Scherr, 2000, WBGU, 2004]. Between 10 and 20% of the Earth' drylands are severely degraded, particularly in Sub-Saharan Africa, South-East Asia and South China [Bai et al., 2008, Lal, 2009, Worldbank, 2010]. About 250 million people live in these regions and are directly affected by permanent losses of ecosystem services [Millennium Ecosystem Assessment, 2005], a situation that could seriously deteriorate with climate change and population growth [Reynolds et al., 2007].

Information about the spatial distribution and severity of soil degradation was taken from the Global Assessment of Soil Degradation (GLASOD) database [Oldeman et al., 1991]. GLASOD remains the only available source of global degradation information to date, although it is based on expert judgments collated in the late 1980s. On the basis of

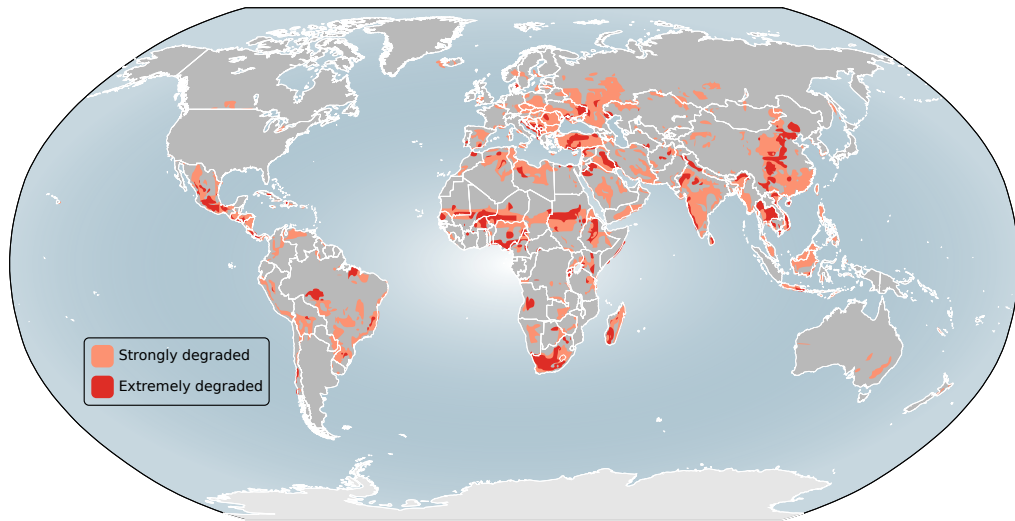


Figure 4.12: Global distribution of strongly degraded (GLASOD Category 3, total area 2400 million hectares) and extremely degraded (GLASOD Category 4, total area 680 million hectares) areas [Oldeman et al., 1991].

physical geographic map units, GLASOD describes the type, degree, extent, cause and rate of degradation within that unit. In addition, a combined score based on severity and degree of degradation is provided that was used here to localize the most degraded that are assumed to be irreclaimable.

Global Lakes and Wetlands Database (GLWD) Natural wetlands such as swamps, marshes, river deltas, peatlands, estuaries, mangroves and tundra occupy only 6% of the planetary surface, but contribute disproportionately to many essential ecosystem services such as carbon storage, flood control and maintenance of biodiversity. Wetlands are estimated to hold between 300 and 700 gigatons of carbon, equivalent to around 20% of the world's soil carbon [Davidson and Janssens, 2006, Keddy et al., 2009]. Wetlands are critical components of watersheds, they recharge water supplies, reduce erosion, provide water filtration and storage, buffer against flooding, provide habitat for a large number of species including many commercial and game fish and are home to some of the Earth's richest diversity in species and ecosystems[Zedler and Kercher, 2005].

More than 50% of global wetlands have already been destroyed through drainage and conversion to other land uses in the past 100 years with many of the remaining wetland areas being degraded or fragmented. The progressive loss of wetlands is responsible for large amounts of carbon emissions as well as serious damage to the provision of ecosystem services. Oil palm cultivation, for example, is responsible for the rapid destruction of Southeast Asian peatlands that leads to substantial biodiversity losses [Fitzherbert et al., 2008] and CO₂ emissions between 350 and 870 Mt per year [Hooijer et al., 2006].

The Convention on Wetlands of International Importance, called the Ramsar Con-

4.1 Simulating large scale energy crop cultivation: motivation and methods

vention, is an intergovernmental treaty that was already established in 1971 to promote the conservation and sustainable use of wetlands. Acknowledging the fundamental ecologic, economic and cultural value of wetlands and that pressure on these ecosystems will increase further with the rising demand for food and bioenergy, there are some initial attempts to integrate wetland protection into sustainability policies for biomass production and trade. The Brazilian government, for example, has announced to exclude the Pantanal wetlands from biofuel production [Sawyer, 2008].

The Global Lakes and Wetlands Database (GLWD) depicts the distribution of lakes and wetlands around the world [Lehner and Döll, 2004] and was used here for exclude these areas from the conversion into agricultural land for energy crops. because of the severe consequences of land use change on biodiversity and substantial emissions of greenhouse gases that are much larger than the climate change mitigation effect of bioenergy use [Gibbs et al., 2008, Koh and Ghazoul, 2008].

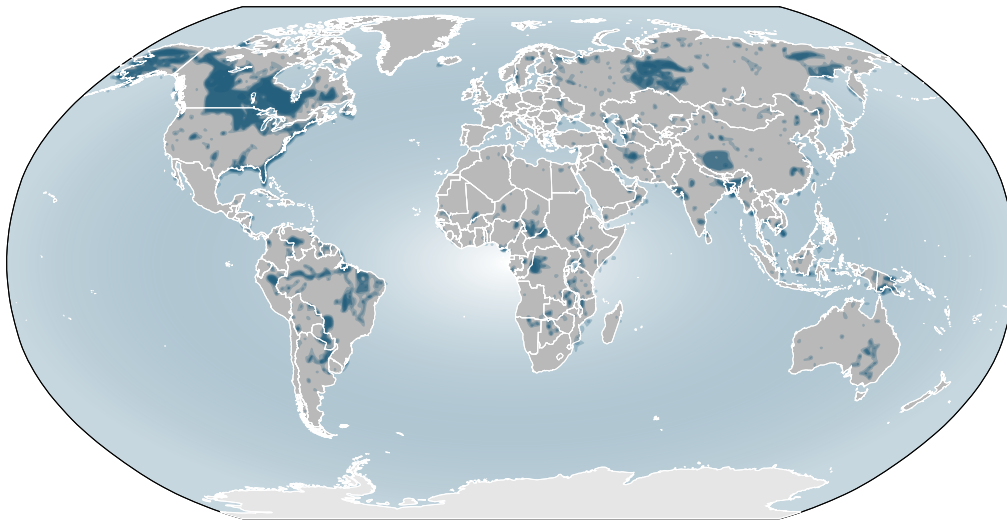


Figure 4.13: Global distribution of wetlands excluded from biomass cultivation. Based on the Global Lakes and Wetlands Database [Lehner and Döll, 2004].

Current cropland area Information about past and present global land use (figure 4.14) is derived from a combination of different datasets that provide historical cropland fractions with a spatial resolution of 0.5° [Monfreda et al., 2008, Ramankutty et al., 2008], relative shares of 18 different crop types for each grid cell [Leff et al., 2004] and the geographic distribution of pastureland [Klein Goldewijk, 2001]. Irrigation is possible where irrigation facilities are available [Portmann et al., 2008]. Urban areas were not included in the land use data, because they cover only about 2% of the land surface and can therefore be neglected [Lambin et al., 2001, Schneider et al., 2009].

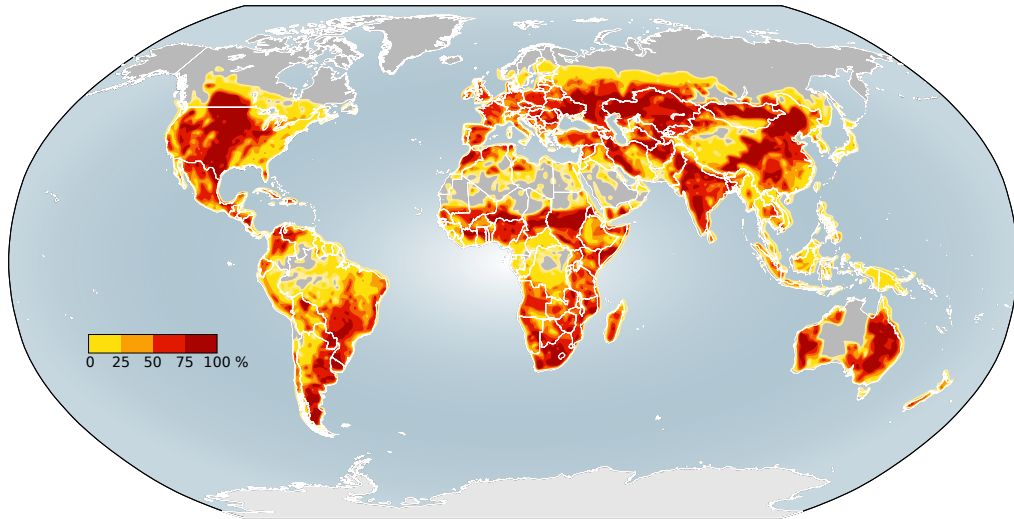


Figure 4.14: Global distribution of agricultural areas for the year 2005 [Bondeau et al., 2007, Klein Goldewijk, 2001, Monfreda et al., 2008, Ramankutty et al., 2008].

Climate data For the simulations presented in this theses LPJmL was driven with a number of climate scenarios that were produced for the Fourth Assessment Report of the IPCC [IPCC, 2007]. From a total of 23 climate models five models were selected that showed the best agreement between simulated and observed values for temperature and precipitation in the period 1961-1990 (table).

4.2 Bioenergy production potential of global biomass plantations under environmental and agricultural constraints

4.2.1 Abstract

We estimate the global bioenergy potential from dedicated biomass plantations in the 21st century under a range of sustainability requirements to safeguard food production, biodiversity and terrestrial carbon storage. We use a process-based model of the land biosphere to simulate rainfed and irrigated biomass yields driven by data from different climate models and combine these simulations with a scenario based assessment of future land availability for energy crops. The resulting spatial patterns of large scale lignocellulosic energy crop cultivation are then investigated with regard to their impacts on land and water resources.

Calculated bioenergy potentials are in the lower range of previous assessments but the combination of all biomass sources may still provide between 130 and 270 EJ per year in 2050, equivalent to 15-25 % of the World's future energy demand. Energy crops account

Table 4.4: Overview of 22 global climate models that contributed climate simulations to the Fourth Assessment Report of the IPCC ranked according to their

Rank	Model	Climate sensitivity
1	ECHAM5	3.4
2	HadCM3	3.3
3	ECHO-G	3.2
4	CCSM3.0	2.7
5	CM2.1	3.4
6	MIROC3.2 medres	4.0
7	CGCM3.1	3.4
8	MIROC3.2 hires	4.3
9	CGCM3.1 T63	3.4
10	CM3	–
11	MK3.0	3.1
12	AOM	–
13	CM2.0	2.9
14	INMCM3.0	2.1
15	GISS Model E R	2.7
16	GISS Model E H	2.7
17	HadGEM1	4.4
18	FGOALS1.0G	2.3
19	CM4	4.4
20	BCM2	–
21	PCM1	2.1
22	CM1	–

for 20-60 % of the total potential depending on land availability and share of irrigated area.

However, a full exploitation of these potentials will further increase the pressure on natural ecosystems with a doubling of current land use change and irrigation water demand. Despite the consideration of sustainability constraints on future agricultural expansion the large scale cultivation of energy crops is a threat to many areas that have already been fragmented and degraded, are rich in biodiversity and provide habitat for many endangered and endemic species.

4.2.2 Introduction

Recent analyses of the transformations required in the global energy system to mitigate dangerous climate change arrive at the conclusion that bioenergy will play an important part in the global energy mix of the next decades [van Vuuren et al., 2010a]. Scenarios that assume, not unrealistically, that CO₂ emissions will continue to rise as they currently do for several more years and peak not before 2020 show a large bioenergy sector that would have to additionally be coupled with carbon capture and storage [Edenhofer et al., 2010, Leimbach et al., 2010] in order to still achieve a 2 degree target of maximal global warming with sufficient likelihood. Transitioning to a low-carbon energy economy while meeting increasing future energy demands would therefore require the rapid development of a large global bioenergy sector, producing between 150 and 400 EJ/year [van Vuuren et al., 2010b]. At this level, all available sources of biomass, dedicated energy crops, harvest and process residues as well as organic waste materials, need to be exploited at a large scale.

Additional arguments have been made for an expansion of bioenergy production: globally traded biomass could add to energy security by reducing dependence of nations on oil, coal and gas imports from limited regions [IEA Bioenergy, 2009, Ragauskas et al., 2006] bioenergy could, some proponents have argued, also create employment in struggling rural economies in the developed world, and provide new income opportunities for farmers in the developing countries and thus help alleviate poverty [Faaij and Domac, 2006, Mathews, 2007]. Private businesses have entered this developing market, anticipating large commercial potentials, scaling up their investments in biofuels and other processing technologies [WBGU, 2009]. At the same time, there are major concerns about the introduction of another large land use sector that could further accelerate deforestation and biodiversity loss [Ehrlich and Pringle, 2008, Melillo et al., 2009]. If not managed correctly, the large scale cultivation of energy crops and a substantial utilization of residues from agriculture and forestry, may actually increase GHG emissions, environmental degradation, introduce new risks for food security and/or marginalize local communities [WBGU, 2009]. Clearing carbon-rich ecosystems for biomass plantations leads to substantial losses of CO₂ from vegetation and soils into the atmosphere. If tropical forests or peatlands are converted, it may take more than 100 years until the associated carbon debt is compensated by the replacement of fossil fuels [Gibbs et al., 2008, Searchinger et al., 2008]. The destruction or fragmentation of pristine ecosystems for new cultivated areas also contributes to the ongoing degradation of the World's

biodiversity [Eggers et al., 2009, Fitzherbert et al., 2008]. Most plants converted into biofuels today are modern food crops that are responsible for massive N₂O emissions and nitrogen leaching due to their overdependence upon agrochemicals [Crutzen et al., 2008, Donner and Kucharik, 2008]. In addition, biomass production is very water intensive and may thus contribute to regional water shortages, salinization and water logging [Gerbens-Leenes et al., 2009, Tilman et al., 2001]. Some, however argue that biomass plantations, if managed well, may actually increase biodiversity Baum et al. [2009b], Semere and Slater [2007] and soil qualities [Baum et al., 2009a, Tilman et al., 2006], at least on previously degraded land.

While the environmental sustainability of large scale bioenergy production raises serious questions, the technology is still regarded as a key bridging technology during the transformation towards a low carbon society because it has the potential to deliver negative carbon emissions at comparatively low costs required for substantial emission reductions [WBGU, 2009]. In this context, attempts have been made to estimate “sustainable bioenergy potentials” on the basis of land use restrictions to avoid additional greenhouse gas emissions and biodiversity loss [Fang et al., 2005, van Vuuren et al., 2009, WBGU, 2009]. Here we study the global potential of dedicated biomass plantations for bioenergy under environmental and agricultural constraints using an advanced biogeochemical model of plant carbon and water balances and study some of the broad implications that follow.

Biomass for bioenergy – The role of dedicated energy crops as a source of biomass

Different sources of biomass are available for energy production. These fall into three main categories: residues from agriculture and forestry, organic wastes, surplus forestry, and energy crops. Dedicated energy crops are generally assumed to make up most of the total potential [Berndes et al., 2003, IEA Bioenergy, 2009], although their large scale cultivation is also one of the most controversial aspects of bioenergy. By contrast, residues and waste materials are considered to be more sustainable because they entail fewer direct impacts on land use [WBGU, 2009]; their indirect impacts, however, are also discussed controversially.

Agricultural residues, for example, are also required to maintain soil organic matter and prevent erosion and their excessive removal can damage soil quality and reduce agronomic productivity [Blanco-Canqui and Lal, 2009, Lal, 2010]; in forests, detritus supports important elements of the ecosystem [Chapin et al., 2002] and its removal may lead to the depletion of nutrient pools essential for long-term soil fertility and plant growth [Åkselsson et al., 2007].

Recent analyses of energy crops have shown that current practices to convert food-product carbohydrates or plant oils into ethanol and biodiesel have only limited, if any capabilities to curb emissions [Crutzen et al., 2008, Fargione et al., 2008]. They also compete directly with food production for the most fertile lands [Lapola et al., 2010, Melillo et al., 2009, Searchinger et al., 2008]. High hopes rest therefore on the development of second generation bioenergy technologies based on the conversion of lignocellulosic plant materials from fast growing tree and grass species. These energy

4 Global bioenergy scenarios

crops, such as poplar, willow, Miscanthus and Panicum (switchgrass) are less dependent on favorable climatic and soil conditions and require fewer inputs of agrochemicals, thus reducing their direct competition with food production. Because most of the harvested aboveground biomass is fed into a conversion process, per area energy yields and the potential to reduce GHG emissions are inherently higher [Adler et al., 2007, Farrell et al., 2006, Schmer et al., 2008]. Although technologies required to process cellulosic feedstocks into electricity, heat, biofuels or biomaterials are not yet commercially competitive, they are expected to mature within the next 10 to 20 years [Faaij and Domac, 2006, Ragauskas et al., 2006].

But how large is the potential of global bioenergy plantations when environmental and agricultural constraints are taken into account? The literature on this question is quickly growing but currently shows a wide variety of estimates, ranging from some 30 to 700 EJ for the World's total bioenergy potential, not taking into account some extreme scenarios [Campbell et al., 2008, de Vries et al., 2007, Dornburg et al., 2008, Field et al., 2008, Reinhardt et al., 2007, Tilman et al., 2006, van Vuuren et al., 2009, WBGU, 2003, 2009, Wise et al., 2009]. For comparison, the World's current total primary energy supply is about 510 EJ/a [IEA, 2010] and expected to reach 600-1000 EJ/a by 2050 [IEA Bioenergy, 2009].

This is partially due to differences in assumptions and effects included, and partly due to tradeoffs with other interests on land determining the potential. Such tradeoffs cannot be resolved by science, only investigated. The requirements of environmental conservation, such as limiting future deforestation, and the emerging need to provide an additional 2-3 billion people with food and fiber by mid-century are the main factors competing with bioenergy production for land. Some published estimates indicate that a large bioenergy potential can be realized through the use of marginal or abandoned lands and utilizing the agricultural intensification potentials offering themselves on land, at least theoretically.

There are, however, major social risks involved in the use of abandoned or marginal land for biomass cultivation. These areas are often not privately owned and used by small scale farmers and the rural poor for food crops, livestock grazing, or fuelwood collection [WBGU, 2009]. Large scale land privatization may therefore lead to the displacement of rural communities [Cotula et al., 2009, Friends of the Earth Europe, 2010].

However, many of these studies have not been based on rigorous biogeochemical and bioclimatic analysis of plant growth potentials around the world, but have extrapolated findings from plantation field studies to the larger scale and have assumed rapid progress in corresponding bioenergy plant breeding [Smeets et al., 2007]. For example, the strong limitations imposed upon global biomass potential due to limitations in the water available for plant transpiration [Rost et al., 2009] has been frequently underestimated or downplayed, if not ignored [Berndes, 2002]. The magnitude of global bioenergy potential including such effects therefore remains uncertain.

The scope of this paper

It is the purpose of this paper to investigate the potential of lignocellulosic biomass plantations to contribute to a future global bioenergy mix, and to investigate some of the implied consequences. Assessments of global bioenergy potentials suffer inherently from a lack of data and limited field experience from extensive biomass cultivation. Large scale plantations of lignocellulosic crops do not exist yet and it is debatable whether yield levels observed at controlled test sites are transferable to huge areas with less favorable climate, soil and management conditions.

Therefore, we use here a well-established and well-tested global biogeochemical model of plant growth, carbon exchange, and water limitations, LPJmL [Bondeau et al., 2007], expanded to include biomass plantations, to compute state-of-the-art biogeochemical potentials under spatially varying present and future climatic conditions. Available observations from test plantations are used to validate the model and climate scenarios from the latest IPCC assessment report [Meehl et al., 2007] to simulate global future yield potentials. These estimates are combined with a set of four scenarios of land availability for biomass plantations that consider the spatial requirements for future food production and nature conservation. We then analyze the environmental consequences of these scenarios in terms of ecosystem change, freshwater consumption and fertilizer demand to highlight the order-of-magnitude of some inevitable consequences of currently so-called “sustainable” bioenergy potentials.

Our study follows strictly a food first paradigm, assuming that a strongly increasing world calorie demand in the next 50 years will already require an increase in global food production by about 70 % [FAO, 2009b] that will in itself be a challenge and therefore land currently used for food and fiber production will not be available for dedicated biomass plantations, at least not by mid-century. In accordance with projections of the FAO [2003], we therefore exclude current agricultural lands from bioenergy production, recognizing that there may indeed be additional potential on these lands at least in some regions, and in some in the interim.

We note that our computations are made in the face of a number of fundamental uncertainties that remain: the extent of future yield improvements in species suitable for biomass plantations, most of which have not undergone extensive cultivation and breeding for this purpose [Karp and Shield, 2008]; the magnitude of carbon dioxide fertilization effects on plant growth and the associated plant physiological effects of increased plant water use efficiency [Long et al., 2006, Oliver et al., 2009]. Our study does not investigate the economic, political or institutional realism of these potentials, as we aim at determining the magnitude of the potential that could be achieved as the maximum under environmental and agricultural constraints. Real-world potentials will be lower and follow complex deployment pathways in time [Knopf et al., 2010].

4.2.3 Methods

LPJmL DGVM

LPJmL is a model of the terrestrial land surface that represents both natural and managed ecosystems at the global scale [Bondeau et al., 2007, Sitch et al., 2003]. Major ecosystem processes controlling plant geography, physiology, biogeochemistry and vegetation dynamics are represented in the model to simulate the exchange of carbon and water between the atmosphere and the land biota. Photosynthesis is calculated using a modified Farquhar scheme [Farquhar et al., 1980, Collatz et al., 1992] coupled to a soil water scheme [Neilson, 1995] to compute gross primary production and plant respiration [Haxeltine and Prentice, 1996]. Soil respiration is estimated as a function of temperature and soil moisture based on a modified Arrhenius formulation [Lloyd and Taylor, 1994] in combination with an empirical soil moisture relationship [Foley, 1995]. The diversity of the world's flora is described in the form of 9 plant functional types (PFTs), representing natural vegetation, and 12 crop functional types (CFTs), representing the most important economic crops [Bondeau et al., 2007, Gerten et al., 2004]. LPJmL is driven by monthly fields of temperature, precipitation, cloud cover, atmospheric CO₂ concentration, and soil texture [Sitch et al., 2003]. The model has been successfully evaluated against various observational data, such as net primary production [Cramer et al., 1999], vegetation activity measured by leaf area index [Lucht et al., 2002], biosphere-atmosphere carbon exchange over both natural and agricultural lands [Bondeau et al., 2007, Erbrect and Lucht, 2006, Peylin et al., 2005], and runoff [Gerten et al., 2004]. The plant water balance as a limitation to agricultural production has also been studied [Rost et al., 2009].

Recently, we developed LPJmL further to simulate the cultivation of cellulosic energy crops on dedicated biomass plantations. Three additional highly productive bioenergy functional CFTs were introduced into the model (Table 4.5), two tree species for temperate and tropical regions, and one fast growing grass. Note that due to the inherent uncertainty in the future performance of lignocellulosic energy crops, differentiating more types, though possible, does not yield increased accuracy, and that environmental variations alter potentials depending on location and year. Tree CFTs were parametrized as temperate deciduous, to match the field performance of poplars and willows, and tropical evergreens, respectively, to reproduce growth and biomass production of appropriate Eucalyptus species. Energy trees are managed as short rotation crops and coppiced every 8 years [Lemus and Lal, 2005]. The implementation of energy grasses reflects growth and productivity characteristics of *Miscanthus* and switchgrass cultivars. To be noted is the fact that in contrast to other important agronomic species that use the C₄ photosynthetic pathway, such as Maize or sugarcane, *Miscanthus* can maintain high rates of photosynthesis at low ambient temperatures around 5°C [Naidu et al., 2003]. Simulated grasses are harvested annually at the end of the growing season.

Freshwater availability for irrigation is calculated on the watershed level [Arnell, 2004], including only renewable water resources [Rost et al., 2008a]. Irrigation of biomass plantations is possible where excess surface runoff is available after sufficient water has

Table 4.5: CFT parameter values: minimum canopy conductance (g_{min}), leaf longevity (a_{leaf}), leaf sapwood ($f_{sapwood}$), and fine root (f_{root}) turnover times, minimum temperature of the coldest month for survival ($T_{c,min}$), maximum temperature of the coldest month for establishment ($T_{c,max}$), rotation length (R) and maximum time before replanting of plantation (R_{max})

CFT	g_{min} ($mm s^{-1}$)	a_{leaf} (yr)	f_{leaf} (yr^{-1})	$f_{sapwood}$ (yr^{-1})	f_{root} (yr^{-1})	$T_{c,min}$ ($^{\circ}C$)	$T_{c,max}$ ($^{\circ}C$)	R (yr)	R_{max} (yr)
Tropical tree	0.2	2.0	2	10	2	7	-	8	40
Temperate tree	0.3	0.5	1	10	1	-30	8	8	40
C ₄ grass	0.5	0.5	1	-	2	-40	-	-	-

been allocated to food production and natural ecosystems [Smakhtin et al., 2004].

Fig. 4.15 shows simulated rainfed yield potentials of grasses and trees under current climate. In the the lower panels, the reduction of yield levels relative to irrigated biomass cultivation highlights the spatial pattern of the impact of water stress on biomass cultivation (here measured as the ratio of not water-stressed to actual net primary production, i.e. annual growth).

This modified version of LPJmL was validated against observations both from existing biomass plantations as well as predictions of biomass yield levels in 2050 [Aylott et al., 2008, Baral and Guhab, 2004, Clifton-Brown et al., 2004, Dowell et al., 2009, NRDC, 2004, Pellis et al., 2004, Stape et al., 2010].

Compared to the reference data, we find that LPJmL simulations of biomass yields are in the right order of magnitude and show a realistic spatial variability (Fig. 4.16). Among the different ecophysiological processes affected by climate change, the positive impact of elevated CO₂ on vegetation productivity, known as CO₂ fertilization, is the most important driver of rising biomass yields in the simulations. The magnitude of this effect is debated [Korner et al., 2005, Norby et al., 2005]. Modeled net primary production of woody energy crops in 2050 is 20-30% higher compared to present climate and atmospheric CO₂ concentrations. CO₂ induced stomatal closure is responsible for higher water use efficiency through reduced transpiration and thus increasing soil water availability. Largest gains in NPP occur in warm and dry regions where potential evapotranspiration is highest. These gains are well within the range of observed CO₂ fertilization in FACE experiments with poplar and other species grown as SRWC [Calfapietra et al., 2003, Hickler et al., 2008, Liberloo et al., 2006, Norby et al., 2005].

For this study, we ran LPJmL with 21st century climate projections from 5 general circulation models based on SRES emission trajectories A1B, A2 and B1 [IPCC, 2000] that were produced for the IPCC's fourth assessment report. The climate models selected due to their ability to reproduce current temperatures and precipitation correctly were ECHAM5 [Röckner et al., 2003], HadCM3 [Pope et al., 2000], CM2.1 [Delworth et al., 2006], ECHO-G [Legutke and Voss, 1999] and CCSM3.0 [Collins et al., 2006].

Scenarios of sustainable land use

General land use constraints In order to estimate future land availability for energy crop cultivation we used four scenarios (developed jointly with the WBGU for it's latest flagship report [WBGU, 2009]). These scenarios prioritize food security and climate change mitigation as central elements of sustainable land management [Steffen, 2009] and define a set of spatial constraints to reduce adverse effects of large scale biomass cultivation on food production, biodiversity and greenhouse gas emissions .

Some areas are completely excluded from any human use in all scenarios, such as conservation areas [UNEP-WCMC, 2009] and wetlands [Lehner and Döll, 2004], that are home to a diverse range of species and store large amounts of carbon. Forests and other important carbon reservoirs where simulated carbon losses after land use change are not compensated for by subsequent biomass yields within 10 years are also not used to calculate global bioenergy potentials. Likewise, the conversion of current croplands

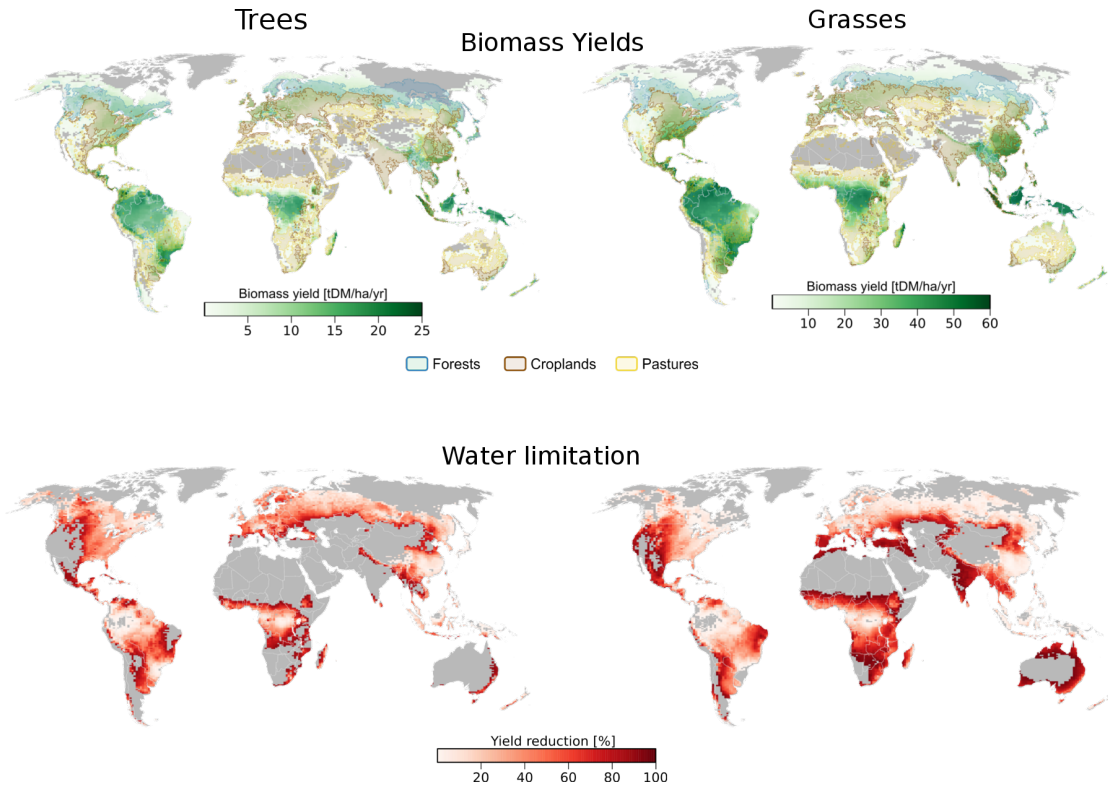


Figure 4.15: LPJmL simulations of rainfed biomass yields and water limitation under current climate. The upper images show simulated biomass yields for woody and herbaceous energy crops averaged over the 1966-2005 period. Current distributions of croplands, pastures and forests are taken from the HYDE database [Klein Goldewijk et al., 2010]. The lower part of this figure illustrates the reduction of potential rainfed biomass yields due to water limitations relative to irrigated biomass yields assuming unlimited water supply.

4 Global bioenergy scenarios

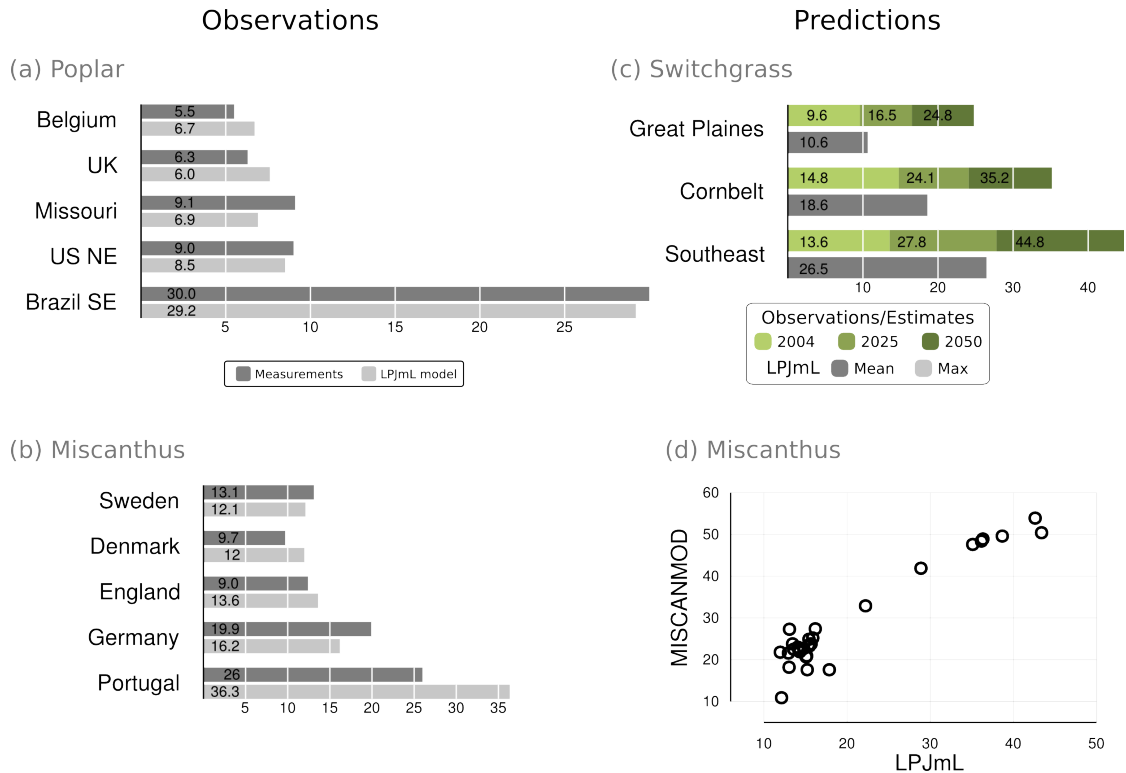


Figure 4.16: Comparison of simulated biomass yields with observed (a) Poplar [Aylott et al., 2008, Baral and Guhab, 2004, Dowell et al., 2009, Pellis et al., 2004, Stape et al., 2010] and Eucalyptus yields, (b) observed Miscanthus yields [Clifton-Brown et al., 2004], current and predicted yields of (c) Switchgrass in different regions of North America [NRDC, 2004], and with simulation results for Miscanthus cultivation in Europe from the specialized energy crop model MISCANMOD [Clifton-Brown et al., 2004]. Annual biomass yields are given in metric tons dry-matter per hectare and year.

and pastures [Fader et al., 2010] was not allowed. Soil degradation may now affect nearly a quarter of the land surface [Bai et al., 2008], so that some areas potentially available for biomass plantations are likely to suffer from accelerated erosion, nutrient depletion, or salinization and thus reduced yield potentials [Lal, 2009]. It is assumed biomass cultivation is impossible on the most severely degraded soils [Oldeman et al., 1991] and achievable yield levels are reduced by 50% where degradation is high.

Land for food production The first scenario (F1) follows a prediction by the United Nations Food and Agriculture Organization (FAO) in which cropland for food production expands by 120 Mha until 2030 [FAO, 2003]. Based on LPJmL simulations of food crops, additional areas were allocated to the most productive lands. The second scenario (F2) assumes no further expansion of agriculture over the present extent. This implies that any increases in food demand are covered exclusively through intensified production. It

also implies that the current agricultural land expansion [FAOSTAT, 2010] is brought to a halt. At the same, recent trends of declining yield increases have to be reversed and stabilized at about 1.2 % per year, slightly below historical rates of yield increases that averaged 1.4 % between 1970 and 1995 [Lotze-Campen et al., 2010]. In view of progressive soil degradation [Millennium Ecosystem Assessment, 2005] and the increasing effects of climate change [Lobell et al., 2008] this is nevertheless an optimistic scenario.

Biodiversity and nature conservation Likewise, two scenarios account for future needs in nature protection [Brooks and Mittermeier, 2002, Naidoo et al., 2008, Rodrigues et al., 2004]. Seven data sets featuring pristine wilderness areas (High-Biodiversity Wilderness Areas [Mittermeier et al., 2003], Frontier Forests [Bryant et al., 1997], Last of the Wild [Sanderson et al., 2002]) and areas with exceptional concentrations of biodiversity (Biodiversity Hotspots [Myers et al., 2000], Endemic Bird Areas [Stattersfield et al., 1998], Centres of Plant Diversity [WWF and IUCN, 1994] and Global 200 [Olson and Dinerstein, 2002]) were used to derive conservation priorities. Following the approach of Brooks et al. [2006], the more of these data sets occur in an area, the higher the share of this area taken to be unavailable for energy crops (see Table 4.6 for an overview).

Table 4.6: Share of natural areas within a grid cell excluded from biomass cultivation to conserve hotspots of biodiversity and valuable wilderness areas. The spatial agreement between seven indicator data sets [Brooks et al., 2006] is used to assess the need for future protection: High-Biodiversity Wilderness Areas [Mittermeier et al., 2003], Frontier Forests [Bryant et al., 1997], Last of the Wild [Sanderson et al., 2002], Biodiversity Hotspots [Myers et al., 2000], Endemic Bird Areas [Stattersfield et al., 1998], Centres of Plant Diversity [WWF and IUCN, 1994] and Global 200 [Olson and Dinerstein, 2002].

Scenario	Number of spatial agreements between data sets							
	Wilderness indicators		Biodiversity indicators					
C1	0	1 - 3	0	1	2	3	4	
C2	0 - 1	2 - 3	0 - 2			3	4	
	0%	100%	0%	10%	20%	30%	50%	80%
	Share of exclusion areas in grid cell							

Criteria for wilderness areas and biodiversity indicators are applied separately, with the more stringent rule applied. In the more restrictive conservation scenario C1, all wilderness areas included in at least one of the data sets are fully protected, while in scenario C2 areas are excluded if two or more wilderness indicators concur. For the biodiversity indicators, following the Convention on Biological Diversity's recommendations to establish a comprehensive and representative system of protected areas including all ecoregions [Secretariat of the Convention on Biological Diversity, 2006], 10 % of all natural areas are always protected in C1. The proportion of land under protection rises to 20 % where one biodiversity indicator is present, and to 30%, 50%, and 80%, respectively, where two, three, and four data sets concur. Scenario C2 is less stringent and

excludes wilderness areas only if they appear in two or more data sets. In addition, 50 % and 80 % of the areas with high biological diversity are protected where three or four, respectively, indicators agree spatially.

Four scenarios of land availability are derived from the combination of all spatial constraints and scenarios for food production and nature conservation (Table 4.7). Fig. 4.17 shows the spatial distribution of the different exclusion criteria in scenario III and the resulting land availability for biomass plantations.

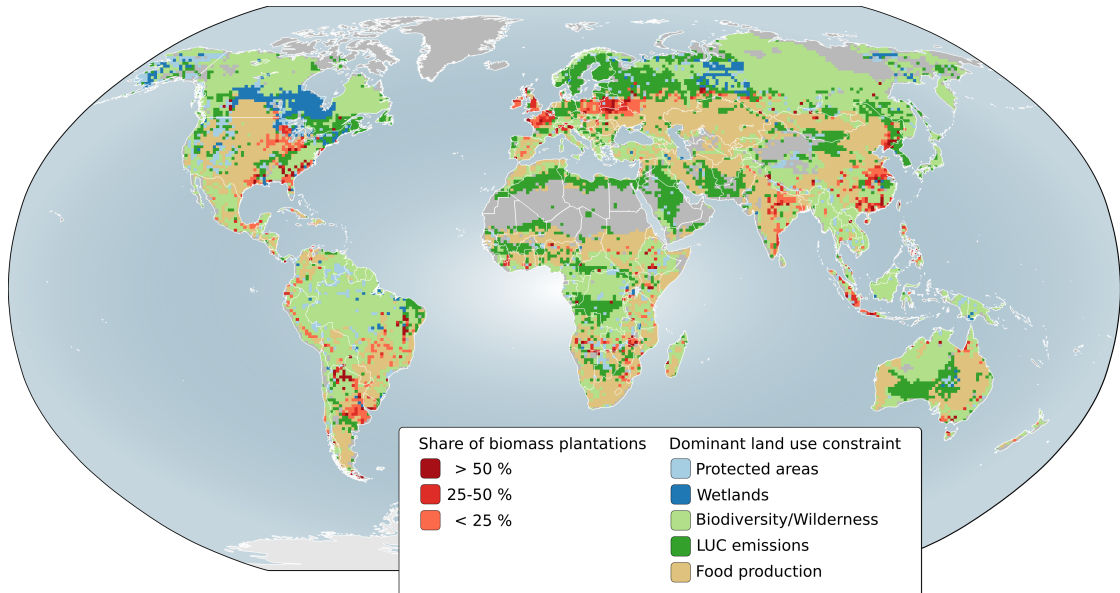
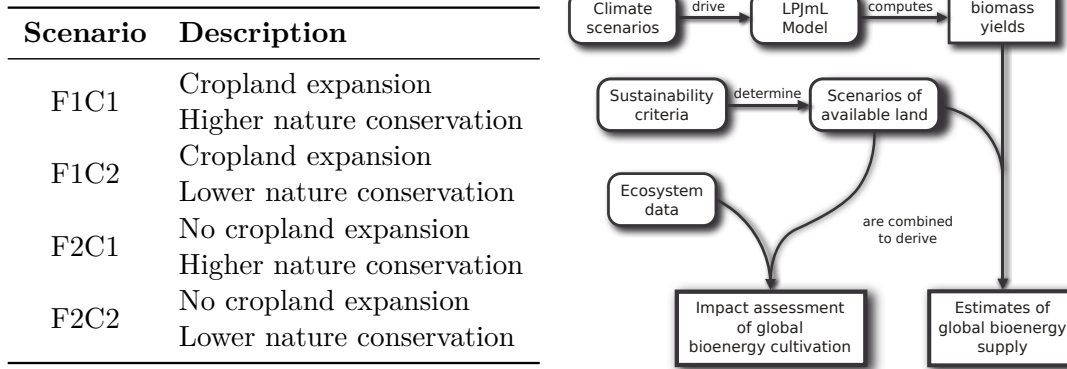


Figure 4.17: Spatial distribution of potential bioenergy plantations and their relative share within grid cells in scenario F2C1. Dominant land use constraints are shown where the cultivation of energy crops is not allowed in this scenario. These areas are excluded because they are already protected (*Protected areas*), belong to the World’s remaining wetlands (*Wetlands*), contain large contiguous areas of undisturbed ecosystems with high nature conservation value due to the provision of important ecosystem services or high concentrations of biodiversity (*Wilderness/Biodiversity*), carbon losses would result from land conversion that can not be compensated by subsequent carbon uptake within a compensation period of 10 years (*LUC emissions*), or because they are already agricultural areas required for food production (*Food production*). Note that in most cases several constraints apply at the same time.

4.2.4 Results

We find that global rainfed bioenergy potentials range between 26 and 116 EJ/yr by 2050 (Fig. 4.18). Of these, around a quarter originate from woody plantations assuming that short rotation and herbaceous crops are cultivated in equal shares where climatic conditions allow. Using renewable surface runoff for irrigation could increase bioenergy production from dedicated plantations to 52-174 EJ per year. These potentials imply

Table 4.7: Brief overview of the four scenarios that define land availability for energy crop plantations. The flow diagram shows the methodology used here to estimate global bioenergy potentials and to evaluate potential impacts of large scale biomass cultivation.



142 to 454 Mha of new biomass plantations replacing natural vegetation, expanding the world's cropland area by another 10-30% over the current extent.

In our simulations water consumption for irrigation of biomass plantations amounts to 1481-3880 km³/yr. In other words, while using all renewable water resources for biomass cultivation increases bioenergy production by 70% on average, agricultural irrigation water use would approximately double compared to current values of about 2500 km³/yr [Rost et al., 2008a]. Realistic and achievable shares of irrigated energy crop cultivation are probably much smaller, because major parts of the land that might be used for energy crops are located in developing countries where water requirements for food production are expected to increase significantly during this century [CAWMA, 2007] and economic conditions may constrain the implementation of large scale irrigation systems and advanced water management strategies [Rost et al., 2009].

Some regions with favorable climatic conditions and abundant land resources appear particularly suitable for the large scale cultivation of energy crops. South America alone is responsible for about a quarter of the total bioenergy potentials in the four scenarios. Together with Sub-Saharan and Southern Africa, North America, China and Europe, they provide about 75 % of global biomass yields (Table 4.8).

Establishing and maintaining large supplies of bioenergy from dedicated energy crops as described by our scenarios will increase the pressure on the World's land resources substantially and thus poses large challenges for infrastructural and institutional capacities, especially if, for example, modern irrigation technologies need to be installed or biomass certification systems have to be implemented. Converting 142-454 Mha of natural ecosystems into modern biomass plantations until 2025 means that on average between 10 and 30 Mha of new plantations are taken into operation each year. Compared to the 1961-2005 period when about 14 Mha of new permanent crops and pastures were developed annually [FAOSTAT, 2010], land use change activities would have to double on average for bioenergy alone.

Table 4.8: Relative contribution of different world regions to global bioenergy potentials from biomass plantations averaged over all scenarios.

Share of global bioenergy potential in world regions [%]					
	NAM	SAM	ESA	AFR	EUR
2050	26	18	17	14	11
2100	21	20	15	16	14

NAM: North America; SAM: South America; ESA: Eastern and Southern Asia; AFR: Sub-Saharan Africa; EUR: Europe.

Nutrients extracted from the soil when biomass is harvested need to be replaced in order to sustain high yields in the long term [Karp and Shield, 2008]. Following Crutzen et al. [2008], we estimate the global demand for fixed nitrogen from the nitrogen content of the biomass removed from the fields. Assuming that cellulosic biomass contains about 0.5 % N in the dry matter [Karp and Shield, 2008, Kauter et al., 2001], we estimate the global demand for fixed nitrogen from dedicated biomass plantations to range between 7 and 31 Mt N. This corresponds to average application rates of 50-70 kgN/ha/yr, which is in line with recent studies of well managed energy crop cultivation at different sites [Fike et al., 2006, Karp and Shield, 2008, Lewandowski and Schmidt, 2006, Schmer et al., 2008]. At this scale, the cultivation of biomass will increase the projected demand for nitrogen fertilizer in 2030 by 4-23% [Tenkorang and Lowenberg-DeBoer, 2008] beyond expected short-term production surpluses of 15 Mt in 2011/2012 [FAO, 2008b].

4.2.5 Discussion

We find that there are some significant potentials for biomass plantations to become a significant source of renewable energy even if sustainability guidelines for climate mitigation and nature protection constrain the availability of land resources. Given that residues from agriculture and forestry, municipal solid waste and animal manures may provide around 100 EJ per year [Haberl et al., 2010, IEA Bioenergy, 2009, Reinhardt et al., 2007, WBGU, 2009], the total bioenergy potential for the year 2050 ranges between 126 and 216 EJ, equivalent to about 13-22 % of the World's primary energy demand in 2050 [IEA Bioenergy, 2009].

Our results are in the lower range of recent bioenergy modeling studies. These tend not to consider water constraints on rainfed and irrigated biomass cultivation, as well as the impacts of future climate change on plant productivity [Hoogwijk et al., 2005, Smeets et al., 2007]. In addition, these assessments assumed massive increases in crop yields above historic levels so that large amounts of agricultural land are abandoned in the future and become available for bioenergy crops. Assuming extensive land abandonment also contradicts recent findings from international assessments of future changes in land use that project further expansion of croplands [Field et al., 2008]. A worldwide decrease in meat consumption could reduce agricultural land demand for food and feed production significantly [Stehfest et al., 2009] and improve the opportunities for biomass cultivation

4.2 Bioenergy production potentials

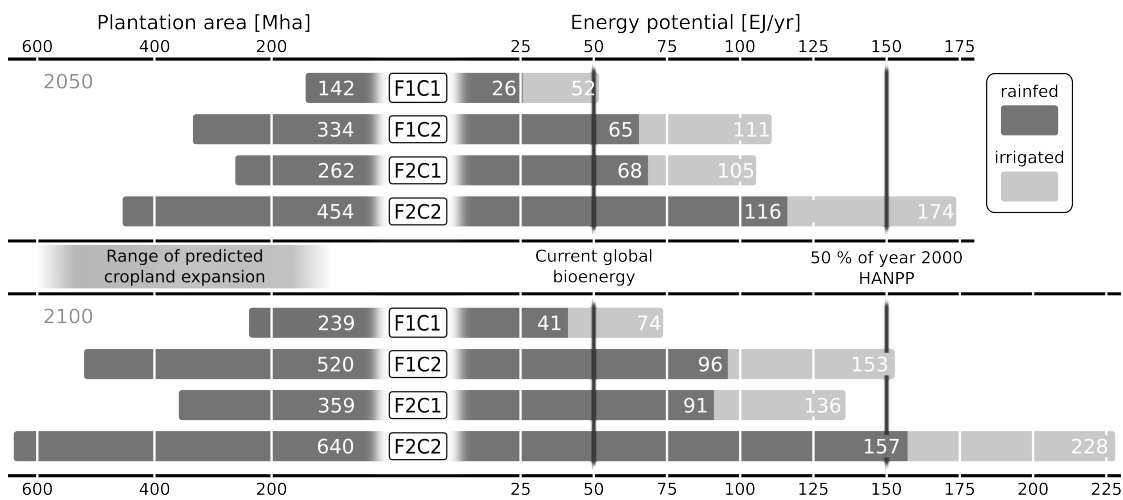


Figure 4.18: Global bioenergy potentials and corresponding land requirements for dedicated biomass plantations in 2050 for all scenarios. The respective values appear inside the bars. For comparison, the current global bioenergy production is around 50 EJ per year. The gross calorific value of all harvested biomass in the year 2000 amounted to about 300 EJ [Haberl et al., 2007]. Increasing the World's energy crop production to 150 EJ would thus raise the human appropriation of net primary production (HANPP) by 50%. Recent estimates of future agricultural expansion for food production range between 100 and 600 Mha [Erb et al., 2009b, IAASTD, 2009, OECD, 2008, Rockström et al., 2007]

[Erb et al., 2009a]. But recent trends in dietary habits towards larger shares of animal products as a main driver of deforestation and expansion of agricultural areas do not show any signs of a decline in global meat demand [McAlpine et al., 2009, Nepstad et al., 2008].

Exploiting these potentials will, however, incur significant additional human interventions in the environment as newly established energy crop plantations are responsible for the largest share of global biomass production. Human land use is already the most important driver behind environmental degradation [Foley et al., 2005], biodiversity loss [Butchart et al., 2010] and fresh water consumption [Rodell et al., 2009], and if energy crops are not restricted to abandoned and surplus agricultural land, the spatial expansion of agricultural activities could affect a large number of natural ecosystems, many of which already under significant pressure from habitat loss and fragmentation. Limiting extensive biomass plantations to marginal lands could reduce some of the environmental risks, but may threaten rural livelihoods. Due to its large requirements for space and the need for a rapid development of new plantations in the face of climate change and the peak oil debate, bioenergy may become one of the most important drivers of global environmental and social change in the coming decades.

In our scenarios, about 40% of the prospective biomass plantations replace natural grasslands and shrublands, 10% semi-natural vegetation in the vicinity of existing agricultural areas and about 30% would be developed on now forested areas [ESA, 2009]. Even though the use of sustainability constraints preserves the most important hotspots of biodiversity and carbon reservoirs in these scenarios, the ecological, economic and social value of natural areas that remain potentially available for energy crop cultivation can still be very high. A spatial analysis with the “Terrestrial Ecoregions of the World” data set [Olson et al., 2001] reveals that many of the affected regions feature a large diversity of wildlife.

Examples include European and North American temperate forests and grasslands, that have a long history of human land use and where the remaining patches provide habitat for endangered and endemic species. Even though favorable climatic and soil conditions allow for high potential yield levels and greenhouse gas emission reductions, converting these iconic landscapes into large scale biomass plantations may not be regarded as socially acceptable. Available lands in South America are mainly located in the semi-arid scrub forests of the Caatinga, the biologically rich Cerrado savanna, the savannas and thorn forests of the Chaco and the grasslands of the Humid Pampas. All of these regions are rich in biodiversity with a large share of endemic species and have been greatly reduced by human activities. A similar picture emerges for Africa, India, and China, where population growth, land fragmentation and overexploitation of water resources drive wide-spread habitat destruction and degradation.

Despite the consideration of land use constraints for climate mitigation and nature conservation, the environmental sustainability of dedicated biomass plantations outside areas of abandoned or degraded croplands seems questionable. A possible twofold increase in irrigation water requirements, global cropland increasing by up to 30 % for energy crops alone, and additional nitrogen demand that may exceed future fertilizer production illustrate the great challenges of integrating large scale bioenergy into global

4.2 Bioenergy production potentials

sustainable land use. Bioenergy will only contribute to greater energy security, reduced emissions of greenhouse gases, and rural development if coordinated transformations in agriculture, energy systems, environmental protection, international trade and global cooperation are achieved. Global land policy, including but extending climate policy, needs to develop a range of new cross-sectoral instruments, including biomass certification schemes [WBGU, 2009] and precise carbon accounting [Searchinger et al., 2009], to optimize environmental and social benefits of bioenergy.

5 Summary and Outlook

5.1 Summary

This thesis deals with large scale climate anomalies and human land use as dominant drivers of global environmental change.

5.1.1 Main results of chapters 2 and 3

1. Impacts of temperature and precipitation anomalies on terrestrial ecosystems explain most of the two largest perturbations of the global carbon cycle that were observed over the last 30 years. Variations in the land carbon sink during these two events were mainly driven by soil processes rather than changes in photosynthetic activity.
2. According the LPJ model, the land carbon sink grew by -0.86 GtC per year during 1992 and 1993 relative to the 1979-2003 mean. Enhanced oceanic carbon uptake and reduced emissions from the combustion of fossil fuels combined explain -0.7 GtC of the observed global carbon sink anomaly after the eruption of Mount Pinatubo.
3. Decreased temperatures and precipitation over land in the aftermath of the volcanic eruption reduced both NPP and R_h . The response of R_h was substantially stronger so that less carbon was released from terrestrial ecosystems. Water-limitation of NPP and above-average emissions from natural fires possibly related to the concurrent El Niño attenuated the strength of the global carbon sink.
4. The observed strengthening of the terrestrial carbon was not related to a single “Pinatubo effect”, but resulted from complex regional response patterns of canopy photosynthesis and soil decomposition reacting to changes in climatic conditions. Modeling results show two different modes of climate-biosphere interactions. Increased carbon storage in boreal ecosystems throughout the growing season resulted from a stronger decline in soil respiration relative to NPP and explains about 35% of the simulated carbon anomaly. A combination of increased rainfall and lower temperatures lead to enhanced plant productivity and reduced soil decomposition in the mid-latitudes responsible for about 65% of the anomalous sink.
5. The positive effect of increased diffuse radiation on canopy NPP contributed only marginally to the strengthening of the global carbon sink, because cloud cover

5 Summary and Outlook

and volcanic aerosols reduced the total amount of solar radiation available at the land surface significantly and thus counterbalanced gains in canopy radiation use efficiency.

6. During the 1997/98 El Niño event, the observed anomalous flux of 2.8 GtC was also largely related to terrestrial ecosystems. Drier and warmer conditions in tropical and sub-tropical regions reduced plant productivity, enhanced soil decomposition and promoted extensive wildfires. An anomalous release of 2.6 GtC from the land biosphere in 1998 is explained by LPJ simulations and estimates of fire emissions from the land biosphere.
7. These results are supported a high level of agreement between simulated and observed patterns of vegetation and carbon flux anomalies from remote sensing data and air measurements.

In short, the present study suggests that soil processes were responsible for the two largest perturbations of the global carbon cycle observed during the previous 30 years [Keeling et al., 2009]. These results highlight the importance of soils for terrestrial carbon balance that is often only associated with changes in NPP. Although the notion of a “global carbon sink” gives the impression of a homogeneous response of the land biota to climatic conditions, the variability of the terrestrial carbon cycle result from a complex pattern of relative changes in plant productivity and soil decomposition. LPJ is able to reproduce observed vegetation activity which increases the confidence in global vegetation modeling as an appropriate tool for the analysis of large scale biosphere processes.

Next steps

Although global vegetation modeling has been very successful in predicting the response of terrestrial ecosystems to climatic conditions and changes in land use, a number of unresolved issues remain that require further development and testing of DGVMs.

Some model parameters, for example, that describe rates of biogeochemical processes or allometric relations in plant growth are fixed in most models, but observations have shown that these traits can change when plants acclimate to increasing CO₂ concentrations [Ainsworth and Long, 2005, Korner et al., 2005], changing the magnitude of feedbacks of terrestrial ecosystems to climate change.

Similar uncertainties persist regarding soil processes, such as the temperature and moisture sensitivity of soil decomposition, that might represent a very strong positive feedback to global warming. Physiological adaption of the below ground biota to changing environmental conditions and long-term shifts in species composition are also believed to affect the future development of soil carbon stocks and fluxes.

Process-based representations of nutrient cycles are also still missing from most Dynamic Global Vegetation Models. Nitrogen constraints, for example, will reduce the amount of CO₂ taken up by the land biosphere, so that models that do not consider

this process likely overestimate the strength of the terrestrial carbon sink under rising atmospheric CO₂ concentrations.

The representation of different management regimes in agriculture and forestry is also still at the beginning or not included in DGVMs at all and requires further development and diversification. Such improvements are necessary for the analysis of different land use strategies with regard to their spatial and environmental possibilities, constraints and consequences.

5.1.2 Main results of chapter 4

1. The annual global bioenergy potential from dedicated energy crops is found to range between 30 and 170 EJ, corresponding to 3-17% of the World's projected primary energy demand in 2050. Major potentials for large scale biomass plantations are found in Latin America, Sub-Saharan Africa, Eastern and Southern Asia, Europe, and North America that contribute about 26%, 18%, 17%, 14%, and 11% to the total potential, respectively.
2. Assuming that other sources of biomass, such as residues from agriculture and forestry, animal manures or municipal solid waste together could provide around 100 EJ per year, the total potential of bioenergy may amount to 130-270 EJ/yr or 15-25% of the global energy demand in 2050.
3. Despite the consideration of extensive sustainability constraints that limit agricultural land use expansion, the environmental impacts of global large scale biomass cultivation would be serious. Future cropland demand for energy crop cultivation ranges between 140 and 450 Mha in the different scenarios by 2050. These plantations would primarily replace savannas, grasslands and, to a lesser extent, forests. Many of these natural ecosystems have already been fragmented and degraded by human activities, provide habitat for a large number of threatened and endemic species and are therefore of considerable ecologic, economic and social value for local communities but also from a regional and global conservation perspective.
4. Irrigation is required to realize the full potentials and hence water demand for the cultivation of biomass could range to 1480-3880 km³ in 2050, significantly increasing the current agricultural consumption of 2500 km³ per year [Rost et al., 2008a]. Annual nitrogen demand for fertilization could amount to 13-56 Mt, exceeding expected near-term production surpluses [FAO, 2008a].

LPJ is among the first DGVMs capable of simulating the cultivation of lignocellulosic energy crops as a new form of human land use. Results from the model have been used in various recent sustainability and development assessments, such as the WBGU flagship report on "Future Bioenergy and Sustainable Land Use" [2009], the World Development Report "Development in a Changing Climate" [Beringer and Lucht, 2010, Worldbank, 2010], and the forthcoming "Global Energy Assessment" [IIASA, 2011].

Next steps

The bioenergy scenarios presented here are only first steps towards a more comprehensive assessment of possible trajectories of future land use and the emerging trade-offs between potentially competing development objectives aiming at food and energy security, climate mitigation or nature conservation.

The next generation of these scenarios will therefore be extended in different directions. Sugarcane was recently added to LPJmL [Lapola et al., 2010] so that now all important types of crops required to produce first and second generation biofuels are represented in the model allowing for comparative studies with regard to carbon and water impacts of different bioenergy feedstocks. Regionally differentiated scenarios of future changes in croplands and pastures will be used to consider the consequences of population growth and changes in global meat demand for the amount of land required to produce food [Erb et al., 2009a, Stehfest et al., 2009].

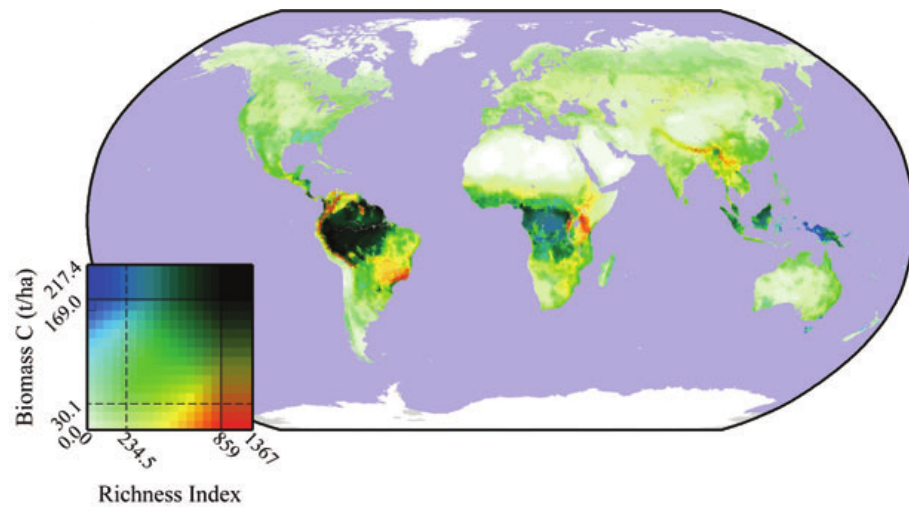


Figure 5.1: Global correspondence of carbon storage in natural ecosystems and overall species richness. The two-dimensional color scale describes both the amount of biomass in vegetation and soils and animal biodiversity as well as their spatial congruence. Carbon density is measured in tons of C per hectare and biodiversity in number of species per cell. Taken from Strassburg et al. [2010].

Improved analyses of environmental risks from accelerating climate change and expanding human land use are urgently needed as a basis for sound evaluations of different development strategies. Given the finite amount of land, water and other natural resources, inevitable trade-offs between food production, biomass cultivation, greenhouse gas mitigation, and biodiversity protection will increase with a growing and more prosperous world population. Such trade-off analyses need to consider the whole range of ecosystem impacts from human activities. Metrics that quantify the effects of different land use scenarios on biodiversity, for example, can illustrate the undesirable side effects of policy strategies that focus too much on the reduction of greenhouse gas emissions from land use change. For example, carbon storage in the Cerrado savanna of South

America is significantly smaller compared to tropical rainforests in the Amazon basin. Species richness in both regions, however, is almost the same (Figure 5.1).

It is also necessary to complement global assessments of bioenergy potentials as presented here with more detailed regional analyses of local environmental, social, and political conditions to evaluate the actual feasibility of large scale biomass cultivation. Such a reality check would be an important step forward given the great expectations that now rest on biomass because it is a very versatile source of renewable energy and storage in solid, liquid, or gaseous form is relatively straightforward. A first step in this direction has been made by the WBGU (Figure 5.2) that used the Failed States Index (FSI) to evaluate the short-term feasibility of large scale biomass plantations in regions where socio-economic conditions are difficult.

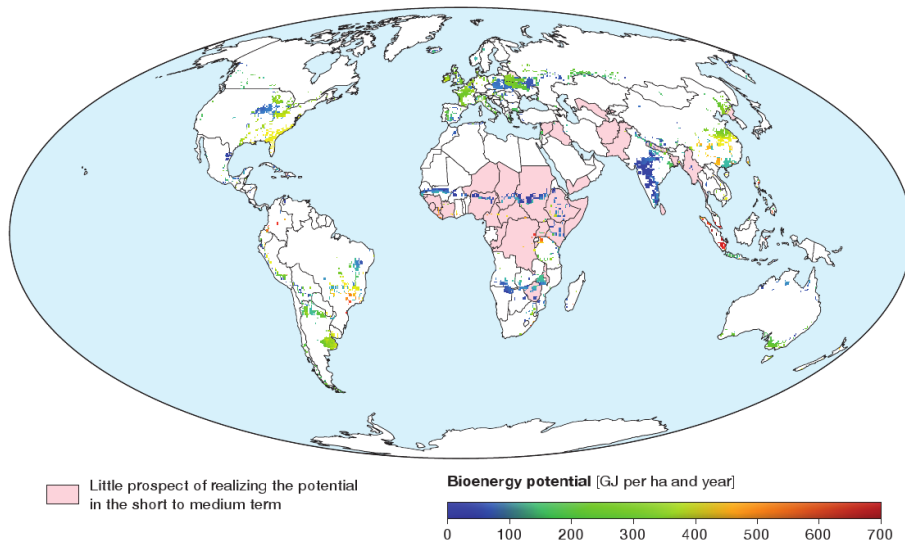


Figure 5.2: Regions with potential for sustainable bioenergy from crops and countries that are affected by state fragility or collapse of the state. The map shows the distribution of possible areas for the cultivation of energy crops and the potential production in the year 2050 for a WBGU scenario involving a low level of need for agricultural land, high level of biodiversity conservation and non-irrigated cultivation. One pixel corresponds to $0.5^\circ \times 0.5^\circ$. In order to assess whether the identified sustainable bioenergy potentials are likely to be realizable, the quality of governance in individual countries was rated using the Failed States Index (FSI). The countries coloured light red have an FSI > 90, indicating that in the short to medium term the prospect for realizing bioenergy potentials can be regarded as poor. Taken from WBGU [2009].

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Selbständigkeitserklärung

Ich erkläre, dass ich die vorliegende Arbeit selbständig und nur unter Verwendung der angegebenen Literatur und Hilfsmittel angefertigt habe.

Berlin, den 31.03.2011

Tim Beringer