Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical programming approach

Hermann Lotze-Campen*, Christoph Müller, Alberte Bondeau, Stefanie Rost, Alexander Popp, Wolfgang Lucht

Potsdam Institute for Climate Impact Research (PIK), PO Box 60 12 03, 14412 Potsdam, Germany
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Abstract

In the coming decades, an increasing competition for global land and water resources can be expected, due to rising demand for food and bio-energy production, biodiversity conservation, and changing production conditions due to climate change. The potential of technological change in agriculture to adapt to these trends is subject to considerable uncertainty. In order to simulate these combined effects in a spatially explicit way, we present a model of agricultural production and its impact on the environment (MAgPIE). MAgPIE is a mathematical programming model covering the most important agricultural crop and livestock production types in 10 economic regions worldwide at a spatial resolution of three by three degrees, i.e., approximately 300 by 300 km at the equator. It takes regional economic conditions as well as spatially explicit data on potential crop yields and land and water constraints into account and derives specific land-use patterns for each grid cell. Shadow prices for binding constraints can be used to valuate resources for which in many places no markets exist, especially irrigation water. In this article, we describe the model structure and validation. We apply the model to possible future scenarios up to 2055 and derive required rates of technological change (i.e., yield increase) in agricultural production in order to meet future food demand.

JEL classification: C61, F15, Q24, Q25

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1. Global land-use challenges in the 21st century

World population will grow to about 10–14 billion people by the year 2100, with a median projection at 8.8 billion for the year 2050 (IPCC, 2000; Lutz et al., 2001). As income rises, people tend to consume more calories in total, and the share of animal calories increases. Global meat consumption can be expected to rise by up to 3% annually over the next decades (Keyzer et al., 2001). While global food supply may still outpace demand up to 2020, growth rates in production are likely to slow down in the longer run (Harris and Kennedy, 1999; Rosegrant et al., 1997). The potential of biotechnology and genetic engineering for increasing agricultural yields remains unclear and subject to a strong public debate (Qaim and Zilberman, 2003). Moreover, the total land area available for agricultural production will be increasingly constrained by land requirements for other purposes, like infrastructure development, urbanization, bio-energy production, or biodiversity protection (Sands and Leimbach, 2003), but also by soil degradation (McNeill and Winiwarter, 2004; Oldeman et al., 1990). In addition to land constraints, water may pose a serious limitation to future global food supplies. Irrigated areas account for nearly two-thirds of the world’s rice and wheat production. Rising irrigation output per unit of land and water is essential to feed growing populations. However, the size of potential water savings in agricultural irrigation systems is unclear. While specific water uses can be made more efficient through better technology, the potential overall savings in many river basins are probably much smaller, because much of the water currently lost from irrigation systems is re-used elsewhere (Rosegrant and Cai, 2003). The future global challenge with respect to agriculture and water is that over the next 25 years food production has to be increased by about 40% while reducing the renewable water resources used in agriculture by 10–20% (Rijsberman and Molden, 2001). An additional constraint to agricultural production in the second half of the 21st century is global climate change. A rise in atmospheric CO₂-levels and a corresponding

*Corresponding author. Tel.: +49-331-2882699; fax +49-331-288 2620. E-mail address: lotze-campen@pik-potsdam.de (H. Lotze-Campen).
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. Regional impacts of climate change vary quite significantly, with tropical regions potentially suffering from droughts. The combined effects of various changes are still highly uncertain (IPCC, 2007). Global land-use patterns will change in the future, reacting to the pressures described above. Projecting their future development is important to study both their impacts on the Earth System as well as the limitations of land use, since freshwater and fertile land are only available in limited amounts.

2. Current status in global land-use modeling

Agricultural land-use patterns are determined by a multitude of environmental, economic, and socio-cultural conditions, and their interactions. The challenge of projecting future land-use patterns is to account, within one modeling framework, for the socio-economic determinants of agricultural demand, as well as for the spatial heterogeneity of the land’s suitability for agricultural production. Land suitability for agricultural production is largely determined by environmental conditions, but also by socio-economic factors, such as management practices and property rights. Demand, on the other hand, is determined by the number of consumers and their per-capita consumption, which is strongly modulated by their income, market access, and cultural background. The disciplines involved in studying land-use change processes differ significantly in methodologies and data used. Economic sector models typically operate with administrativ units, i.e., countries or regional groups of countries in the case of global models. They usually provide little spatial detail on agricultural production and resource constraints. Biophysical models, on the other hand, typically operate on geographic grids. These divide the terrestrial land area into distinct spatial units that are exactly localized. For projecting future land-use patterns, the spatial heterogeneity of land suitability and water availability, which is largely captured by highly resolved geographic grids, is an important factor that strongly determines the size of agricultural area (Müller et al., 2006). The economic structure of land-use models has to harmonize country-level information on food demand and trade flows with gridded information on local production conditions for various crops.

Current large-scale approaches to land-use modeling pursue different strategies to project future land-use patterns, as described in more detail by Heistermann et al. (2006). Approaches with a disciplinary focus concentrate on either the supply side or the demand side, while exogenously prescribing or ignoring the other. So-called geographic approaches, like the CLUE (Verburg et al., 1999) and SALU (Stephene and Lamin, 2001) models, concentrate on the supply side and compute land-use patterns based on spatially explicit data on land suitability and on external assumptions on agricultural demand. They are strong in capturing the spatial determination of land use and in quantifying supply side constraints based on land resources. However, they lack the potential to treat the interplay between supply, demand, and trade endogenously.

Economic models, on the other hand, as for example, different versions of the GTAP model (Hertel, 1997; Lee et al., 2005) or the WATSIM model (Kuhn, 2003) can consistently address the links between demand, supply, and trade via endogenous price mechanisms. However, they account only to a limited extent for physical resource constraints, do not commonly reflect the impact of demand on actual land-use change processes, and rarely represent behavior not reflected by price mechanisms. Land is usually implemented as a constraint in the production of land-intensive commodities, and economic competition of different types of production within one sector is represented endogenously. The simulation of management types, as well as the competition for land (and water) among different sectors, are supported by the structure of such models but seldom actually included. This limits the representation of land-use change processes.

Integrated approaches, accounting for both economic and environmental processes, pursue different strategies. Some employ land allocation schemes, which use demand or price information from economic models to update land-use patterns in detailed environmental models, e.g., ACCELERATES (Rounsevell et al., 2003) and IFPSIM/EPIC (Tan et al., 2003). Others improve the representation of resource constraints in detailed economic models, as in the FARM model with respect to land use (Darwin, 1999) and the impact-water model with respect to water use (Rosegrant et al., 2002). The dynamic coupling of the IMAGE and GTAP-LEI models (Klijn et al., 2005; van Meijl et al., 2006) is the first approach at the global scale that addresses the trade-off between spatial expansion of agricultural production and intensification. GTAP-LEI (van Meijl et al., 2006) introduces land supply curves, representing the impact of land scarcity on land rent. If land rent increases too strongly, the model endogenously switches to intensified agricultural production, which demands higher levels of inputs. This information is transferred to IMAGE (IMAGE team, 2001), where the actual spatially explicit land-use pattern is computed. However, the separate representation of land-use in both models yields the risk of inconsistencies, and agricultural water use is currently not explicitly covered in this linked modeling approach.

3. A model of agricultural production and its impact on the environment (MAgPIE)

In contrast to these available models, we have developed a mathematical programming approach, which is coupled to a grid-based dynamic vegetation model, to simulate spatially explicit land-use and water-use patterns. This approach provides most flexibility to integrate various types of biophysical constraints into an economic decision-making process, i.e., it provides a straightforward way to link monetary and physical units and processes. Instead of using empirically based, but rather static yield functions, potential crop productivity and related
water use is explicitly modeled. The dual solution of the mathematical programming model provides valuable insights into the internal use value of resource constraints. The model computes a shadow price for binding constraints in specific grid cells, e.g., in this case related to land and water availability, reflecting the amount a land manager would be willing to pay for relaxing the constraint by one unit.

Our globally applicable land-use model MAgPIE is a nonlinear programming model with a focus on agricultural production, and land and water use. A technical description of the model is provided in the appendix. The information flow in our coupled modeling approach is shown in Fig. 1.

The linear objective function of the land-use model is to minimize total cost of production for a given amount of regional food energy demand. Regional food energy demand is defined for an exogenously given population in 10 food energy categories (cereals, rice, vegetable oils, pulses, roots and tubers, sugar, ruminant meat, non-ruminant meat, and milk), based on regional diets (FAOSTAT, 2004). Food and feed energy for the ten demand categories can be produced by 20 cropping activities (temperate cereals for food or feed, maize for food or feed, tropical cereals for food or feed, rice, five oil crops, pulses, potatoes, cassava, sugar beets, sugar cane, vegetables/fruits/nuts, and two fodder crops) and three livestock activities (ruminant meat, non-ruminant meat, and milk). Feed for livestock is produced as a mixture of grain, green fodder, and pasture at fixed proportions. Fiber demand is currently fulfilled with one cropping activity (cotton). Cropland, pasture, and irrigation water are fixed inputs in limited supply in each grid cell, measured in physical units of hectares (ha) and cubic meters (m³). Variable inputs of production are labor, chemicals, and other capital (all measured in US$), which are assumed to be in unlimited supply to the agricultural sector at a given price. Moreover, the model can endogenously decide to “buy” yield-increasing technological change at additional costs, if otherwise there is no feasible solution (i.e., land use pattern) under a given set of resource constraints. This is implemented by multiplying the production activities with a technological-change variable, which makes a large number of the model constraints non-linear.

For future projections, the model works on a time step of 10 years in a recursive dynamic mode. The link between two consecutive periods is established through the land-use pattern. The optimized land-use pattern from one period is taken as the initial land constraint in the next. If necessary, additional land from the non-agricultural area can be converted into cropland at additional costs.
Potential crop yields for each grid cell are supplied by the Lund–Potsdam–Jena dynamic global vegetation model with managed lands (LPJmL) (Bondeau et al., 2007; Sitch et al., 2003). The LPJmL endogenously models the dynamic processes linking climate and soil conditions, water availability, and plant growth, and takes the impacts of CO₂, temperature, and radiation on yield directly into account. The LPJmL also covers the full hydrological cycle on a global scale, which is especially useful as carbon and water-related processes are closely linked in plant physiology (Gerten et al., 2004). Standard LPJmL outputs include changes in net primary production and different fractions of biomass and changes in carbon pools and water balances. This process-based vegetation model with agricultural crops is coupled here for the first time to a land-use allocation model. Potential crop yields for MAGPIE are computed as a weighted average of irrigated and non-irrigated production, if part of the grid cell is equipped for irrigation according to the global map of irrigated areas (Döll and Siebert, 2000). In case of pure rain-fed production, no additional water is required, but yields are generally lower than under irrigation. If a certain area share is irrigated, additional water for agriculture is taken from available water discharge in the grid cell. Water discharge is computed as the runoff generated under natural vegetation within the grid cells and its downstream movement according to the river routing scheme implemented in LPJmL.

Spatially explicit data on yield levels and freshwater availability for irrigation is provided on a regular geographic grid, with a resolution of three by three degrees, dividing the terrestrial land area into 2178 discrete grid cells of an approximate size of 300 km by 300 km at the equator. Towards higher latitudes, the grid cells become smaller. Each cell of the geographic grid is assigned to one of 10 economic world regions: Sub-Saharan Africa (AFR); centrally planned Asia including China (CPA); Europe including Turkey (EUR); the newly independent states of the former Soviet Union (FSU); Latin America (LAM); Middle East/North Africa (MEA); North America (NAM); Pacific OECD including Japan, Australia, New Zealand (PAO); Pacific (or Southeast) Asia (PAS); and South Asia including India (SAS). The regions are characterized by data for the year 1995 on population (CIESIN et al., 2000), gross domestic product (GDP) (World Bank, 2001), food energy demand (FAOSTAT, 2004, 2005), average production costs for each crop and livestock type. Production activities in MAGPIE have been parameterized to conditions in the year 1995, based on data on food consumption, trade, agricultural production, feed use, and land and water requirements (FAOSTAT, 2004, 2005). In order to ensure consistency of the initial database, the net trade position in terms of food energy units of all regions has been determined by balancing the food demand in different categories, total production of major crops and livestock types, and related demand for concentrate feed and green fodder.

In addition, the Global Trade Analysis Project (GTAP) database (version 4) (McDougall et al., 1998) is used to define the costs of production for each crop and livestock type. Production costs are region-specific and are calculated by dividing total costs of production (labor, chemicals, and capital) from GTAP by the area harvested from FAOSTAT. This provides average production costs per hectare for each production activity in each region. Due to yield variation between the grid cells within each region, this results in considerable spatial variation in production costs per unit food energy produced. Through international trade, the regions compete with each other based on their comparative cost advantages. The extent of international trade is controlled by trade constraints, which limit the regional trade balance to a prescribed minimum self-sufficiency rate.

Using potential crop yields from LPJmL, the model MAGPIE has been calibrated to represent the share of cropland in total area for each region as well as the shares of individual crops in total cropland (i.e., area harvested) in 1995. Two sets of parameters were used for calibration:

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

2. Yield correction at the regional level: potential crop yields as derived by LPJmL differ from actual crop yields observed in the FAO statistics, because crop management is not yet fully reflected in LPJmL simulations. We adjust average yields on the regional level by a regional management factor, but fully maintain yield variability between grid cells as provided by LPJmL. Due to high uncertainty in the global extent of managed grassland, pasture demand for ruminant meat and milk in MAgPIE was calibrated regionally to match with current pasture area, which was derived by Bondeau et al. (2007).

4. Model validation

In order to validate the model, we have conducted a hindcasting exercise from the base year 1995 to the year 1970. By comparing the simulated results with observed data from Ramankutty and Foley (1999) and FAOSTAT (2005), we demonstrate the suitability of the model’s basic mechanisms. For the validation run, we use the same simplifying assumptions as
will be used for future projections, in order to make simulations of the past comparable to projections into the future. For example, we simulate changes in food energy demand based on the regression results presented in Fig. 4 and on changes in population only. The resulting values of food energy demand compare well with FAO statistics for 1970, i.e., the statistical fit is 0.66, the same as for the regression in Fig. 4. Changes in population and income are taken from FAOSTAT (2005) and World Bank (2001). For simplifying matters, trade balances are kept constant at 1995 levels here.

To validate the model performance, the simulated changes in total cropland area as well as endogenously determined technological changes rates between 1970 and 1995 are compared with FAO statistics. Shares of cropland in total area at the grid-cell level are compared with data from Ramankutty and Foley (1999), which is arguably the most reliable source of spatially explicit cropland distribution with global coverage. It is important to note, however, that these data are the result of a fitting procedure based on different primary sources, including official statistics as well as remote sensing information. Hence, they are not truly observed land use patterns, and mismatches between MAgPIE results and Ramankutty and Foley (1999) may be due to errors in both data sets.

4.1. Cropland share in total area

As a first validation test, we check how well the spatial pattern of cropland shares from the model simulation for 1970 corresponds to observed data. Figure 5 shows the related global maps. Figure 6 provides the corresponding scatter plots for all grid cells, distinguished by model region.

With the exception of AFR and MEA, the correlation between simulated and observed cropland shares in the model regions is relatively good for a cross-section regression ($R^2 \geq 0.60$). The overall $R^2$ for a regression across all 2178 grid cells is 0.90. The largest discrepancies can be observed in AFR and MEA. In the simulated data, these two regions have a comparatively large share of grid cells, where the cropland share is zero. This may partly be explained by inadequate spatial patterns of crop yields simulated by LPJmL in these regions. Another factor may be that market and production structures in poor countries and transition countries are not well represented in the model. With high levels of subsistence agriculture, low levels of productivity, and limited market access, land-use patterns are more diverse than can be represented by broad rotational constraints and aggregate regional demands in our model. Moreover, the type of optimization model employed here tends to specialize production activities. In large regions with low average yields and very uneven yield distributions, the model will concentrate agricultural production in the most productive cells. If a region has a large number of grid cells with very low yields, there is more potential for the model to reduce overall crop area through land-use concentration. This effect becomes evident in our model results especially for AFR and MEA. Despite some region-specific shortcomings, the model, which is calibrated to the year 1995, is capable of projecting the global extent and distribution of agricultural cropland for the year.
1970, based on a limited set of socio-economic and biophysical inputs.

4.2. Share of different crop types in total cropland

Moreover, the regional average crop mix within the cropland area is also well represented by the model for 1970. Fig. 7 shows the correlation between simulated and observed average regional crop mix for all regions. As spatially explicit observations on individual crops are not available for 1970, we can only compare regional averages from our simulations with FAO statistics.

4.3. Changes in cropland area and average technological change rates

As a second validation test, the changes in total cropland area, as well as average regional technological change rates from the model simulation, are compared with FAO statistics for the period 1970–1995 (Figs. 8a and b). According to FAO, the average yield of all crops across the world, weighted by area harvested, has increased by 1.32% per year between 1970 and 1995, with a minimum of 0.04% in FSU and a maximum of 2.6% in CPA (i.e., predominantly China). The value for CPA, which may be partly due to the end of central planning, is remarkable as it is equivalent to a doubling of yields within 26 years. The correspondence between simulated and observed changes is relatively good ($R^2 = 0.69$ for area changes, $R^2 = 0.72$ for technological change rates), given the fact that major changes in agricultural, economic, and trade policies occurred in most regions during this time period, which are not adequately accounted for in the current model version.

Taken together, validation results for both the pattern of cropland area as well as the changes in area and yield over time gives us sufficient confidence in the functionality of our model.

5. Valuation of water resources

Apart from spatially explicit land-use patterns, MAgPIE also allows for valuating biophysical supply side constraints, like water shortages. Fig. 9 shows the shadow price for irrigation water in U.S.$ per cubic meter in 1995 for those cells that are at least partly equipped for irrigation, but where agricultural production is limited by the available level of water discharge. The value of the shadow price indicates a potential reduction in production costs if water availability within this cell would increase by 1 m$^3$. The map highlights regions with very low precipitation, where large-scale agriculture is only possible by using river discharge, like Morocco, Egypt, the Middle East, Pakistan, and China.

6. Scenario runs on required technological change in the period 1995–2055

After having validated the model performance against historical data, we now turn to scenario runs on global land-use changes in the future. Besides changes in population, economic growth and environmental production conditions, the issue of technological change in production (i.e., yield increase) is of
Fig. 5. Observed (a) and simulated (b) cropland shares in total area (percent) for 1970.

crucial importance. This can be tackled in two directions. With most other modeling approaches, this is done by assuming a future trend in productivity growth and then deriving the economic and environmental consequences. In contrast, with the mathematical programming model presented here, the issue can be turned around, and the minimum rate of technological change required to meet certain constraints can be derived. Hence, the main question behind the scenarios described here is: “How much yield increase (or technological change) is required to fulfill future global demand for food under different restrictions on land and water use?”

We run the MAgPIE model in six 10-year time steps from 1995 until 2055, in a recursive dynamic manner, where cropping patterns from one period are taken as a starting point for the next period. The model is driven by external scenarios on population and GDP growths taken from the SRES A2 scenario (IPCC, 2000). Global population increases up to about 9 billion in the year 2055, and average world income per capita reaches about
US$15,000 (in 1995 purchasing power parity terms). Regional details on the input data used are available upon request. The link between GDP and food energy demand is given by the regression equation described above and in Fig. 4.

In the baseline scenario, only a minimum of additional land (0.1% per decade) is allowed for land conversion and expansion. This basically keeps the cropland area constant over time. Regional trade balances are also kept constant at 1995 levels. In the scenarios presented in this article, there are no climate impacts on future yields, i.e., relative yield variability between grid cells is constant at 1995 levels.

As the explicit connection between land and water use is a special feature of the model, in the second scenario we focus on different types of technological change with regard to water-use intensity. A crucial parameter for our scenarios is the water-saving rate, which determines how much additional water is required if the crop yield per hectare is increased. In the baseline scenario, the water-saving rate is set at 0.5. This implies that a yield increase by 1% leads to an increase in water use by the plant of 0.5%. A range between 0 and 1 is in principle possible. If the additional crop yield is produced by exclusively increasing the total biomass production of the plant, the connection between increase in yield and in water use will be very close (i.e., a water-saving rate close to 0). If the structure of the plant is changed through plant breeding, i.e., the share of harvested organ in total biomass (harvest index) is increased, the water-saving rate could be close to 1. A water-saving rate of 1 would imply that the additional yield could be produced with
no additional water requirement. Here we compare the baseline scenario to a scenario with low water-saving technological change.

In a third scenario, we combine the baseline conditions with strong cropland expansion. In each 10-year time step, the model may convert up to 5% of current non-agricultural land into cropland for production (equivalent to a cumulated reduction of non-agricultural land by up to 25% over 50 years). The model will expand cropland in the most productive grid cells first, and hence the demand for technological change on the remaining land will be reduced.

The resulting rates of technological change for the baseline, the low water-saving scenario and area expansion scenario are presented in Fig. 10. The model results are compared with FAO statistics from the period 1970–1995. The numbers describe average regional yield increases per year for all crops over a given period (1995–2055 for the future scenarios).

Under our chosen baseline conditions on population growth, income growth, and limited scope for cropland expansion, average global crop yields need to increase by about 0.8% per year until the middle of the century. This is significantly lower than the trend over the last three decades. In most regions, the required future rate of change is lower than the observed rate in the past, except for AFR, FSU, and MEA. For AFR this reflects rather slow productivity increase in the past, and the expected effects of strong growth in population and income in the future. In FSU, the low rate in the past is due to the breakdown of production in the transition period of the 1980s and 1990s. By contrast, in MEA the already strong performance in the past (almost 2% per year) even has to be increased in the future, which is mainly due to expected strong population and income growth. Very low future rates in EUR and PAO are mainly due to expected slow population growth (or even decline) in these regions.

MEA is the region with the strongest impact of water scarcity, which is reflected in the required increase in yields if technological change is low in water saving. If water availability becomes a binding constraint in the model, it is forced to increase average productivity in all grid cells in the region. Hence, more production is shifted to areas where water is still abundant, until net domestic demand can be met. Annual yield increases by up to 3% over several decades are rather high, but historical data for, e.g., CPA show that this is possible. The low water-saving scenario shows that under conditions of restricted crop area expansion and limited trade expansion, water will become a binding constraint to food production in certain regions, like MEA, AFR, and FSU. One way to overcome the binding constraints is through an increase in water-use efficiency of crops. However, this cannot be achieved quickly as it requires changes in the harvest index through plant breeding, which is time consuming and research intensive. The pressure will certainly rise, when additional demand for land and water arises from future biomass energy production and increased demand for biodiversity conservation.

In the area expansion scenario, the required rate of technological change is about 60% lower than in the baseline, even
zero in EUR, LAM, NAM, and PAO. This is, of course, an unrealistic scenario, as in the real world there is increasing demand for land for other purposes, and there are many practical constraints to land expansion. The interesting aspect of our methodology is the fact that we can make land-use change and land expansion spatially explicit. That is, the land-use changes related to the results in Fig. 10 can also be presented as a global map (or even a sequence of maps over time). This adds valuable detail to the plain average numbers from more aggregated modeling approaches. Moreover, in the current scenario, the maximum rate of land conversion is set to be the same for all grid cells. However, we could also prescribe spatially explicit “no-go” areas, e.g., for nature conservation. These options will be explored in future model applications.

It should be noted that the derived rates of technological change from the model are on the optimistic side, as the mathematical programming algorithm shows a tendency for regional specialization of production, which leads to an additional
increase in average yields. In reality, not all of these yield increases will be achievable. Moreover, it is debatable whether the required yield increases from the model runs can be sustained over several decades. Some currently poor regions, like AFR, MEA, PAS, and SAS, have to double their average yields in order to meet future demand. Given the current absolute yield levels on worldwide average this does not seem impossible, but it will certainly require higher levels of fertilizer, machinery, and energy input, as well as research and development on a large scale.

7. Conclusions and outlook

The model MAgPIE computes spatially explicit land- and water-use patterns with global coverage by combining socioeconomic information on population, income, food demand, and production costs with spatially explicit environmental data on potential crop yields, and water availability for irrigation. By reproducing the historical land-use change between 1970 and 1995, we demonstrate the satisfactory overall performance of the model algorithms. The structure of MAgPIE facilitates an integrated environmental-economic assessment. Environmental data are supplied by the LPJmL. Crop functional types in LPJmL represent crop groups with different physiological behavior without distinguishing single crops. This helps to bridge the gap between aggregated economic information on food demand, production costs, and simulated crop yields. MAgPIE currently works on a geographic grid with three by three degrees resolution. This is a trade-off between computational feasibility and accounting for sub-regional spatial heterogeneity in land suitability and water availability. LPJmL simulations of terrestrial biogeochemical budgets are robust against reductions in spatial resolution, as shown in Müller and Lucht (2007), but information on spatial heterogeneity is lost when the spatial resolution is reduced. While computational requirements of the optimization software currently prevent finer spatial resolutions, this is a straightforward approach to generate spatially explicit land-use patterns based on an economic rationale. MAgPIE provides essential inputs for assessing the effects of economically driven land-use changes on the terrestrial land area and the biosphere. The derived shadow prices allow for an economic valuation of biophysical constraints to agricultural production. This is unique in globally applicable land-use models, especially as MAgPIE explicitly considers water as an essential input to agricultural production.

Another unique feature of our mathematical programming approach is the treatment of technological change. Instead of prescribing expected future trends in yield increase (i.e., area productivity), required minimum rates of technological change are endogenously derived as a residual to solve the model under a large set of spatially explicit constraints. This is especially important for the analysis of water scarcity, as water constraints become only meaningful at a spatially disaggregated level. Moreover, different types of technological change can be analyzed, which has been demonstrated here for the case of water-use intensity of crop production.

MAgPIE in its present form can account for several driving processes of land-use change, i.e., dietary changes and food demand, changes in international trade, restrictions on land expansion, and climate change. Other land-intensive goods, such as timber and bio-energy carriers, can be included in the model without any structural changes. These additional sectors will be included in the next model version, which will then internally compute their competition with food production for fertile land. Furthermore, the model structure supports the inclusion of specific crop management aspects, e.g., a separation of rainfed and irrigated production or a distinction between different levels of input use for subsistence and market production. However, economic data to parameterize these management aspects are currently scarce.

In this article, the general applicability and functionality of the model has been demonstrated. The mathematical programming technique is powerful, flexible, and computationally efficient, but it tends to underestimate area demand because of specialization in production. This can be partially prevented by technical rotational constraints and constraints on the maximum land-conversion rate. Inherent potentials to account for additional driving processes of land-use change will be the focus of our future work.

Appendix: MAgPIE—Model description

Variables

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

\[ y_{ld tc} \]  
technological change variable

Parameters

\[ c \]  
production costs per activity unit (US$)

\[ tcc \]  
technological change costs

\[ wat_{tc} \]  
water-saving rate (0 \leq wat_{tc} \leq 1)

\[ d_{food} \]  
demand for food energy (GJ)

\[ y_{food} \]  
food energy delivery (from crops and livestock) (GJ)

\[ y_{feed} \]  
feed energy delivery (from crops and residues) (GJ)

\[ y_{fodd} \]  
green fodder energy delivery (from crops) (GJ)

\[ y_{land} \]  
land delivery (i.e., from conversion activities) (ha)

\[ y_{wat} \]  
water delivery (i.e., from irrigation activities) (m^3)

\[ y_{input} \]  
variable input delivery (i.e., labor, chemicals, capital) (US$)

\[ req_{feed} \]  
feed energy requirement (i.e., per ton of livestock output) (GJ)

\[ req_{fodd} \]  
green fodder energy requirement (i.e., per ton of livestock output) (GJ)
\( \text{req_land} \) land requirements (i.e., cropland, pasture) (ha)

\( \text{req_wat} \) water requirements (m³)

\( \text{req_input} \) variable input requirements (i.e., labor, chemicals, capital) (US$)

\( \text{req_share} \) area to be considered for rotational constraints (ha)

\( \text{land_const} \) available land (cropland, pasture, non-agricultural land) (ha)

\( \text{wat_const} \) available water discharge for irrigation (m³)

\( \text{max_share} \) maximum crop share in average rotation (percent)

Indices

\( i \) number of economic regions (10)

\( j \) number of grid cells per region (total: 2178 grid cells (3 degree by 3 degree))

\( k \) number of activities (21 crops (kcr), 3 livestock (kli), 2 land conversion (klc), 3 input purchases (kin))

\( l \) number of food demand categories (10)

\( m \) number of agricultural land types (3) (cropland, pasture, non-agricultural land)

\( n \) number of rotational constraints (10)

Goal function: Cost minimization (Total costs of production; sum for all \( i \) regions):

\[ C = \sum_{i} \sum_{j} \sum_{k} x_{i,j,k} \times c_{i,k} + \sum_{i} y_{ld, fc_i} \times tcc_i \]

subject to:

Global constraints:

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

\[ \sum_{i} \sum_{j} \sum_{k} x_{i,j,k,l} \times y_{food, i,j,k,l} \times y_{ld, fc_i} \geq d_{food, i,l} \]

(similarly for fiber)

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

Minimum trade balance (regional supply \( \geq \) regional demand \( \times \) self-sufficiency rate):

\[ \sum_{j} \sum_{k} x_{i,j,k} \times y_{food, i,j,k} \times y_{ld, fc_i} \geq d_{food, i,l} \times \text{self_sufficiency}_{i,l} \]

(similarly for fiber)

Feed energy balance (regional demand \( \leq \) regional supply):

\[ \sum_{j} \sum_{k} x_{i,j,k} \times (\text{req_feed}_{i,k} - y_{feed, i,j,k}) \times y_{ld, fc_i} \leq 0 \]

Green fodder balance (regional demand \( \leq \) regional supply):

\[ \sum_{j} \sum_{k} x_{i,j,k} \times (\text{req_fodd}_{i,k} - y_{fodd, i,j,k}) \times y_{ld, fc_i} \leq 0 \]

Input purchase balances (regional demand \( \leq \) regional supply; for all \( kin \) inputs):

\[ \sum_{j} \sum_{k} x_{i,j,k} \times (\text{req_input}_{i,k,kin} - y_{input, i,j,k,kin}) \leq 0 \]

Cellular constraints (for all \( j \) cells):

Land constraints (for initially available cropland and pasture):

\[ \sum_{k} x_{i,j,k} \times (\text{req_land}_{i,k,m} - y_{land, i,j,m}) \leq \text{land_const}_{i,j,m} \]

Land conversion constraint (for non-agricultural land to be potentially converted into cropland and pasture):

\[ \sum_{k} x_{i,j,k} \times y_{land, i,j,m} \leq \text{land_const}_{i,j, "non-agri"} \]

Rotational constraints (for all \( n \) constraint types):

\[ \sum_{k} x_{i,j,k} \times \text{req_share}_{i,j,n} \leq \text{max_share}_{i,n} \times \text{land_const}_{i,j, "cropland"} \]

Water constraints:

\[ \sum_{k} x_{i,j,k} \times (\text{req_wat}_{i,k} - y_{wat, i,j}) \]

\[ \times (1 + y_{ld, fc_i} \times \text{wat}, fc_i) \leq \text{wat_const}_{i,j} \]

The model is written in GAMS (Brooke et al., 2003) and solved with CONOPT (Drud, 1996).

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