Agriculture in a squeeze? – Modelling the combined impacts of rising food demand and climate change on land and water use

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Abstract

In the coming decades, world agricultural systems will face serious transitions. Population growth, income and lifestyle changes will lead to considerable increases in food demand. Moreover, a rising demand for renewable energy and biodiversity protection may restrict the area available for food production. On the other hand, global climate change will affect production conditions for better or worse depending on regional conditions. In order to simulate these combined effects in a spatially explicit way, we have linked the LPJ dynamic global vegetation model with an economic land allocation model. The paper presents the modelling approach and preliminary results.

Contents

1 Agriculture as a crucial link between the anthroposphere and the biosphere

Some of the most important interactions between human activities and the environment occur in the agricultural sector. Agricultural production is – more than most other economic activities – not only affected by socio-economic *and* environmental conditions alike, it also influences both systems to a significant degree.

From an economic perspective, the importance of agriculture varies according to the level of economic development. In poor countries, agricultural and food production contributes a major share to GDP and is an important source of employment and household income. Many economists claim that there is no way out of poverty, except through agricultural and rural development [1]. In the process of economic development the role of agriculture is decreasing, and in rich industrialised countries the share of agriculture in GDP and overall labour force is now below five percent. These trends occur despite wide-ranging government interventions to achieve the contrary. Like most economic sectors, agricultural production is also strongly affected by macroeconomic conditions, lifestyles changes and consumption patterns.

From an environmental point of view, agriculture is of key importance in rich and poor countries, regardless of the level of economic development. On a global scale, agricultural production accounts for about 40 percent of total land use, it uses about 70 percent of all freshwater withdrawals, it affects important nutrient cycles, it contributes significantly to climate change through methane emissions, and it is considered one of the most important causes for biodiversity loss [2]. At the same time, agricultural productivity may be strongly affected by global environmental change.

If we want to understand the interactions between the anthroposphere and the biosphere in general, an in-depth understanding of the links between food consumption, agricultural production and the related environmental impacts is indispensable. The major challenge to this understanding is the fact that socio-economic and environmental driving forces and impacts occur at different spatial, temporal and thematic scales. It is, for instance, not meaningful to talk about environmental impacts without looking at reasonably small regional units. However, economic analysis and the related data are often confined to nation states as the typical unit of analysis.

For the purpose of an integrated environmental-economic analysis of the food system across different scales we are presenting a coupled modelling framework. The biosphere part of the system is represented by the well established Lund-Potsdam-Jena Dynamic Global Vegetation

Model (LPJ), a spatially explicit, grid-based process model which runs on a global scale. The socio-economic part is represented by a resource allocation model which we call a "Management model of Agricultural Production and its Impact on the Environment" (MAgPIE). This model is currently under development and we present preliminary modelling results here for the first time.

At the moment, these two models run sequentially and exchange information on key economic and environmental conditions and driving forces. Changes in economic and environmental conditions can be modelled separately or in combination. Outputs of the modelling framework include standard economic variables as well as environmentally relevant information.

While the scope of our modelling work is global in principle, for the purpose of testing the coupled system and demonstrating the viability of our concept we have zoomed into a small region as a first example. We chose Germany as the sample region to be presented in this paper. It has to be stressed, though, that the resolution of our global models may be too coarse to provide convincing results for a region the size of Germany. However, we are able to show that the concept works and can be extended to the global scale with reasonable effort.

2 Agricultural challenges in the 21st century

Whether food production can keep pace with the demand for improved diets for a rapidly growing world population is a question that has been debated vigorously since it was raised by Malthus two centuries ago. Although much of mankind has experienced improvements in diets over the past century, expert views about prospects for the coming decades differ as sharply as ever [3].

There is a rather optimistic group consisting primarily of economists and modellers in the neoclassical tradition. They note the relatively low crop yields, inefficiencies throughout the food production and consumption chain, and the ample reserves of potential arable land in many developing countries. They further hold the view that sounder government policies, wider application of green revolution technology, reduced inefficiencies, upgraded rural infrastructure, and greater investments in human resources and research will make much larger harvests possible and no insurmountable environmental constraints are foreseen [4-7].

The rather pessimistic group primarily belongs to the ecology and ecological economics communities focussing on carrying capacity of the Earth. They point to the many signs of environmental stress and the increasing difficulties encountered in expanding agricultural land, water supply, and crop yields, and in controlling pests. In their view a large expansion of agricultural output is not feasible, and they even doubt whether current levels of crop production can be sustained in a number of countries. Global warming would impose further stress on agricultural systems, the prospects for increased food production would become even less favourable than they are at present. A major expansion of food supply would require a highly organized global effort by both the developed and the developing countries that has no historic precedent [2, 8].

In the debate about global food security over the next century there is a clear focus on supply-side effects and developments, i.e. technological change in agricultural production, limits to natural resource availability and resource quality, most of all agricultural land and water for irrigation. Surprisingly, the importance of changes in demand growth and demand structure have been studied to a lesser extent. In many scenarios, the current trend towards higher meat consumption at higher income levels is simply extrapolated over a wide range of countries on a global scale in the course of economic development. However, there may be significant scope for altering the relationship between income and food demand. For example, changes in dietary structures may evolve due to increasing knowledge and concerns about health impacts of alternative diets or reduction of waste and other efficiency changes within the food system [9]. These demand-side effects could have a significant impact on the outcome of long-term global food scenarios (Table 1).

Table 1: Conservative estimates of efficiency gains in global food production achievable by the year 2050

Changes compared to 1990 practices		Gains equivalent to global 1990 food energy consumption (percent)
Improved field efficiencies	Better agronomic practices (raise average yields by 20 %)	22
	Higher fertilizer uptake (raise nutrient use efficiency by 30 %)	7
	Reduced irrigation waste (raise water use efficiency by 30 %)	7
Reduced waste	Post-harvest losses (lower by 20 %)	6
	End-use waste (lower by 20 %)	8
Healthier diet	(Limit fat intakes to 30 % of total energy)	10
Total gain		60

Source: [10]

Most scenarios and analyses on the development of the global food system cover the period up to 2025 at most [4-7]. From a social science point of view the time span of one generation is already very long and it may be questionable whether model simulations and scenario analyses beyond two to three decades are possible and have any meaning [10]. A few such analyses beyond the year 2050 have been conducted mainly with respect to the impact of climate change on agricultural production, as significant changes in the global climate system are not to be expected before the middle of the 21st century [11, 12]. Like long-term environmental changes, profound alterations in cultural habits and dietary preferences may also come about only within several decades, so there may be scope for longer-term analyses from this perspective as well.

2.1 Food demand and dietary choices

World population growth is likely to come to an end in the foreseeable future. According to a recent study, there is around an 85 percent chance that the world's population will stop growing before the end of the 21st century. Furthermore, there is a 60 percent probability that the world's population will not exceed 10 billion people before the year 2100, with a median projection for the year 2050 at 8.8 billion [13]. In any case this means that by 2050 about 50% more people have to be fed than currently.

Human diets are largely determined by economic factors, particularly prices and incomes. As income rises, people tend to consume more calories in total, and the share of animal calories increases, especially the consumption of animal fats. In Africa people derive two-thirds of their calories from starchy staple foods and only 6 percent from animal products. In Europe people derive 33 percent of their calories from animal products and less than one third from starchy staples. The average global diet falls somewhere in between these two extremes (Table 2) [14].

Table 2: Major sources of food energy in industrialised and developing countries (1994, percent share)

Product group	Industrialised countries (Percent share)	Developing countries (Percent share)
Cereals	31	56
Meat and dairy products	28	12
Sweeteners & vegetable oils	23	17
Roots and tubers	4	5
Others	14	10

Source: Adapted from [14].

As most developing countries in the future are likely to follow the trends in rich countries, global meat consumption can be expected to rise strongly over the next decades, due to a combination of population growth, growth in per-capita income and a high income elasticity of meat demand. Annual growth rates of aggregate meat consumption until 2030 are estimated between 1.4 and 3.0 percent. This would imply an increase in average global meat consumption per capita from 32.6 kg/year to 44-54 kg/year, depending on different growth assumptions [15].

2.2 Agricultural supply and resource use

In view of the described rapid developments on the demand side, it is heavily debated whether global food supply will keep up with this pace or whether farming activities will run into serious conflict with the concurrent goal of preserving local environmental conditions, which continue to provide the life support systems for future generations. In the past, agricultural production could rely on virtually costless water supplies as well as available land for expansion. Meanwhile, most of the potentially available arable land is already under cultivation and future production increases will have to be achieved through more intensive production technologies on the given area of land. However, improper management and irrigation techniques have already caused serious land degradation on a large scale. In the future, agriculture will have to compete for water and land with other economic activities, like urban development, industrial use, forestry, and nature conservation [2].

With respect to future yield increases one can take an optimistic view and assume that past trends in agricultural productivity growth will continue for some time. Some model calculations show that even at conservatively reduced growth rates, global food supply will outpace demand up to 2020 and real prices for agricultural commodities are likely to continue to fall [5, 16]. However, the assumption of exponential growth paths instead of logistic curves has been questioned. This distinction will become even more important in the very long run [17, 18]. The potential of biotechnology and genetic engineering for accelerating agricultural productivity growth is still very unclear and subject to a strong public debate. Some initial trials show positive effects, but environmental consequences have to be further investigated and widespread social acceptance remains questionable [19].

Land use

The amount of land necessary for the production of various food items differs widely, especially for animal products. Different animals have different feed requirements and feed conversion rates (Table 3) [20].

Table 3: Conversion rates of grain to animal products

Animal product	Kg of feed / kg of output	Kcal of feed / kcal of output
Beef	7.0	9.8
Pork	6.5	7.1
Poultry	2.7	5.7
Milk	1.0	4.9

Note: These conversions are very approximate, as the caloric density of both feeds and animal products can vary greatly. Furthermore, data units are often not specified or precisely comparable.

Source: [20]

This directly contributes to the area of land required for certain food products (Table 4) [21]. However, it has to be considered that the required quality of land differs for various livestock production types. For example, ruminants like cows and goats are able to convert grass from permanent pasture land into valuable food for human consumption, but cattle can also be fattened on a feed mix with a large share of cereals. Pigs can be raised primarily on grains, but also on human food residuals. Hence, the amount and quality of land required for livestock production depend very much on the specific production systems.

Table 4: Specific land requirements per food item (Netherlands, 1990, m^2*year*kg^{-1})

Food item		Specific land requirement (m^2*year*kg^{-1})
Fats	Vegetable oil	20.7
	Low fat spread	10.3
Meat	Beef	20.9
	Pork	8.9
	Chicken filet	7.3
Milk products and eggs	Whole milk	1.2
	Cheese	10.2
	Eggs	3.5
Cereals and other crops	Cereals	1.4
	Sugar	1.2
	Vegetables (average)	0.3

Source: Adopted from [21]

The total amount of land available for agriculture not only depends on biophysical conditions, but also on the demand for land for other economic and environmental purposes. Infrastructure development and urbanisation may reduce agricultural areas around the major population centres. In the course of a major energy transition there might arise a significant demand for bio-fuel production not only from fast growing forests, but also from agricultural crops. Moreover, a certain share of land may have to be set aside for nature conservation and biodiversity management, in order to maintain nature's basic life supporting functions [12, 22].

More intensive production systems may lead to land degradation, if they are applied year after year on the same area. Main types of land degradation are soil erosion from wind and water, chemical degradation (e.g. nutrient loss, salinisation, pollution), and physical degradation (e.g. compaction, water-logging). Land degradation is a very important issue in some geographic regions, but it remains unclear whether it may become a serious threat to global food supply [23, 24]. While in some parts of the industrialised world problems of fertilizer overuse, like nitrate leaching and eutrophication, are of considerable concern, in many developing regions, like Sub-Saharan Africa, inadequate replenishment of removed nutrients reduce soil fertility and increase erosion. Hence, in order to assure sufficient nutrient supply for more intensive production on a global scale, the demand for fertilizer will rise. Especially nitrogen requirements will increase significantly, according to some estimates to 50 percent above current consumption by 2050. What this means for sensitive environmental systems and the nitrogen cycle, which is as yet neither well observed nor understood, remains unclear [5, 25].

Water use

The resource base that may pose the most serious limitations to future global food supplies is water. Irrigated area accounts for nearly two-thirds of world rice and wheat production, so growth in irrigation output per unit of land and water is essential to feed growing populations. Since the development of traditional irrigation and water supplies is increasingly expensive and new sources like desalination are not expected to play a major role soon, water savings at every level are absolutely necessary. Crop output per unit of evaporative loss has to be increased and water pollution has to be reduced. However, the size of potential water savings in agricultural irrigation systems is unclear. While specific water uses can be made more efficient through better technology, especially in many poor countries, the potential overall savings in many river basins are probably much smaller, because much of the water currently lost from irrigation systems is re-used elsewhere. Increasing water demand from households and industry will further exacerbate the challenge [26, 27].

The specific water requirements for various agricultural products differs widely, from less than 200 litres per kg output for potatoes, sugar beets or vegetables, to more than 1000 litres per kg output for wheat and rice [28]. A typical diet with meat consumption at American levels requires about 5400 litres of water for crop evapotranspiration, while a comparable vegetarian diet requires only about half the amount. In comparison, the daily amount of water required for drinking and sanitary purposes is almost negligible at less than 60 litres. The future global challenge with respect to agriculture and water implies that over the next 25 years food production has to be increased by about 40 percent while reducing the renewable water resources used in agriculture by 10-20 percent [29, 30].

Climate change

An additional constraint to agricultural production in the long run, i.e. in the second half of the 21st century, is likely to occur through global climate change. A rise in atmospheric CO_2-levels and a corresponding rise in global temperatures will not only affect plant growth and yields, but also alter the regional patterns of precipitation and water availability as well as land erosion and fertility. Sensitivity studies of world agriculture to potential climate changes have indicated that global warming may have only a small overall impact on world food production because reduced production and yields in some areas are offset by increases in others. However, regional impacts vary quite significantly, with tropical regions especially suffering from droughts. Moreover, the combined effects of various changes in the long run are still highly uncertain [31].

3 An integrated environmental-economic modelling framework

The impacts of agricultural production on natural conditions are strongly depending on specific local conditions. Changes in water or nutrient cycles are related to soil conditions, terrain type and local climate conditions. Hence it is necessary to link economic conditions of agricultural production to the place-specific biophysical conditions, in order to better understand their interactions. The key challenge with respect to modelling is to link place-specific models of agricultural production and land use with models representing important elements of the biosphere and hydrology.

A comprehensive analysis of the world food system can draw upon a substantial volume of existing research in the area of integrated assessment and modelling. Issues of climate change and agricultural land use have been covered in the IMAGE[1] project and the ICLIPS[2] project [32], where greenhouse gas emissions of different land use patterns as well as the potential of bio-fuel production on agricultural land as an alternative energy source have been analysed [12]. The US Department of Agriculture maintains its FARM[3] model, a computable general equilibrium (CGE) model with a focus on the interaction between climate change, economic growth, agricultural production and environmental resource use. The GTAP[4] consortium has developed a CGE modelling framework as well as a database for global economic analysis, and is also extending its focus towards agricultural resource use, especially land use issues. The International Institute for Applied Systems Analysis (IIASA) maintains its Basic Linked System (BLS) which has been applied to various questions on global environmental change [33]. It has also been linked with the agro-ecological zones (AEZ) model to assess future changes in global land use and land cover [34]. The International Food Policy Research Institute (IFPRI) has a long tradition of partial equilibrium agricultural trade modelling with its IMPACT[5] model [5]. Recently the IMPACT model has been coupled with the global hydrological model WaterGAP[6] in order to come up with more reliable global projections for water demand and supply [35].

Our starting point to improve the understanding of society-biosphere interactions is the extension of one of the most advanced and comprehensive models of the global biosphere – the Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ).[7] We suggest a way to integrate human activities into LPJ and come up with a coupled climate-biosphere-economy modelling framework, including the global water cycle. This is an important improvement on existing research, as LPJ endogenously models the linkages between climate and soil conditions, water availability and plant growth in a dynamic way. This yields an advanced representation of global biogeochemical conditions, which can be used to define plausible biophysical constraints to agricultural production, or to human activities in general for that matter.

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[1] Integrated Model to Assess the Greenhouse Effect: http://sedac.ciesin.org/mva/image-2.0/image-2.0-toc.html
[2] Integrated Assessment of Climate Protection Strategies
[3] Future Agricultural Resources Model: www.cru.uea.ac.uk/link/hadcm2/abstracts/darwin_paper.html
[4] Global Trade Analysis Project: www.gtap.agecon.purdue.edu
[5] International Model for Policy Analysis of Commodities and Trade
[6] Water – Global Analysis and Prognosis: http://www.usf.uni-kassel.de/usf/mitarbeit/homepages/doell/research3.htm
[7] For a full documentation see: www.pik-potsdam.de/lpj/

3.1 The Lund-Potsdam-Jena model (LPJ)

LPJ is a coupled non-equilibrium biogeography-biogeochemistry model which combines process-based representations of terrestrial vegetation dynamics and land-atmosphere carbon and water exchanges in a modular framework [36]. LPJ explicitly considers key ecosystem processes such as vegetation growth, mortality, carbon allocation, and resource competition, though their representation is of intermediate complexity to allow for global applications. To account for the variety of structure and functioning among plants, 10 plant functional types (PFTs) are distinguished. Leaf phenology of summergreen and of raingreen PFTs is determined daily, depending on temperature and water stress thresholds. Gross primary production is computed based on a coupled photosynthesis–water balance scheme; net primary production is given by subtracting autotrophic respiration. After additional subtraction of a reproduction cost, the remaining carbon is allocated to three pools for producing new tissue. Carbon from dead leaves and roots enters litter; decomposition of litter and soil organic matter is driven by soil temperature and water content. A PFT-specific mortality rate is determined at the end of each year as a result of heat stress, low growth efficiency, a negative carbon balance, light competition, or violation of bioclimatic limits. The presence and fractional coverage of PFTs is thus determined annually according to individual bioclimatic, physiological, morphological, and fire-resistance features [36]. The structure and distribution of the PFTs is decisive for the simulated site water balance, since evapotranspiration, soil water content, and runoff generation are modulated by PFT-specific attributes such as interception storage capacity, seasonal phenology, rooting depth, and photosynthetic activity.

The fundamental entity simulated in LPJ is the average individual of a PFT. This concept provides a simple way for process acting at the level of the plant individual to be scaled up to the "population" over a grid cell. The grid cell is treated as a mosaic divided into fractional coverages of PFTs and bare ground. It is assumed that the physical environment of the plants is well mixed, i.e., the PFTs do not occupy discrete blocks, but compete locally for resources. The global version of LPJ has a spatial resolution of 0.5°, which is equivalent to a pixel size of about 50 x 50 km at the equator. This implies a total number of about 60,000 grid cells covering the whole terrestrial earth surface.

Overall, LPJ simulates well the global terrestrial carbon pool sizes and fluxes, and captures the biogeographical distribution of Earth's major biomes. Recent applications of the model include assessments of the carbon balance of the terrestrial biosphere, the representation of fire regimes, and the simulation of transient vegetation responses to climate warming.[8]

A typical simulation with LPJ starts from "bare ground" and "spins up" for 1000 model years until approximate equilibrium is reached with respect to carbon pools and vegetation cover. The model can then be driven with a transient climate (i.e. future climate scenarios provided by MPI Hamburg or the Hadley Centre). The standard LPJ simulation is run with the transient CRU data for 1900-1998.

In addition to the PFTs representing natural vegetation, recently 13 crop functional types (CFTs) have been implemented in LPJ in order to simulate potential agricultural production. These CFTs represent 8 classes of agricultural crops, e.g. temperate cereals (wheat), tropical cereals (millet), rice, maize, pulses (lentil), oil crops (sunflower, soybean, groundnut, rapeseed), roots and tubers (sugar beet, maniok), and fodder crops (C3 and C4 grass). As agricultural crops cover about 40% of the global land area, it has been shown that global carbon pools and water runoff are significantly affected when crops are taken into account in a global vegetation model like LPJ [37].

Input data required by LPJ are monthly fields of mean temperature, precipitation and cloud cover, which are taken from the CRU05 (1901-1998) monthly climate data on a 0.5° x 0.5° global grid. A data set of historical global atmospheric CO_2 concentrations extending from 1901-1995 was obtained from CCMLP. Soil texture data are from the FAO soil data set.

Standard LPJ outputs include changes in net primary production and different fractions of biomass, changes in carbon pools (e.g. vegetation carbon, soil carbon), and changes in water balances (e.g. runoff). Under given climate conditions, soil type and water supply, the CFTs generate crop yields in terms of above-ground biomass as well as harvested organs (like grains, roots etc.). The CFTs are currently specified as to represent observable yields at the end of the 20th century.

3.2 MAgPIE – a Management model of Agricultural Production and its Impact on the Environment

MAgPIE is set up as a linear-programming optimisation model with a focus on agricultural production, land and water use. The goal function is to produce a required amount of food energy, defined in GigaJoule (GJ), at minimal costs. Food demand is defined for an exogenously given population in three energy categories: crop energy, meat energy, and milk en-

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[8] See LPJ website at http://www.pik-potsdam.de/lpj/lpj_publicvt1.html for a full list of publications.

ergy.[9] Energy can be produced by choosing from 8 cropping activities (bread grain, feed grain, oil crops, sugar crops, roots/tubers/pulses, vegetables/fruits/nuts, rice, fodder crops) and 3 livestock activities (ruminant meat[10], non-ruminant meat[11], milk).

Input factors of production are labour, chemicals, and other capital (measured in US$), land and water (measured in physical units, ha and m^3, respectively). Labour, chemicals and capital are in unlimited supply at a given price. Land and water are available in fixed amounts and are implemented as physical constraints to production. Available land is divided in crop land and pasture.

Given a certain yield per hectare for each cropping activity, the corresponding energy delivery is calculated with standard energy content parameters. Livestock energy is produced either with feed grains (non-ruminant meat) or with a mixture of pasture, green fodder and feed grain (ruminant meat, milk), in addition to labour, chemicals and capital. Currently we are looking only at one region without external trade. That means, the regional demand for intermediate inputs like feed grain and green fodder has to be met by regional production. In the model, the region is forced to be self-sufficient in food production.

Water supply is currently defined purely by precipitation inflows. There are no managed water stocks like groundwater reservoirs, lakes or water storages. Water demand from production activities is calculated using fixed coefficients per unit of crop or livestock output. Water balances are calculated in the hydrological sub-system of LPJ.

In order to keep the cropping mix within plausible bounds we introduce rotational constraints. In our sample region Germany, for instance, it seems plausible to limit grain production to a maximum of 66% of total crop area, as on average every third year a different crop will be planted for reasons of crop management. For the same reason, sugar beets have been limited to 25% and oil crops to 33% of total crop area.

Even though in this paper we are looking at Germany as an example, we use only data sources which are also available on a global scale. Crop yields are taken from the CFTs in LPJ and are checked for consistency with average regional yields according to FAO statistics. Average

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[9] At the moment we abstract from other vital food ingredients like proteins etc.

[10] i.e. beef, veal, sheep and goat meat.

[11] i.e. pork and poultry meat.

cost structures for production activities are calculated on the basis of FAO production and land use statistics and national social accounting matrices (SAMs) from GTAP.[12]

Output generated by MAgPIE includes the production mix in total food energy production, shares of different crops in total use of arable land, purchases of variable inputs, and shadow prices for inputs in limited supply and other constraints, like rotational limits. The generation of shadow prices (or "opportunity costs") for land and water is probably the most useful feature of this model. It facilitates the assignment of internal use values to factors of production for which no proper markets and, hence, no observable prices exist. This can be particularly useful for the systematic valuation of ecosystem services, like water supply, as this model provides a rigorous economic framework for the use of these services.

Of course, this model is a strong over-simplification of real agricultural production. It is, for instance, not at all clear whether or not actual producers always act as strict cost minimisers or profit maximisers. Hence, the optimised mix of production and resource use generated by the model almost certainly differs from empirical observations. Moreover, in the current version it is a static model with a lot of exogenous inputs. However, this type of model can be easily scaled down to a single farm and scaled up to the world as a whole, thus providing the opportunity for nested modelling structures. It can also in principle be coupled to a food demand model or an economy-wide model, in order to make markets and prices for outputs and inputs endogenous. Here we will build upon recent developments in the area of model coupling and meta-optimisation at PIK [38].

3.3 Spatial scaling, model coupling and information flow

Several challenges have to be overcome in coupling a biosphere model like LPJ with an economic model like MAgPIE.

First, thematic scales have to be matched. CFTs in LPJ, which are defined according to plant-physiological properties, have to be matched with groups of crops which provide a similar type of output for human consumption. Oil crops, for instance, comprise a wide variety of plant species (e.g. rapeseed, groundnuts, sunflowers, oil palms etc.), but they all deliver similar types of oil, which are almost perfectly substitutable in the processing of agricultural products. Currently our 8 cropping activities in MAgPIE match sufficiently well with the CFTs defined in LPJ.

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[12] In the latest version of the GTAP database SAMs are available for 78 regions with up to 57 economic sectors. See: http://www.gtap.agecon.purdue.edu/databases/v5/default.asp .

Second, temporal scales have to be made consistent. Standard LPJ runs into the future cover a period up to the year 2100. Most economic forecasting exercises do not go beyond a time frame of 10-20 years. As they run into the longer-term future, they usually get more aggregated and lack structural detail. One of the reasons is that changes in technology and input use are very hard to predict in the long run. At the moment, we abstract from technical change and restrict ourselves to some stylised scenarios in a comparative static manner. That means, we take "time slices" out of certain LPJ runs, and couple them with static MAgPIE scenarios.

Third, and most importantly for the illustrative purpose here, we have to bridge the gap between the national (or even larger) scale in MAgPIE and the 0.5°-grid scale in LPJ. This is the most challenging aspect in coupling these two models. On the one hand, LPJ provides information on climate, soil, biomass and crop yields, carbon and water balances for about 60,000 grid cells on a global scale. On the other hand, information on food demand, agricultural cost structures, input use, crop shares and many crucial economic indicators are usually only available from official statistics for whole nation states. While it is obviously impossible to model economic activity on a 0.5°-grid, it does not make much sense either to model environmental impacts on the national level.

In order to bridge this gap, we developed a procedure to group the grid cells in LPJ into a small number of "productivity zones", according to the normalised level of crop yields in each grid cell. These zones do not have to form compact geographic regions. However, once the zones are established, they are taken as homogeneous and in MAgPIE all cells within a certain zone are treated in the same way. The zones can differ with respect to climate conditions (temperature, precipitation), crop yields, share of crop land in total area, and their total size (i.e. number of grid cells belonging to the zone).

For the case of Germany we have 185 grid cells grouped in 6 different zones. Effectively this means, that MAgPIE can choose among 8 cropping activities and 3 livestock activities in 6 different zones, yielding in total 66 different production activities in the given region. With this procedure we are able to generate considerable differences in regional cropping patterns without being too demanding with respect to required data, especially on the economic side of our modelling framework.

We are also able to distinguish between constraints to be fulfilled in each zone and constraints to be fulfilled at the regional level. This introduces aspects of trade between zones. For instance, feed grain produced in any zone is pooled across all zones and can be used in the whole region, as long as the overall balance is maintained. In contrast, green fodder realistically has to be used locally (usually even on the same farm) and, hence, we impose a separate constraint for each zone. Land and water are also constrained in each zone, as they cannot be easily moved around.[13]

Having separate constraints for different zones implies that MAgPIE generates different shadow prices for each zone which is a useful feature. Moreover, we get different patterns of specialisation and land use shares for each zone.

The sequence of our joint modelling exercises runs as follows:

1. Run LPJ for all crops separately with one CFT at a time, in order to determine potential crop yields for all crops in each grid cell at a certain point in time
2. Group the grid cells into productivity zones, according to normalised crop yields (*Note*: depending on climate and soil conditions, some crops are more productive than others - and vice versa - in different zones)
3. Deliver information on zones (number of grid cells, average fraction of arable land, average precipitation) and crop yields (ton/ha, average for each crop in each zone) from LPJ to MAgPIE
4. Optimise production pattern and resource use for the whole region in MAgPIE
5. Deliver land use shares for all crops in all zones from MAgPIE to LPJ
6. Calculate impacts of different land use patterns on carbon and water balances in LPJ.

4 Scenarios and selected model results

For the analysis in this paper we define the situation in Germany in the year 2000 as our reference scenario, i.e. climate conditions, yields, the fraction of arable land and pasture in total area, and cost structures in agricultural production are taken for this point in time. Then we look at 4 different scenarios which are either driven by climate change through LPJ or by stylised socio-economic changes through MAgPIE. In a fifth scenario we combine all separate scenarios into one.

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[13] For the moment we abstract from the possibility of water transport through rivers, canals and pipes.

Scenarios:

(a) Climate conditions as predicted for the year 2050 (stylised representation of a typical environmental driving force)

(b) Increase in total food energy demand by 10 % (stylised representation of an increase in food exports driven by increased global food demand)

(c) Decrease in meat energy demand by 10 % (stylised representation of a change in life-styles towards more vegetarian diets)

(d) Decrease in available crop land by 10 % (stylised representation of increased demand for land for non-food purposes, e.g. bio-fuel production)

(e) Joint scenario - all 4 previous scenarios combined

For our sample region Germany we have restricted our set of relevant cropping activities in MAgPIE to 5 crop types (bread grain, feed grain, oil crops (i.e. rapeseed), sugar crops (i.e. sugar beets), and green fodder (i.e. silage maize)). According to FAO statistics these crop types currently account for about 87 % of total crop land.

In **Step (1)** of our analysis we run LPJ for a selection of 185 grid cells, covering Germany, with all CFTs separately in order to define potential yields for each grid cell. We do this twice, with current climate for the year 2000 and with the ECHAM4 climate scenario for the year 2050. [14]

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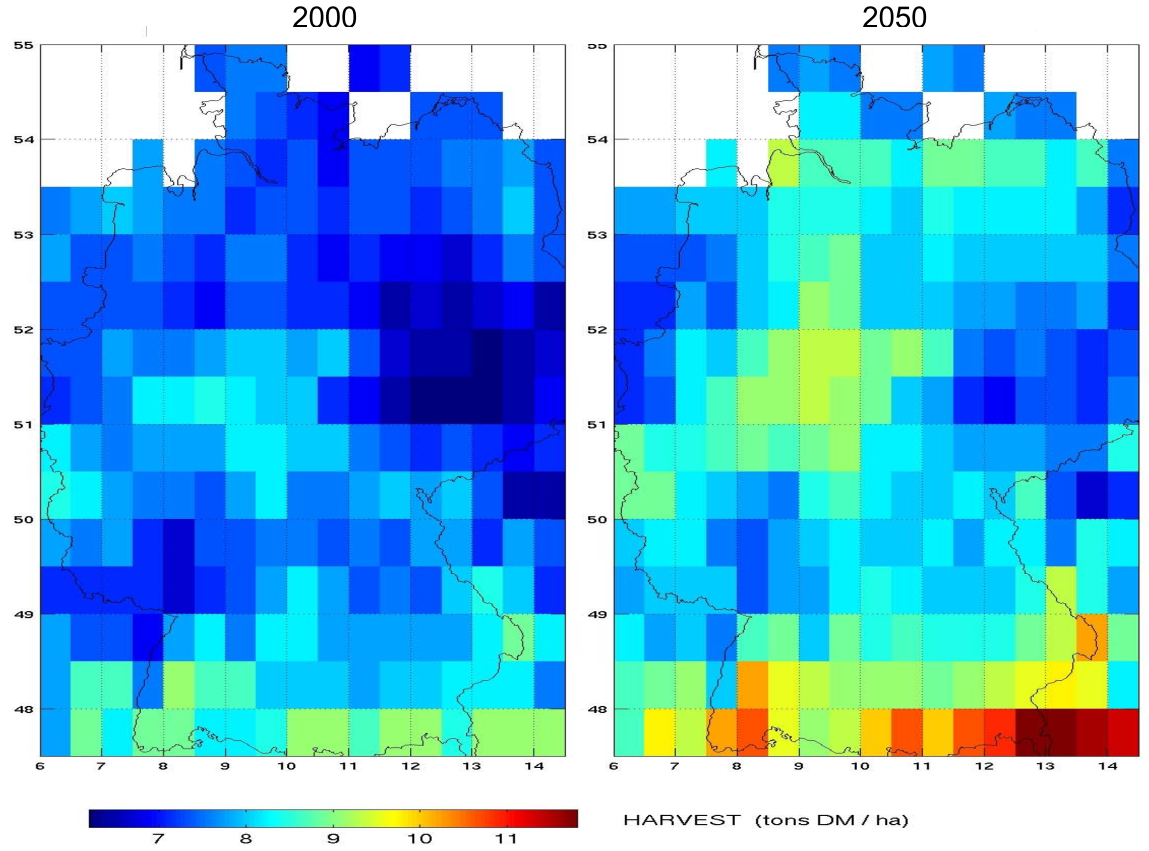
[14] For more information on ECHAM4 and other climate model scenarios see: http://ipcc-ddc.cru.uea.ac.uk/dkrz/dkrz_index.html .

Figure 1 shows yield distributions for the CFT "temperate cereals" (i.e. wheat) in both years. The maps reveals significant variation in yields across the region. However, yields seem to depend strongly on precipitation and less on soil conditions. This is partly to be explained by the rather crude soil classification in the global FAO soil data set used in LPJ.

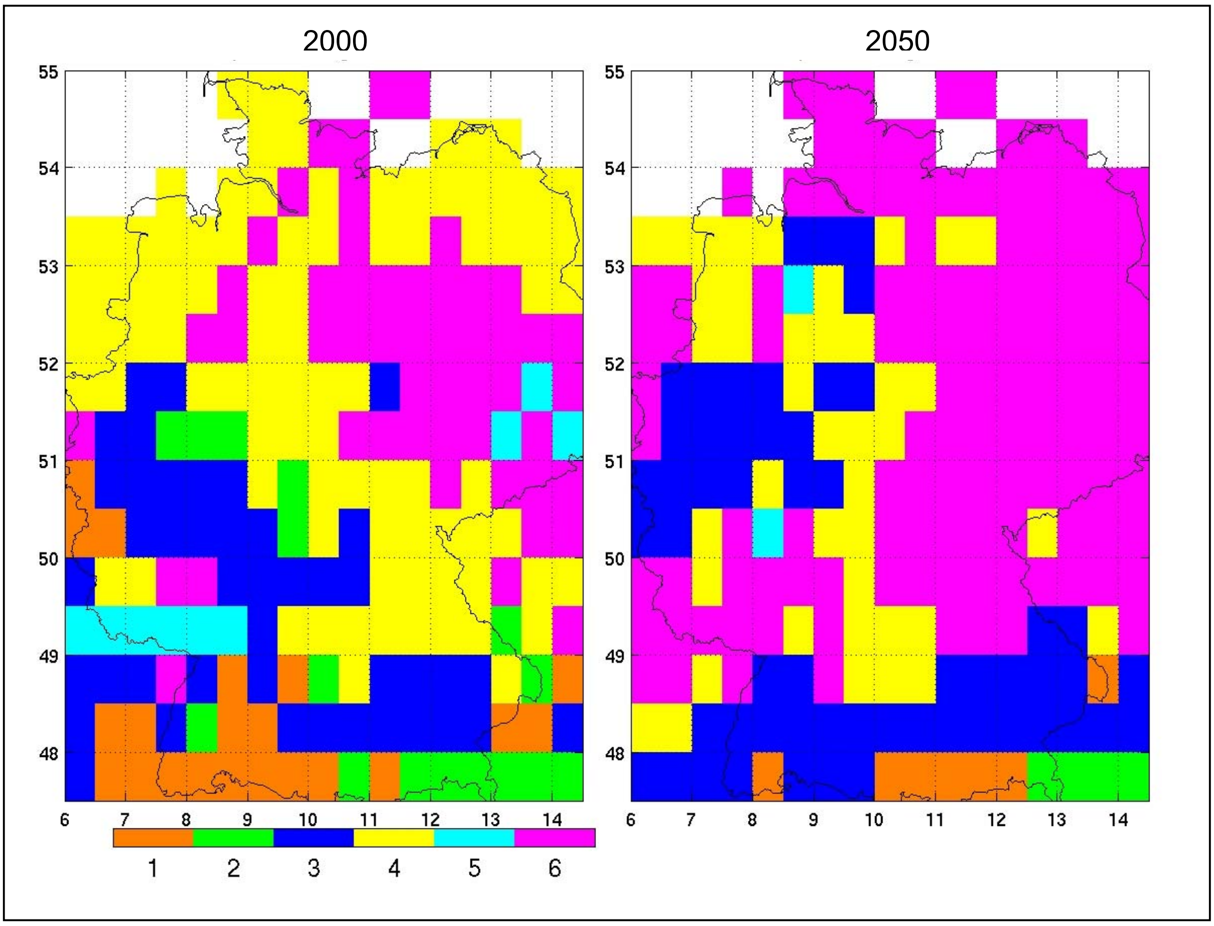
Figure 1: Regional distribution of cereal yields in Germany under different climate conditions



Source: Own calculations (LPJ), ECHAM4 climate scenario

In **Step (2)** we use normalised yields of all CFTs in order to define 6 productivity zones. These can be roughly characterised by high, medium and low cereal yields in combination with high and low silage maize yields. The spatial distribution of our 6 zones in 2000 and 2050 is shown in Figure 2. Due to different climate conditions and yields, the spatial distribution of zones varies considerably between both years. Under 2050 climate conditions grid cells tend to move from zones 1, 2, 4 and 5 into zones 3 and especially 6.

Figure 2: Regional distribution of 6 productivity zones in Germany under different climate conditions



Definition of zones according to yield potentials:

	Temperate cereals:	Silage maize:
Zone 1:	high	high
Zone 2:	high	low
Zone 3:	medium	high
Zone 4:	medium	low
Zone 5:	low	high
Zone 6:	low	low

Source: Own calculations (LPJ), ECHAM4 climate scenario

Table 5 shows average yields for the 5 cropping activities in different zones as calculated in LPJ. A comparison with official FAO statistics on crop yields for Germany shows that LPJ currently overestimates yields in cereals and oil crops, while sugar beet yields are underestimated.

Table 5: Characteristics of productivity zones under different climate conditions

Zone	Share of regional crop land (%)	Precipitation (mm/year)	Yield (ton/ha)			
			Cereals	Sugar beet	Rapeseed	Silage maize
Climate 2000						
1	9	953	9,7	43,0	6,1	34,1
2	7	1016	9,9	32,0	5,7	23,0
3	19	755	8,7	42,1	5,5	32,7
4	39	691	8,6	35,4	5,4	25,6
5	4	653	7,8	39,3	5,0	31,9
6	22	593	7,8	36,0	4,9	26,3
Climate 2050						
1	3	967	10,8	49,7	6,7	36,1
2	2	1305	12,1	34,4	6,4	5,8
3	24	737	8,9	46,2	5,6	34,2
4	18	632	8,3	41,6	5,2	29,0
5	1	627	7,7	42,8	4,8	31,9
6	52	552	7,0	35,6	4,4	26,1

Source: Own calculations (LPJ), ECHAM4 climate scenario

In **Step (3)** of our analysis these characteristics of zones and yields are implemented in MAgPIE, and in **Step (4)** agricultural production and resource use are optimised for Germany.

Total food energy demand for Germany is calculated by multiplying a population of 82 million by an average daily food availability of 3411 kcal or 14272 MJ (according to the FAO food balance sheets). Note that this is not strictly food consumption, but rather food availability for consumption. More precise data on effective food intake are not available. The shares in total food energy consumption are 69 % for plant-based energy, 17 % for meat-based energy, and 14 % for milk-based energy.

With the current specification of MAgPIE, in the reference situation total food demand in Germany can be met, in fact the self-sufficiency ratio is about 110 %. Under these conditions the model leaves in the optimised solution about 10 % of crop land and 9 % of pasture unused. The resulting average land use shares for the whole region in all scenarios are shown in Table 6.

Table 6: Average land use shares for Germany under various scenarios (%)

Scenario ID	(reference)	(a)	(b)	(c)	(d)	(e)
Description	Year 2000	Climate 2050	Demand increase	Reduced meat	Reduced crop land	Combined scenario
Bread grain	16	11	11	21	11	13
Feed grain	50	53	55	45	55	52
Rapeseed	14	15	19	9	22	18
Sugar beet	0	0	3	0	1	0
Silage maize	10	11	12	10	11	12
Unused crop land	10	9	0	15	0	5
Unused pasture	9	1	4	9	10	1

Source: Own calculations (MAgPIE)

To illustrate the variation in land use patterns among the zones, Table 7 shows the shares for all zones in scenario (b).

Table 7: Land use in all zones in Scenario (b) – "Demand increase by 10 %"

	Zone					
	1	2	3	4	5	6
Bread grain	66	66	3	0	0	0
Feed grain	0	0	63	66	66	66
Rapeseed	14	9	16	22	0	26
Sugar beet	0	0	8	0	24	0
Silage maize	20	25	10	12	10	8
Unused crop land	0	0	0	0	0	0
Unused pasture	0	55	0	0	0	0

Source: Own calculations (MAgPIE)

As a further important economic output of our modelling exercise we show calculated shadow prices for the combined Scenario (e) in Table 8. The results show considerable variation between zones, as e.g. crop land and pasture are scarce in some zones, but not in all. Water is not a binding constraint in any zone, i.e. the shadow price is always zero. The rotational constraint on cereals is binding in all zones, except zone 2, which is, however, rather small in this scenario.

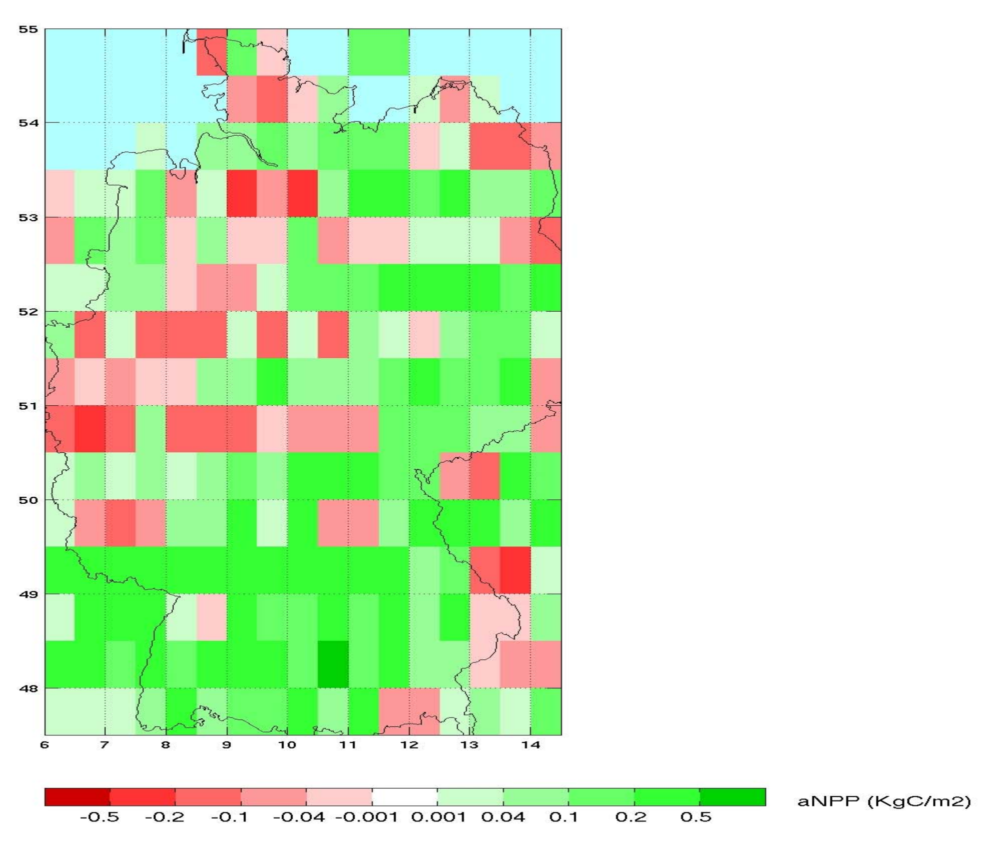
Table 8: Regional and zone-specific shadow prices in Combined Scenario (e)

Zone	**1**	**2**	**3**	**4**	**5**	**6**
Regional constraints/balances						
Crop energy	-17					
Meat energy	-852					
Milk energy	-526					
Feed grain balance	-18					
Zone-specific constraints						
Green fodder balance	-14	-127	-12	-14	-11	-13
Crop land	-612	-1288	-319	-213	-106	0
Pasture	-2800	0	-2848	-2819	-2875	-2841
Rotation cereals	-291	0	-319	-310	-301	-272
Water	0	0	0	0	0	0

Source: Own calculations (MAgPIE)

In **Step (5)** the land use patterns for each zone are implemented LPJ and in **Step (6)** the impacts on net primary production (NPP), carbon and water balances are calculated. Figure 3 shows the difference in NPP in scenario (e) compared to the reference situation in 2000. In this case the differences are mainly due to changes in climate conditions.

Figure 3: Regional changes in Net Primary Production (NPP), Scenario (e) compared to reference



Source: Own calculations (LPJ)

5 Scope for future research

With the preceding analysis we have shown how a grid-based dynamic global vegetation model and a non-spatial economic optimisation model can be coupled. The preliminary results are promising and show the viability of the concept.

However, several caveats apply. The 0.5°-resolution of the current version of LPJ is appropriate on the global scale, but too coarse for the analysis of specific smaller regions. Crop yields and crop growth functions in LPJ have to be further evaluated. The specification of production activities in MAgPIE is rather preliminary, especially the linkages between livestock and crop production, and water requirements by crops have to be refined. The linear-programming technique is powerful, flexible, and computationally very efficient. However, LP models tend to be sensitive to minor changes in certain parameters and may not be robust in the case of large structural breaks. Our current approach to define productivity zones has to be reconsidered to be applicable for global-scale analyses.

Immediate further research steps include the definition of two or more economic regions and to allow for trade in products among them. Activities of land conversion (e.g. deforestation or bio-fuel production on crop land) are also indispensable for modelling agricultural production on a global scale. A dynamic version of MAgPIE would be required to model perennial crops or forest management, and also to implement management of stocks of natural resources, like water. A dynamic optimisation model would also be more appropriate to be linked to the time-step mode of LPJ.

The most challenging task will probably be the implementation of technological change, which is crucial for scenario analysis in the very long-run. Many aspects of water and nutrient cycles, especially nitrogen cycles, are only poorly monitored and not yet well understood, but they are strongly influenced by agricultural production technologies. A theoretical challenge would be to further enhance the knowledge about how technological changes are triggered by environmental conditions for production.

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