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Comparative impact of climatic and non-climatic factors on global terrestrial carbon and water cycles

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Abstract

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

1 Introduction

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

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

Land use is increasingly recognized as a force of global importance [Foley et al., 2005]. However, the development of land-use patterns is rarely addressed explicitly in studies on global change – regardless of its close entanglement with the natural environment and society

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

prescribe special carbon allocation schemes for the NPP of natural vegetation to simulate harvest and land-management, Gitz and Ciais [2004] account for land-use transitions but assign a single global average value to determine NPP of crops in their bookkeeping approach [Gitz and Ciais, 2003].

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

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

2 Methods

2.1 Modeling Strategy

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

As reference land-use pattern, we use the observed crop area based on Ramankutty and Foley [1999] and Leff et al. [2004] (figure 1). Although we consider all major crops (except cotton seed (2.8%) and 3 forage categories (1.0-1.5%) all crops with an area larger 1% of the total arable land according to FAOSTAT data [2005] have been considered), these account for 9.5 million km² (75% of the total arable land) only. The land-use mask as supplied by Leff et al. [2004] on the contrary covers the total agricultural area of 15.8 million km², which includes forage crops but does not include managed grasslands. Since this area is considerably larger than the 9.5 million km² that are currently (i.e. 1995) needed to produce the agricultural commodities considered in this study, we scaled the cropland area of each grid cell accordingly. We assume the remainder to be managed grassland as this is not included in the land-use datasets used. All grassland simulated in our scenarios is highly productive grassland and is thus not comparable to the much larger area classified as grassland by FAOSTAT data [2005] or the HYDE data base [Klein Goldewijk, 2001]. These datasets include natural grassland as well and are not well differentiated from shrub-land and forests [FAOSTAT data, 2005].

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

2.2 LPJmL Dynamic Global Vegetation Model

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

In LPJmL, agricultural land use is simulated within the same framework using crop functional types (CFTs) [Bondeau et al., in press]. The world's most important field crops as well as pastures are represented by a total of 13 different CFTs (table 1) either rain-fed or irrigated. Grid cells may fractionally consist of both natural and agricultural vegetation, and several agricultural crops may be present within the same grid cell with individual cover fractions. Natural PFTs compete for resources, whereas each CFT has its own specific water budget. Management options such as irrigation, removal of residues, multiple cropping, intercropping, and grazing intensity are specified. LPJmL's crop modules simulate crop phenology, growth, and carbon allocation at a daily time step. Carbon is allocated to several plant compartments, including a storage organ that represents the economic yield at harvest. The model estimates several crop variety-specific parameters as a function of climate, thereby taking into account the adaptation of crop varieties to specific climatic environments in which they are cultivated. The implementation of the crop-specific processes is described in detail and validated against the USDA crop calendar [USDA, 1994] and satellite data [Myneni et al., 1997] for phenology, against FAO data [FAOSTAT data, 2005] for yield simulations, and against eddy flux measurements [Baldocchi et al., 2001; Lohila et al., 2004] for carbon fluxes in the study of Bondeau et al. [in press]. Crop yield for each grid cell was simulated by LPJmL as limited by soil moisture and climate only (for exemplary spatial distribution of yield levels of temperate cereals and of maize see supplementary figure S1). To account for differences between current (1995) and simulated crop yields as caused by different management practices (pest control, fertilization), we employed national *management factors (MF).* To derive the MFs, we scaled the computed average yield of actual production sites according to Ramankutty and Foley [1999] and Leff et al. [2004] to national yield averages supplied by the FAO [FAOSTAT data, 2005] as in equation (1):

$$MF_{c,n} = \frac{Ycur_{c,n}}{\sum\left(Ysim_{c,i} * A_{c,i}\right) / \sum A_{c,i}} \quad (1)$$

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

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

2.3 Computation of demand for agricultural products

We define total demand for agricultural commodities by the number of people and their per-capita consumption. We computed 6 different demand scenarios for agricultural products by changing population (table 2) and diet (table 3). For population, we used the population count of 1995 (5.6 billion) and scaled it to 12 billion, extrapolating national population growth projections for 2050 [U.S. Census Bureau, 2004]. A population of 12 billion marks the upper limit of the 80% confidence interval of potential population trajectories [Lutz et al., 2001]. We distributed total population to the grid cells based on the *Gridded Population of the World* (GPW) dataset [CIESIN et al., 2000] in order to determine local (i.e. 0.5° x 0.5° grid cells) demand.

For diets, we assumed three different settings, reflecting current global trends in lifestyle change towards increased meat consumption. Again, we used 1995 data as baseline and doubled or halved consumption of animal products respectively in order to explore the order-of-magnitude impacts. A doubling of per-capita meat demand is projected for China, India, and other countries by the year 2020 [Rosegrant et al., 1999]. For the world as a whole, a general assumption of doubled consumption of animal products may be a rather drastic increase, but one that is by no means completely out of range. Halving current meat consumption would require a considerable change in dietary habits in many cultures, or at least a regional decoupling of the historically prominent link between economic wealth and meat consumption. We used *FAO data* [FAOSTAT data, 2004] to determine the regional demands in 1995 (setting 1 in table 3) for the most important agricultural products (table 4) for 11 regions (table 2), assuming diets to be homogenous in each region. Food demand as computed here accounts for direct human consumption and for losses during production and food processing. FAO food balance sheets [FAOSTAT data, 2004] provide detailed information of origin (production, import) and usage (food, feed, seed, food manufacture, waste, export and other uses) for each commodity, summing up to a total supply. We subtracted *feed use* from total supply to determine total demand, implicitly accounting for losses in the process of food production. For Latin America, we reduced sugar crop demand by one third to account for the exceptionally large share of sugar exports. We computed total per-capita energy consumption for each region as the weighted sum of each commodity's energy content as reported by Wirsenius [2000]. We kept these energy consumption levels constant for all diets by scaling direct human crop consumption to counterweight the changed consumption of animal products (hereafter: *meat consumption*). In order to translate the demand for animal products into demand for field crops, we used regional feed mix data [FAOSTAT data, 2004] and added demands for green fodder (grass and whole-maize) in the case of ruminant meat and milk based on Wirsenius [2000] and FAOSTAT data [2004]. Whole-maize (for feed) is computed as the sum of grain yield and 90% of the harvested residues. Feed demand differs between regions as animal production systems vary between regions. We did not explicitly include the use of residues and by-products for feed since we assume that they are included in our definition of commodity demand (see above).

2.4 Land allocation

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

In a second setting, production was allocated locally (*localized production*), i.e. we forced each grid cell to satisfy, as far as possible, its own demand (cell's population multiplied with the corresponding regional per-capita demand). Again, land was allocated with the objective to minimize production area, allowing 100% agricultural land use. If the grid cell's productivity was too low to satisfy the demand, we maximized production in that grid cell and distributed the remaining demand in two subsequent steps to the available land in neighboring cells (squares of 3.5°x3.5° and 9.5°x9.5° respectively). Neighboring cells could supply additional land, if their domestic demand could be met without utilizing the entire area. If a cell's demand could not be satisfied within its neighborhood, it was pooled globally. Demand that could not be satisfied within a grid cell at all, i.e., if current yield of the corresponding crops in that cell is zero, was pooled globally, too. The pooled global demand was located as in the globalized production scheme but constrained additionally by the production already allocated in the preceding steps.

3 Results

We assess the range of potential land-use impacts on global carbon pools and water fluxes (table 5) by comparing the results of the different land-use simulations. To supply a measure of relative importance, we compare the results to the effects of projected climate change by the period 2071-2100, given by [Schaphoff et al., 2006] for the climate projections of 5 GCMs (CGCM1, ECHAM4, CCSR, CSIRO and HadCM3) under the IS92a emission scenario; these projections were derived from the same model (LPJ) but without cropland. All results are expressed as averages of the period 1990-1999 and (except table 5) as differences to the reference run which is based on the actual area demand for the crops considered here, according to FAOSTAT data [2005]. Total agricultural area ranges between 2 and 35 million km² for the different settings (see figures 2, 3, table 5). Accordingly, the carbon and water budgets (table 5) show weak to strong responses, depending on the setting.

3.1 Terrestrial carbon fluxes and pools

The potential effects of changed land-use patterns on carbon pools are – depending on the setting – comparable to those of projected climate change by the end of the 21st century (figure 4) [Schaphoff et al., 2006]. Only NPP (table 5) is less sensitive to the different land-use scenarios than to CO_2 fertilization and climate change. NPP of cropland is similar to that of natural vegetation. Locally, it may be higher or lower, depending on CFT, local conditions, and management (here irrigation only). Under the globalized scenarios, only highly productive areas are used agriculturally, in which cropland NPP tends to be higher than NPP of potential natural vegetation. If meat consumption increases, the size of agricultural area but also the share of highly productive pastures in total agricultural area increase. Thus, NPP increases with agricultural area in these cases, while it generally decreases with the size of agricultural area (table 5, figure 6). Carbon pools, however, change significantly under cultivation even with similar NPP because large parts of the accumulated carbon are removed at harvest, strongly reducing the turnover time. Carbon pool sizes are linearly determined by total agricultural area (figure 6). Agricultural land-use usually reduces both vegetation and soil carbon. Under the different scenarios, vegetation carbon ranges from 90 to 114% of the reference run and soil carbon from 92 to 109%, reflecting total agricultural area (table 5).

The sign and magnitude of the changes in carbon pools are mainly determined by the production scheme, which largely determines area demand. Carbon pools are significantly smaller than in the reference run under most localized scenarios, while they are much larger under the globalized production scenarios. Following the production scheme, population and diet also strongly affect the carbon pools, most prominently under the localized productions scenarios. NPP may differ between field crops and natural vegetation. Under the IS92a emission scenario and corresponding climate change projections, NPP increases by ~10 to ~21 PgC/a [Schaphoff et al., 2006], while we compute only small differences (–4.5 to 1.4 PgC/a) between the reference run and our land-use patterns. Correspondingly, CO_2 fertilization and climate change as studied by Schaphoff et al. [2006] mainly affect the vegetation carbon pool while the different land-use patterns also strongly affect the soil carbon pools (figure 4), because large parts of the NPP are removed at harvest and do not enter the litter pools.

3.2 Terrestrial water balance

As for the carbon cycle, the water cycle responds strongly to the different production schemes, especially to the localized production scheme (figure 5, table 5). The impact of land use on the water cycle is also mainly determined linearly by total agricultural area (figure 6). Generally, transpiration and interception are reduced by agricultural land use as compared to potential natural vegetation, while evaporation and runoff increase. In case of irrigated agriculture however, runoff is reduced in comparison to rain-fed vegetation as irrigation water is taken from runoff. At the global scale, the corresponding reduction of runoff is counterbalanced by the general increase of runoff on arable land, leaving global runoff within narrow bounds (± 3% compared to reference run, see figure 5). For transpiration, evaporation, and interception (not shown), stronger differences between the land-use patterns and the same general pattern as for the carbon cycle can be observed (figure 5, table 5). The production scheme mainly determines the sign and magnitude of land-use effects on the global water cycle, followed by the differences in population. Differences in diet are in our simulations of minor importance for the water cycle at the global level.

4 Discussion

Although based on stylized scenarios of possible global land-use changes, the present study clearly demonstrates that the individual effects of different drivers of land-use change (demography, diet, production pattern) are of major importance for the global carbon and water budgets. Their effects on the carbon cycle are comparable in size to the cumulative fossil-fuel emissions from pre-industrial times to the year 2000 of 280 PgC and to the total carbon loss of 200-220 PgC from land-use change in the same period [House et al., 2002] (compare figure 4). It should be noted that our scenarios are designed to provide a first-order assessment of the range of potential impacts of land use and can thus be compared to the climate projections as studied by Schaphoff et al. [2006] only to gain an impression of the comparative magnitude of effects. To ensure direct comparability of the drivers of land-use change, we studied their effects in a static comparative setting, i.e. we excluded climate change and kept management constant at 1995 levels. For future land-use patterns, these two factors potentially amplify or counteract the effects studied here.

The general result that the land-use pattern is an important factor in the global carbon balance agrees with the findings of Gitz and Ciais [2004]. Levy et al. [2004] attribute only smaller parts of projected changes in future carbon budgets to land-use change, based on 3 SRES scenarios that imply only slightly increasing or substantially decreasing total agricultural areas. Levy et al. [2004] acknowledge that scenarios with substantial expansion of cultivated land should be considered (as in the present study), given the large uncertainties in the future development of land use.

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

We note that the management factors (MF) used may lead to artifacts in local crop productivity if, for a certain CFT, the most productive cells of a country, as simulated by LPJmL, are currently not used for this CFT according to Ramankutty and Foley [1999] and Leff et al. [2004], i.e. $A_{c,i}=0$ (compare equation 1). If there are no restrictions on including these grid cells in the land-use pattern, as, e.g., in the globalized scenarios, these grid cells with unrealistically high yield levels will decrease total area demand. For grasslands no yield data are available to determine the MF. Also, the different land-use patterns are based on simple assumptions. Feed-mixes and consumption patterns are derived from coarse regional estimates for the most important commodities only (table 1) [Wirsenius, 2000; FAOSTAT data, 2004] and changes in consumption are merely based on consumption of animal products and its implications for the consumption of vegetal products. Forestry and timber extraction are not considered. The different production schemes used reduce the complexity of land-use change processes [Heistermann et al., 2006] to the objective of area minimization.

Carbon pools and fluxes as well as water flows are linearly related to total agricultural area (figure 6), as the difference between natural and agricultural sites is much more important than the differences between different crops or different types of natural forest. For assessing the impact of land use on the terrestrial carbon and water cycles, it is therefore crucial to precisely determine the total size of the agricultural area. Total area demand, however, is not related to total demand for agricultural products but varies greatly between different production schemes and demand structures (table 5). Spatial explicitness is crucial to determine the area demand for agriculture, as crop productivity varies greatly between different sites and crops. Constraints on localization of production, as represented by the two different production schemes, strongly affect the area needed to meet the demand for agricultural products and thus determine the consequences for the carbon and water cycles. Climate change and technology development, which are excluded here, could significantly affect local productivity and thus land-use efficiency and agricultural area demand. By distributing agricultural production to the most productive grid cells, total agricultural area could be much reduced. All production schemes allocate land with the objective to minimize area, but are differently constrained, leading to strong differences in area demand. According to FAO, 9.5 million km² were under cultivation in 1995 to produce the field-crops (except green fodder) included in this study [FAOSTAT data, 2005]. If the agricultural commodities would be produced at average western European levels, this area could be reduced by 50% (20-80% for single crops). This reduction can be reinforced if production is allocated to the most productive sites, which may exceed the average western European levels 2 to 3 times. The current agricultural production is neither globalized nor localized. It is situated well between these two extreme assumptions that define the range of possibilities. It has to be noted that the reference run does not quite reflect the actual land-use pattern but is adopted to be consistent with our 1995-baseline demand.

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

5 Conclusions

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

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

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Figures:

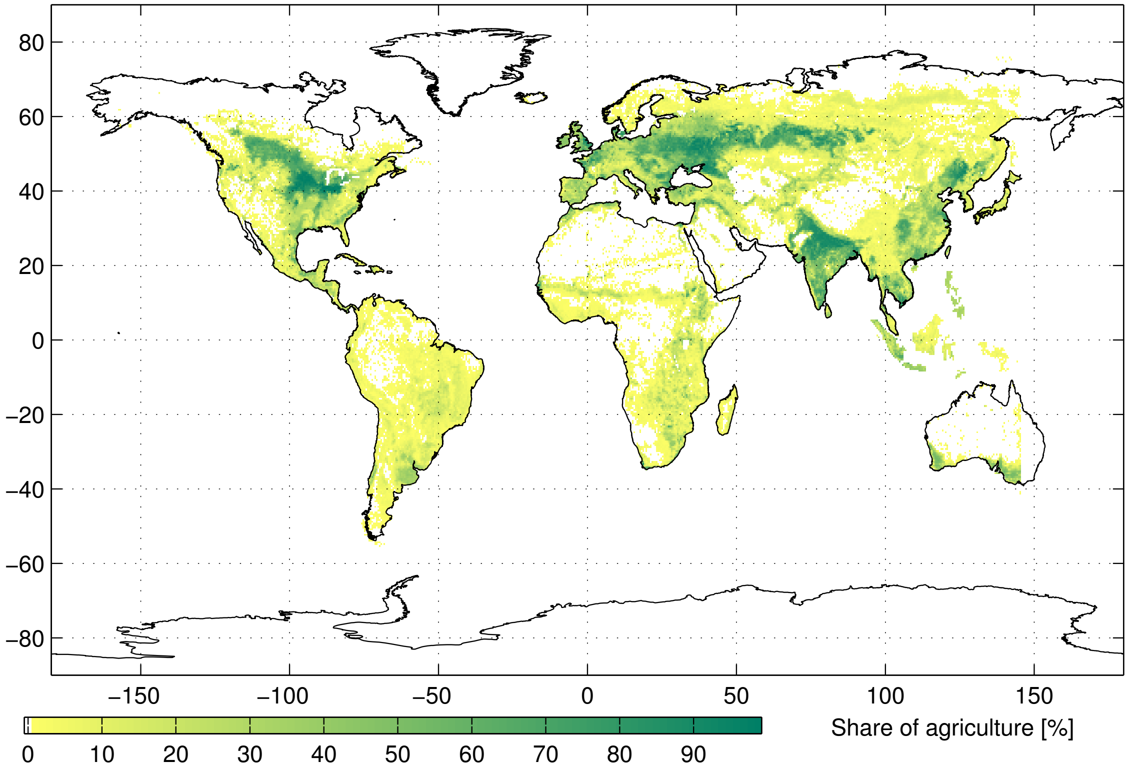


Figure 1. Agricultural land-use pattern of reference run, as derived from Ramankutty and Foley [1999] and Leff et al. [2004].

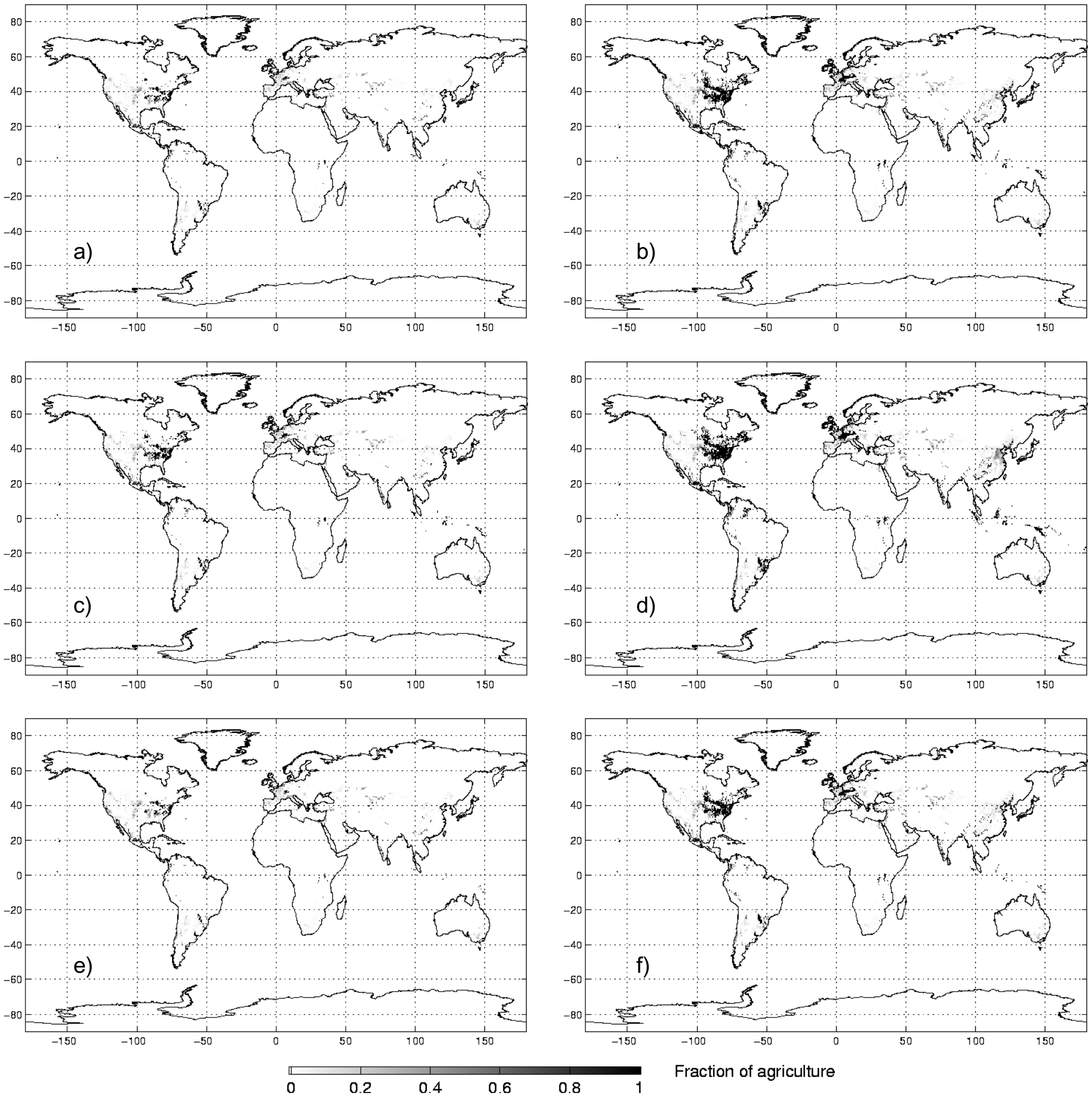


Figure 2. Agricultural land-use patterns for the globlized production scheme: a) population of 5.6 billion, diet of 1995; b) population of 12 billion, diet of 1995; c) population of 5.6 billion, doubled meat consumption; d) population of 12 billion, doubled meat consumption; e) population of 5.6 billion, halved meat consumption; f) population of 12 billion, halved meat consumption.

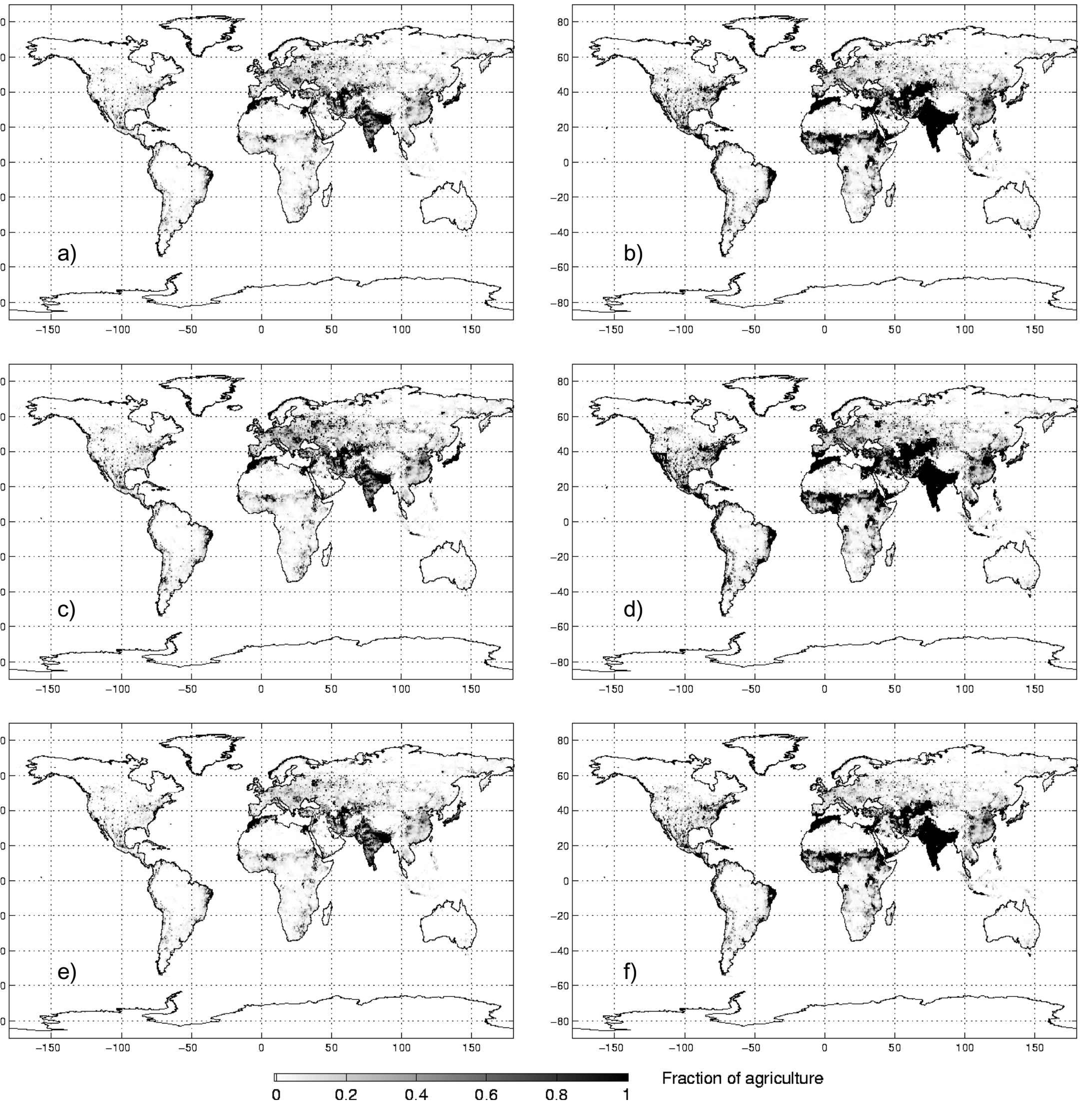


Figure 3. Agricultural land-use patterns for the localized production scheme: a) population of 5.6 billion, diet of 1995; b) population of 12 billion, diet of 1995; c) population of 5.6 billion, doubled meat consumption; d) population of 12 billion, doubled meat consumption; e) population of 5.6 billion, halved meat consumption; f) population of 12 billion, halved meat consumption.

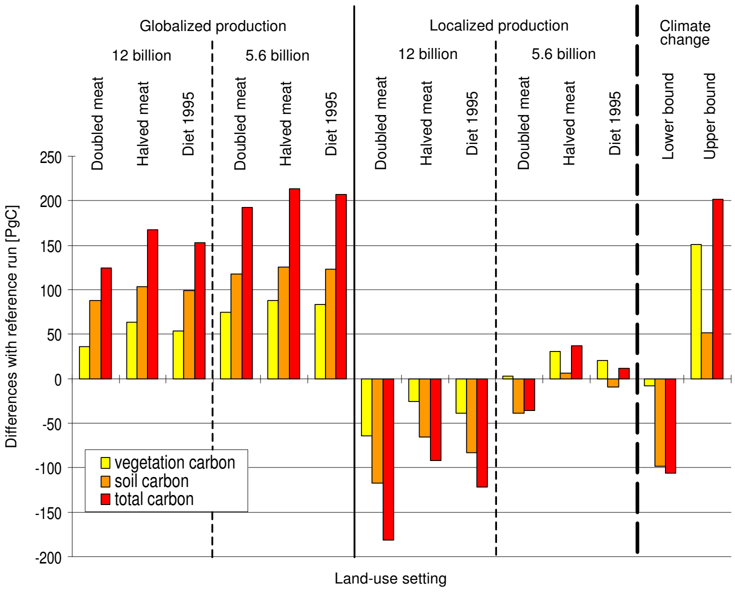


Figure 4. Effects of different land-use patterns on global carbon pools, presented as differences with the reference run. Estimates of climate change impacts (right of bold dashed line) from Schaphoff et al. [2006], representing the minimum (lower bound) and maximum (upper bound) of climate-change induced changes in carbon pool sizes. Total carbon is the sum of soil and vegetation carbon.

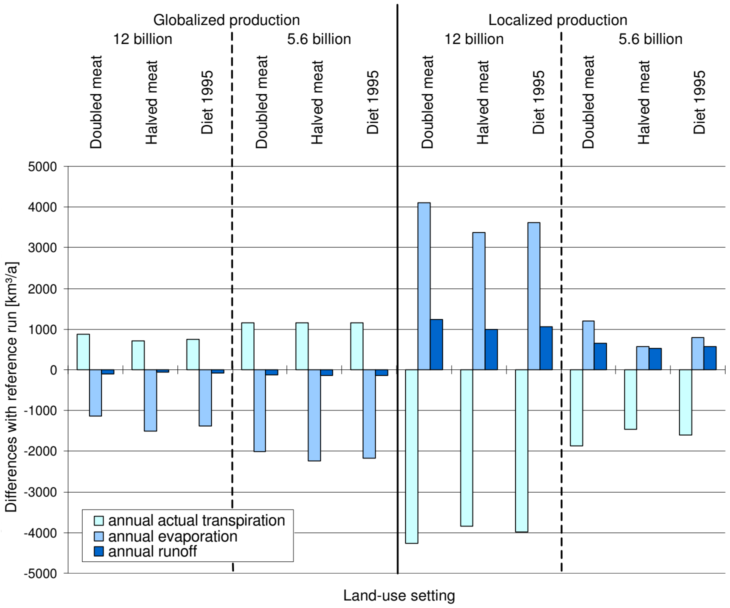


Figure 5. Effects of different land-use patterns on global water flows, presented as differences with the reference run.

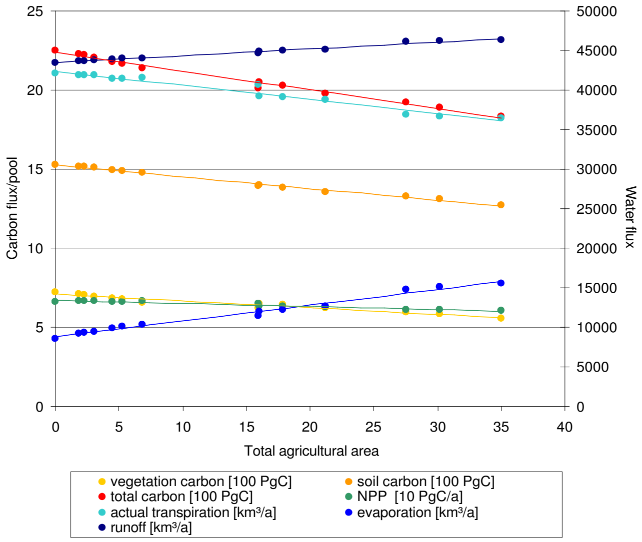
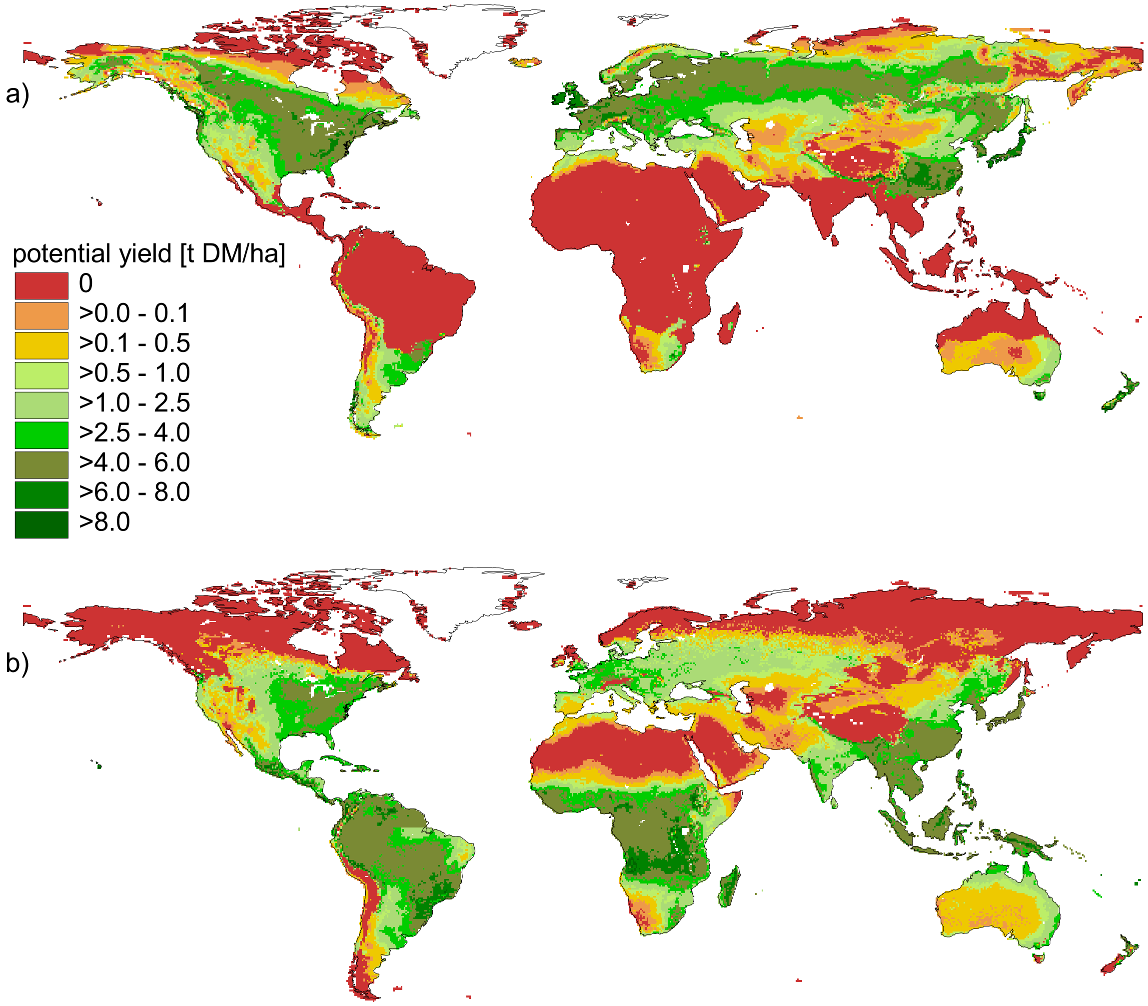


Figure 6. Linear relationships between total agricultural area and carbon pools/water fluxes.



Supplementary figure S1. Rain-fed yields for temperate cereals (a) and maize (b) as simulated by LPJmL [Bondeau et al., in press], averaged for 1991-2000. Note that yields here are not adopted to match current yield levels by country-specific parameterization as described by Bondeau et al. [in press].

Table 1. Crop functional types.

Crop Functional Type (CFT)	Main representative
Temperate Cereals	Summer/winter wheat
Tropical Cereals	Millet
Temperate Corn	Corn
Tropical Rice	Rice
Temperate Pulses	Lentil
Temperate Roots and Tubers	Sugar beet
Tropical Roots and Tubers	Manioc
Temperate Soybean	Soybean
Temperate Sunflower	Sunflower
Tropical Peanuts	Peanut
Temperate Rapeseed	Rapeseed
Managed C3-grassland	C3 pasture
Managed C4-grassland	C4 pasture

Table 2. Regional distribution of population based on national population counts for 1995 and extrapolated national population growth projections for 2050 [U.S. Census Bureau, 2004].

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

Table 3. Global agricultural demand for direct human consumption. For halved and doubled consumption of animal products, the direct consumption of vegetal commodities was scaled to keep total energy consumption constant.

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

Table 4. Agricultural products considered in this study, corresponding crop functional types and FAO categories used to determine the baseline demand. Feed mix assignments for animal products differ regionally (see text).

Agricultural products	Crop functional types (CFT)	FAO categories for aggregate demand
Grain cereals	Temperate cereals (wheat), tropical cereals (millet)	Wheat, rye, barley, oat, millet, sorghum
Maize	Maize	Maize
Rice	Rice	Rice, paddy
Roots and tubers	Potatoes, manioc	Roots and tubers
Pulses	Pulses	Pulses
Soybeans	Soybeans	Soybeans
Oilcrops	Rapeseed, peanut, sunflower	Rapeseed, peanut, sunflower
Sugar	Sugar cane[1], sugar beet	Sugar crops
Ruminant meat	Feed mix assignment	Bovine meat, sheep and goat meat
Non-ruminant meat	Feed mix assignment	Pig meat
Poultry meat	Feed mix assignment	Poultry meat
Milk	Feed mix assignment	Milk, cream, butter/ghee
Eggs	Feed mix assignment	Eggs

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[1] Simulated as Maize with a special MF assignment (see text).

Table 5. Selected results: agricultural area, carbon and water budgets; 10-year averages (1990-1999).

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