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PIK

1   <u>Title:</u>

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

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11   **Abstract**

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

28

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

2   World population will grow to about 10-14 billion people by the year 2100, with a median

3   projection at 8.8 billion for the year 2050 (IPCC, 2000; Lutz et al., 2001). As income rises,

4   people tend to consume more calories in total, and the share of animal calories increases.

5   Global meat consumption can be expected to rise by up to 3 percent annually over the next

6   decades (Keyzer et al., 2001). While global food supply may still outpace demand up to 2020,

7   growth rates in production are likely to slow down in the longer run (Rosegrant et al., 1997;

8   Harris and Kennedy, 1999). The potential of biotechnology and genetic engineering for

9   increasing agricultural yields remains unclear and subject to a strong public debate (Qaim and

10   Zilberman, 2003). Moreover, the total land area available for agricultural production will be

11   increasingly constrained by land requirements for other purposes, like infrastructure

12   development, urbanization, bio-energy production, or biodiversity protection (Sands and

13   Leimbach, 2003), but also by soil degradation (Oldeman et al., 1990; McNeill and

14   Winiwarter, 2004). In addition to land constraints, water may pose a serious limitation to

15   future global food supplies. Irrigated areas account for nearly two-thirds of world rice and

16   wheat production. Rising irrigation output per unit of land and water is essential to feed

17   growing populations. However, the size of potential water savings in agricultural irrigation

18   systems is unclear. While specific water uses can be made more efficient through better

19   technology, the potential overall savings in many river basins are probably much smaller,

20   because much of the water currently lost from irrigation systems is re-used elsewhere

21   (Rosegrant and Cai, 2003). The future global challenge with respect to agriculture and water

22   is that over the next 25 years food production has to be increased by about 40 percent while

23   reducing the renewable water resources used in agriculture by 10-20 percent (Rijsberman,

24   2001). An additional constraint to agricultural production in the second half of the 21st century

25   is global climate change. A rise in atmospheric CO_2-levels and a corresponding rise in global

1   temperatures will not only affect plant growth and yields, but also alter the regional patterns

2   of precipitation and water availability as well as land erosion and fertility. Regional impacts

3   of climate change vary quite significantly, with tropical regions potentially suffering from

4   droughts. The combined effects of various changes are still highly uncertain (IPCC, 2007).

5   Global land-use patterns will change in the future, reacting to the pressures described above.

6   Projecting their future development is important to study both their impacts on the Earth

7   System as well as the limitations of land use, since freshwater and fertile land are only

8   available in limited amounts.

9   **2.   Current status in global land-use modeling**

10   Agricultural land-use patterns are determined by a multitude of environmental, economic and

11   socio-cultural conditions and their interactions. The challenge of projecting future land-use

12   patterns is to account, within one modeling framework, for the socio-economic determinants

13   of agricultural demand as well as for the spatial heterogeneity of the land's suitability for

14   agricultural production. Land suitability for agricultural production is largely determined by

15   environmental conditions, but also by socio-economic factors such as management practices

16   and property rights. Demand, on the other hand, is determined by the number of consumers

17   and their per-capita consumption, which is strongly modulated by their income, market

18   access, and cultural background. The disciplines involved in studying land-use change

19   processes differ significantly in methodologies and data used. Economic sector models

20   typically operate with administrative units, i.e. countries or regional groups of countries in the

21   case of global models. They usually provide little spatial detail on agricultural production and

22   resource constraints. Biophysical models, on the other hand, typically operate on geographic

23   grids. These divide the terrestrial land area into distinct spatial units that are exactly localized.

24   For projecting future land-use patterns, the spatial heterogeneity of land suitability and water

25   availability, which is largely captured by highly resolved geographic grids, is an important

1 factor that strongly determines the size of agricultural area (Müller et al., 2006). The

2 economic structure of land-use models has to harmonize country-level information on food

3 demand and trade flows with gridded information on local production conditions for various

4 crops.

5 Current large-scale approaches to land-use modeling pursue different strategies to project

6 future land-use patterns, as described in more detail by Heistermann et al. (2006). Approaches

7 with a disciplinary focus concentrate on either the supply side or the demand side, while

8 exogenously prescribing or ignoring the other. So-called geographic approaches, like the

9 CLUE (Verburg et al., 1999) and SALU (Stephenne and Lambin, 2001) models, concentrate

10 on the supply side and compute land-use patterns based on spatially explicit data on land

11 suitability and on external assumptions on agricultural demand. They are strong in capturing

12 the spatial determination of land use and in quantifying supply side constraints based on land

13 resources. However, they lack the potential to treat the interplay between supply, demand, and

14 trade endogenously.

15 Economic models, on the other hand, as for example different versions of the GTAP model

16 (Hertel, 1997; Lee, 2005) or the WATSIM model (Kuhn, 2003) can consistently address the

17 links between demand, supply and trade via endogenous price mechanisms. However, they

18 account only to a limited extent for physical resource constraints, do not commonly reflect the

19 impact of demand on actual land-use change processes, and rarely represent behavior not

20 reflected by price mechanisms. Land is usually implemented as a constraint in the production

21 of land-intensive commodities, and economic competition of different types of production

22 within one sector is represented endogenously. The simulation of management types as well

23 as the competition for land (and water) among different sectors are supported by the structure

24 of such models but seldom actually included. This limits the representation of land-use

25 change processes.

1 Integrated approaches, accounting for both economic and environmental processes, pursue

2 different strategies. Some employ land allocation schemes, which use demand or price

3 information from economic models to update land-use patterns in detailed environmental

4 models e.g. ACCELERATES (Rounsevell et al., 2003) and IFPSIM/EPIC (Tan et al., 2003).

5 Others improve the representation of resource constraints in detailed economic models, as in

6 the FARM model with respect to land use (Darwin, 1999) and the IMPACT-Water model

7 with respect to water use (Rosegrant et al., 2002). The dynamic coupling of the IMAGE and

8 GTAP-LEI models (Klijn et al., 2005; van Meijl et al., 2006) is the first approach at the global

9 scale that addresses the trade-off between spatial expansion of agricultural production and

10 intensification. GTAP-LEI (van Meijl et al., 2006) introduces land supply curves,

11 representing the impact of land scarcity on land rent. If land rent increases too strongly, the

12 model endogenously switches to intensified agricultural production, which demands higher

13 levels of inputs. This information is transferred to IMAGE (IMAGE team, 2001), where the

14 actual spatially explicit land-use pattern is computed. However, the separate representation of

15 land-use in both models yields the risk of inconsistencies, and agricultural water use is

16 currently not explicitly covered in this linked modeling approach.

17 **3.   A Model of Agricultural Production and its Impact on the Environment**

18 **(MAgPIE)**

19 In contrast to these available models, we have developed a mathematical programming

20 approach, which is coupled to a grid-based dynamic vegetation model, to simulate spatially

21 explicit land-use and water-use patterns. This approach provides most flexibility to integrate

22 various types of biophysical constraints into an economic decision-making process, i.e. it

23 provides a straightforward way to link monetary and physical units and processes. Instead of

24 using empirically based, but rather static yield functions, potential crop productivity and

25 related water use is explicitly modeled. The dual solution of the mathematical programming

1 model provides valuable insights into the internal use value of resource constraints. The

2 model computes a shadow price for binding constraints in specific grid cells, e.g. in this case

3 related to land and water availability, reflecting the amount a land manager would be willing

4 to pay for relaxing the constraint by one unit.

5 Our globally applicable land-use model MAgPIE is a non-linear programming model with a

6 focus on agricultural production, land and water use. A technical description of the model is

7 provided in the appendix. The information flow in our coupled modeling approach is shown

8 in Figure 1.

9

10   [Insert Figure 1 about here]

11

12 The linear objective function of the land-use model is to minimize total cost of production for

13 a given amount of regional food energy demand. Regional food energy demand is defined for

14 an exogenously given population in ten food energy categories (cereals, rice, vegetable oils,

15 pulses, roots and tubers, sugar, ruminant meat, non-ruminant meat, and milk), based on

16 regional diets (FAOSTAT, 2004). Food and feed energy for the ten demand categories can be

17 produced by 20 cropping activities (temperate cereals for food or feed, maize for food or feed,

18 tropical cereals for food or feed, rice, five oil crops, pulses, potatoes, cassava, sugar beets,

19 sugar cane, vegetables/fruits/nuts, two fodder crops) and 3 livestock activities (ruminant meat,

20 non-ruminant meat, milk). Feed for livestock is produced as a mixture of grain, green fodder,

21 and pasture at fixed proportions. Fiber demand is currently fulfilled with one cropping activity

22 (cotton). Cropland, pasture and irrigation water are fixed inputs in limited supply in each grid

23 cell, measured in physical units of hectares (ha) and cubic meters (m³). Variable inputs of

24 production are labor, chemicals, and other capital (all measured in US$), which are assumed

25 to be in unlimited supply to the agricultural sector at a given price. Moreover, the model can

1 endogenously decide to "buy" yield-increasing technological change at additional costs, if

2 otherwise there is no feasible solution (i.e. land use pattern) under a given set of resource

3 constraints. This is implemented by multiplying the production activities with a technological-

4 change variable, which makes a large number of the model constraints non-linear.

5 For future projections the model works on a time step of 10 years in a recursive dynamic

6 mode. The link between two consecutive periods is established through the land-use pattern.

7 The optimized land-use pattern from one period is taken as the initial land constraint in the

8 next. If necessary, additional land from the non-agricultural area can be converted into

9 cropland at additional costs.

10 Potential crop yields for each grid cell are supplied by the Lund-Potsdam-Jena dynamic global

11 vegetation model with managed Lands (LPJmL) (Sitch et al., 2003; Bondeau et al., 2007).

12 LPJmL endogenously models the dynamic processes linking climate and soil conditions,

13 water availability and plant growth, and takes the impacts of CO_2, temperature and radiation

14 on yield directly into account. LPJmL also covers the full hydrological cycle on a global

15 scale, which is especially useful as carbon and water-related processes are closely linked in

16 plant physiology (Gerten et al., 2004). Standard LPJmL outputs include changes in net

17 primary production and different fractions of biomass, changes in carbon pools and water

18 balances. This process-based vegetation model with agricultural crops is coupled here for the

19 first time to a land-use allocation model. Potential crop yields for MAgPIE are computed as a

20 weighted average of irrigated and non-irrigated production, if part of the grid cell is equipped

21 for irrigation according to the global map of irrigated areas (Döll and Siebert, 2000). In case

22 of pure rain-fed production, no additional water is required, but yields are generally lower

23 than under irrigation. If a certain area share is irrigated, additional water for agriculture is

24 taken from available water discharge in the grid cell. Water discharge is computed as the

1 runoff generated under natural vegetation within the grid cells and its downstream movement

2 according to the river routing scheme implemented in LPJmL.

3 Spatially explicit data on yield levels and freshwater availability for irrigation is provided on a

4 regular geographic grid, with a resolution of three by three degrees, dividing the terrestrial

5 land area into 2178 discrete grid cells of an approximate size of 300 km by 300 km at the

6 equator. Towards higher latitudes the grid cells become smaller. Each cell of the geographic

7 grid is assigned to one of ten economic world regions: Sub-Saharan Africa (AFR), Centrally-

8 planned Asia including China (CPA), Europe including Turkey (EUR), the Newly

9 Independent States of the Former Soviet Union (FSU), Latin America (LAM), Middle

10 East/North Africa (MEA), North America (NAM), Pacific OECD including Japan, Australia,

11 New Zealand (PAO), Pacific (or Southeast) Asia (PAS), and South Asia including India

12 (SAS). The regions are characterized by data for the year 1995 on population (CIESIN et al.,

13 2000), gross domestic product (GDP) (World Bank, 2001), food energy demand (FAOSTAT,

14 2004), average production costs for different production activities (McDougall, 1998), and

15 current self-sufficiency ratios for food (FAOSTAT, 2005) (Figure 2 and 3). While all supply-

16 side activities in the model are grid-cell specific, the demand side is aggregated at the regional

17 level. That is to say, aggregate demand within each region, defined by total population,

18 average income and net trade, is being met by the sum of production from all grid cells within

19 the region.

20

21   [Insert Figure 2 about here]

22

23   [Insert Figure 3 about here]

24

1   Trade in food products between regions is simulated endogenously, constrained by minimum

2   self-sufficiency ratios for each region. This is to say that some minimum level of domestic

3   demand has to be produced within the region, while the rest can be allocated to other regions

4   according to comparative advantages. If, for instance, a region currently has a self-sufficiency

5   ratio of 1.2 for a certain product, then in future projections this may either be kept constant or

6   gradually reduced over time to account for global trade liberalization.

7   Land conversion activities provide for potential expansion and shifts of agricultural land in

8   specific locations. For the base year 1995, total agricultural land is constrained to the area

9   currently used within each grid cell, according to Ramankutty and Foley (1999). However, if

10 additional land is required for fulfilling demand, this can be taken from the pool of non-

11 agricultural land at additional costs. These land-conversion costs force the model to utilize

12 available cropland first, and land conversion will become relevant only if land becomes scarce

13 in a certain location or if the marginal cost reductions by producing crops on converted land

14 outweigh the costs of conversion. LPJmL computes trends in potential crop yields and

15 irrigation water requirements for the 20th and 21st century, taking climate change impacts

16 into account (Bondeau et al., 2007). Under plausible scenarios of population and income

17 growth, MAgPIE allows for future projections of spatially explicit land-use patterns, for

18 deriving future technological change rates, and for valuating constraints on land and water

19 availability or trade restrictions. Future trends in food demand are computed as a function of

20 GDP per capita based on a cross-country regression (Figure 4).

21

22   [Insert Figure 4 about here]

23

24 Production activities in MAgPIE have been parameterized to conditions in the year 1995,

25 based on data on food consumption, trade, agricultural production, feed use, and land and

1   water requirements (FAOSTAT, 2004, 2005). In order to ensure consistency of the initial

2   database, the net trade position in terms of food energy units of all regions has been

3   determined by balancing the food demand in different categories, total production of major

4   crops and livestock types, and related demand for concentrate feed and green fodder.

5   In addition, the Global Trade Analysis Project (GTAP) database (version 4) (McDougall,

6   1998) is used to define the costs of production for each crop and livestock type. Production

7   costs are region-specific and are calculated by dividing total costs of production (labor,

8   chemicals, capital) from GTAP by the area harvested from FAOSTAT. This provides average

9   <u>production</u> <u>costs per hectare</u> for each production activity in each region. Due to yield variation

10   between the grid cells within each region, this results in considerable spatial variation in

11   <u>production costs per unit food energy</u> produced. Through international trade the regions

12   compete with each other based on their comparative cost advantages. The extent of

13   international trade is controlled by trade constraints, which limit the regional trade balance to

14   a prescribed minimum self-sufficiency rate.

15   Using potential crop yields from LPJmL, the model MAgPIE has been calibrated to represent

16   the share of cropland in total area for each region as well as the shares of individual crops in

17   total cropland (i.e. area harvested) in 1995. Two sets of parameters were used for calibration:

18   (1) <u>Rotational constraints</u>: for each crop type a maximum share in total cropland in each grid

19   cell has been defined. This reflects technological constraints within an average crop rotation.

20   For reasons of pest control certain crops like potatoes or sugar beets usually can be grown

21   only every 3-4 years. This would imply an upper limit of 25-33 percent in the average

22   cropland share. For cereals, rotational constraints are set to 70 percent in most cases.

23   (2) <u>Yield correction at the regional level</u>: potential crop yields as derived by LPJmL differ

24   from actual crop yields observed in the FAO statistics, because crop management is not yet

25   fully reflected in LPJmL simulations. We adjust average yields on the regional level by a

1   regional management factor, but fully maintain yield variability between grid cells as

2   provided by LPJmL. Due to high uncertainty in the global extent of managed grassland,

3   pasture demand for ruminant meat and milk in MAgPIE was calibrated regionally to match

4   with current pasture area, which was derived by Bondeau et al. (2007).

5   **4.   Model validation**

6   In order to validate the model, we have conducted a <u>hindcasting</u> exercise from the base year

7   1995 to the year 1970. By comparing the simulated results with observed data from

8   Ramankutty and Foley (1999) and FAOSTAT (2005), we demonstrate the suitability of the

9   model's basic mechanisms. For the validation run we use the same simplifying assumptions as

10 will be used for future projections, in order to make simulations of the past comparable to

11 projections into the future. For example, we simulate changes in food energy demand based

12 on the regression results presented in Figure 4 and on changes in population only. The

13 resulting values of food energy demand compare well with FAO statistics for 1970, i.e. the

14 statistical fit is 0.66, the same as for the regression in Figure 4. Changes in population and

15 income are taken from FAOSTAT (2005) and World Bank (2001). For simplifying matters,

16 trade balances are kept constant at 1995 levels here.

17 To validate the model performance, the simulated changes in total cropland area as well as

18 endogenously determined technological changes rates between 1970 and 1995 are compared

19 with FAO statistics. Shares of cropland in total area at the grid-cell level are compared with

20 data from Ramankutty and Foley (1999), which is arguably the most reliable source of

21 spatially explicit cropland distribution with global coverage. It is important to note, however,

22 that these data are the result of a fitting procedure based on different primary sources,

23 including official statistics as well as remote sensing information. Hence, they are not truly

24 observed land use patterns, and mismatches between MAgPIE results and Ramankutty and

25 Foley (1999) may be due to errors in both data sets.

1   *Cropland share in total area*

2   As a first validation test, we check how well the spatial pattern of cropland shares from the

3   model simulation for 1970 corresponds to observed data. Figure 5 shows the related global

4   maps. Figure 6 provides the corresponding scatter plots for all grid cells, distinguished by

5   model region.

6

7   [Insert Figure 5 about here]

8   [Insert Figure 6 about here]

9

10   With the exception of AFR and MEA, the correlation between simulated and observed

11   cropland shares in the model regions is relatively good for a cross-section regression

12   ($R^2 \geq 0.60$). The overall R^2 for a regression across all 2178 grid cells is 0.90. The largest

13   discrepancies can be observed in AFR and MEA. In the simulated data, these two regions

14   have a comparatively large share of grid cells, where the cropland share is zero. This may

15   partly be explained by inadequate spatial patterns of crop yields simulated by LPJmL in these

16   regions. Another factor may be that market and production structures in poor countries and

17   transition countries are not well represented in the model. With high levels of subsistence

18   agriculture, low levels of productivity, and limited market access, land-use patterns are more

19   diverse than can be represented by broad rotational constraints and aggregate regional

20   demands in our model. Moreover, the type of optimization model employed here tends to

21   specialize production activities. In large regions with low average yields and very uneven

22   yield distributions, the model will concentrate agricultural production in the most productive

23   cells. If a region has a large number of grid cells with very low yields, there is more potential

24   for the model to reduce overall crop area through land-use concentration. This effect becomes

25   evident in our model results especially for AFR and MEA. Despite some region-specific

1   shortcomings, the model, which is calibrated to the year 1995, is capable of projecting the

2   global extent and distribution of agricultural cropland for the year 1970, based on a limited set

3   of socio-economic and biophysical inputs.

4   ***Share of different crop types in total cropland***

5   Moreover, the regional average crop mix within the cropland area is also well represented by

6   the model for 1970. Figure 7 shows the correlation between simulated and observed average

7   regional crop mix for all regions. As spatially explicit observations on individual crops are not

8   available for 1970, we can only compare regional averages from our simulations with FAO

9   statistics.

10

11   [Insert Figure 7 about here]

12

13   ***Changes in cropland area and average technological change rates***

14   As a second validation test, the changes in total cropland area as well as average regional

15   technological change rates from the model simulation are compared with FAO statistics for

16   the period 1970-1995 (Figure 8a and 8b). According to FAO, the average yield of all crops

17   across the world, weighted by area harvested, has increased by 1.32 percent per year between

18   1970 and 1995, with a minimum of 0.04 percent in FSU and a maximum of 2.6 percent in

19   CPA (i.e. predominantly China). The value for CPA, which may be partly due to the end of

20   central planning, is remarkable as it is equivalent to a doubling of yields within 26 years. The

21   correspondence between simulated and observed changes is relatively good ($R^2 = 0.69$ for

22   area changes, $R^2 = 0.72$ for technological change rates), given the fact that major changes in

23   agricultural, economic and trade policies occurred in most regions during this time period

24   which are not adequately accounted for in the current model version.

1

2   [Insert Figure 8a and 8b about here]

3

4   Taken together, validation results for both the pattern of cropland area as well as the changes

5   in area and yield over time gives us sufficient confidence in the functionality of our model.

6   **5.   Valuation of water resources**

7   Apart from spatially explicit land-use patterns, MAgPIE also allows for valuating biophysical

8   supply side constraints, like water shortages. Figure 9 shows the shadow price for irrigation

9   water in US\$/m³ in 1995 for those cells that are at least partly equipped for irrigation, but

10   where agricultural production is limited by the available level of water discharge. The value

11   of the shadow price indicates a potential reduction in production costs if water availability

12   within this cell would increase by 1 m³. The map highlights regions with very low

13   precipitation, where large-scale agriculture is only possible by using river discharge, like

14   Morocco, Egypt, the Middle East, Pakistan and China.

15

16   [Insert Figure 9 about here]

17

18   **6.   Scenario runs on required technological change in the period 1995-2055**

19   After having validated the model performance against historical data, we now turn to scenario

20   runs on global land-use changes in the future. Besides changes in population, economic

21   growth and environmental production conditions, the issue of technological change in

22   production (i.e. yield increase) is of crucial importance. This can be tackled in two directions.

23   With most other modeling approaches, this is done by assuming a future trend in productivity

1 growth and then deriving the economic and environmental consequences. In contrast, with the

2 mathematical programming model presented here, the issue can be turned around, and the

3 minimum rate of technological change required to meet certain constraints can be derived.

4 Hence, the main question behind the scenarios described here is: "How much yield increase

5 (or technological change) is required to fulfill future global demand for food under different

6 restrictions on land and water use?"

7 We run the MAgPIE model in six 10-year time steps from 1995 until 2055 in a recursive

8 dynamic manner, where cropping patterns from one period are taken as a starting point for the

9 next period. The model is driven by external scenarios on population growth and GDP growth

10 taken from the SRES A2 scenario (IPCC, 2000). Global population increases up to about 9

11 billion in the year 2055, and average world income per capita reaches about 15,000 US$ (in

12 1995 purchasing power parity terms). Regional details on the input data used are available

13 upon request. The link between GDP and food energy demand is given by the regression

14 equation described above and in Figure 4.

15 In the baseline scenario, only a minimum of additional land (0.1 percent per decade) is

16 allowed for land conversion and expansion. This basically keeps the cropland area constant

17 over time. Regional trade balances are also kept constant at 1995 levels. In the scenarios

18 presented in this paper, there are no climate impacts on future yields, i.e. relative yield

19 variability between grid cells is constant at 1995 levels.

20 As the explicit connection between land and water use is a special feature of the model, in the

21 second scenario we focus on different types of technological change with regard to water-use

22 intensity. A crucial parameter for our scenarios is the water-saving rate, which determines

23 how much additional water is required if the crop yield per hectare is increased. In the

24 baseline scenario, the water-saving rate is set at 0.5. This implies that a yield increase by 1

25 percent leads to an increase in water use by the plant of 0.5 percent. A range between 0 and 1

1   is in principle possible. If the additional crop yield is produced by exclusively increasing the

2   total biomass production of the plant, the connection between increase in yield and in water

3   use will be very close (i.e. a water-saving rate close to 0). If the structure of the plant is

4   changed through plant breeding, i.e. the share of harvested organ in total biomass (harvest

5   index) is increased, the water-saving rate could be close to 1. A water-saving rate of 1 would

6   imply that the additional yield can be produced with no additional water requirement. Here we

7   compare the baseline scenario to a scenario with low water-saving technological change.

8   In a third scenario we combine the baseline conditions with strong cropland expansion. In

9   each 10-year time step, the model may convert up to 5% of current non-agricultural land into

10   cropland for production (equivalent to a cumulated reduction of non-agricultural land by up to

11   25% over 50 years). The model will expand cropland in the most productive grid cells first,

12   and hence the demand for technological change on the remaining land will be reduced.

13   The resulting rates of technological change for the baseline, the low water-saving scenario

14   and area expansion scenario are presented in Figure 10. The model results are compared with

15   FAO statistics from the period 1970-1995. The numbers describe average regional yield

16   increases per year for all crops over a given period (1995-2055 for the future scenarios).

17

18   [Insert Figure 10 about here]

19

20   Under our chosen baseline conditions on population growth, income growth, and limited

21   scope for cropland expansion, average global crop yields need to increase by about 0.8

22   percent per year until the middle of the century. This is significantly lower than the trend over

23   the last three decades. In most regions the required future rate of change is lower than the

24   observed rate in the past, except for AFR, FSU and MEA. For AFR this reflects rather slow

25   productivity increase in the past, and the expected effects of strong growth in population and

1   income in the future. In FSU the low rate in the past is due to the breakdown of production in

2   the transition period of the 1980s and 1990s. By contrast, in MEA the already strong

3   performance in the past (almost 2 percent per year) even has to be increased in the future,

4   which is mainly due to expected strong population and income growth. Very low future rates

5   in EUR and PAO are mainly due to expected slow population growth (or even decline) in

6   these regions.

7   MEA is the region with the strongest impact of water scarcity, which is reflected in the

8   required increase in yields if technological change is low in water saving. If water availability

9   becomes a binding constraint in the model, it is forced to increase average productivity in all

10   grid cells in the region. Hence, more production is shifted to areas where water is still

11   abundant, until net domestic demand can be met. Annual yield increases by up to 3 percent

12   over several decades are rather high, but historical data for e.g. CPA show that this is

13   possible. The low water-saving scenario shows that under conditions of restricted crop area

14   expansion and limited trade expansion, water will become a binding constraint to food

15   production in certain regions, like MEA, AFR and FSU. One way to overcome the binding

16   constraints is through an increase in water-use efficiency of crops. However, this cannot be

17   achieved quickly as it requires changes in the harvest index through plant breeding, which is

18   time consuming and research intensive. The pressure will certainly rise, when additional

19   demand for land and water arises from future biomass energy production and increased

20   demand for biodiversity conservation.

21   In the area expansion scenario the required rate of technological change is about 60% lower

22   than in the baseline, even zero in EUR, LAM, NAM and PAO. This is, of course, an

23   unrealistic scenario, as in the real world there is increasing demand for land for other

24   purposes, and there are many practical constraints to land expansion. The interesting aspect of

25   our methodology is the fact, that we can make land-use change and land expansion spatially

1   explicit. That is, the land-use changes related to the results in Figure 10 can also be presented

2   as a global map (or even a sequence of maps over time). This adds valuable detail to the plain

3   average numbers from more aggregated modeling approaches. Moreover, in the current

4   scenario, the maximum rate of land conversion is set to be the same for all grid cells.

5   However, we could also prescribe spatially explicit "no-go" areas, e.g. for nature

6   conservation. These options will be explored in future model applications.

7   It should be noted that the derived rates of technological change from the model are on the

8   optimistic side, as the mathematical programming algorithm shows a tendency for regional

9   specialization of production, which leads to an additional increase in average yields. In

10 reality, not all of these yield increases will be achievable. Moreover, it is debatable whether

11 the required yield increases from the model runs can be sustained over several decades. Some

12 currently poor regions, like AFR, MEA, PAS and SAS have to double their average yields in

13 order to meet future demand. Given the current absolute yield levels on worldwide average

14 this does not seem impossible, but it will certainly require higher levels of fertilizer,

15 machinery and energy input as well as research and development on a large scale.

16 **7.   Conclusions and outlook**

17 The model MAgPIE computes spatially explicit land-use and water-use patterns with global

18 coverage by combining socio-economic information on population, income, food demand and

19 production costs with spatially explicit environmental data on potential crop yields and water

20 availability for irrigation. By reproducing the historical land-use change between 1970 and

21 1995, we demonstrate the satisfactory overall performance of the model algorithms. The

22 structure of MAgPIE facilitates an integrated environmental-economic assessment.

23 Environmental data are supplied by the Lund-Potsdam-Jena dynamic global vegetation model

24 with managed Lands (LPJmL). Crop functional types in LPJmL represent crop groups with

25 different physiological behavior without distinguishing single crops. This helps to bridge the

1   gap between aggregated economic information on food demand, production costs and

2   simulated crop yields. MAgPIE currently works on a geographic grid with three by three

3   degrees resolution. This is a trade-off between computational feasibility and accounting for

4   sub-regional spatial heterogeneity in land suitability and water availability. LPJmL

5   simulations of terrestrial biogeochemical budgets are robust against reductions in spatial

6   resolution, as shown in Müller and Lucht (2007), but information on spatial heterogeneity is

7   lost when the spatial resolution is reduced. While computational requirements of the

8   optimization software currently prevent finer spatial resolutions, this is a straightforward

9   approach to generate spatially explicit land-use patterns based on an economic rationale.

10 MAgPIE provides essential inputs for assessing the effects of economically driven land-use

11 changes on the terrestrial land area and the biosphere. The derived shadow prices allow for an

12 economic valuation of biophysical constraints to agricultural production. This is unique in

13 globally applicable land-use models, especially as MAgPIE explicitly considers water as an

14 essential input to agricultural production.

15 Another unique feature of our mathematical programming approach is the treatment of

16 technological change. Instead of prescribing expected future trends in yield increase (i.e. area

17 productivity), required minimum rates of technological change are endogenously derived as a

18 residual to solve the model under a large set of spatially-explicit constraints. This is especially

19 important for the analysis of water scarcity, as water constraints become only meaningful at a

20 spatially disaggregated level. Moreover, different types of technological change can be

21 analyzed, which has been demonstrated here for the case of water-use intensity of crop

22 production.

23 MAgPIE in its present form can account for several driving processes of land-use change, i.e.

24 dietary changes and food demand, changes in international trade, restrictions on land

25 expansion, and climate change. Other land-intensive goods, such as timber and bio-energy

1   carriers, can be included in the model without any structural changes. These additional sectors

2   will be included in the next model version, which will then internally compute their

3   competition with food production for fertile land. Furthermore, the model structure supports

4   the inclusion of specific crop management aspects, e.g. a separation of rain-fed and irrigated

5   production or a distinction between different levels of input use for subsistence and market

6   production. However, economic data to parameterize these management aspects are currently

7   scarce.

8   In this paper, the general applicability and functionality of the model has been demonstrated.

9   The mathematical programming technique is powerful, flexible, and computationally

10   efficient, but it tends to underestimate area demand because of specialization in production.

11   This can be partially prevented by technical rotational constraints and constraints on the

12   maximum land-conversion rate. Inherent potentials to account for additional driving processes

13   of land-use change will be the focus of our future work.

1   **8.   Appendix: MAgPIE - Model description**

2   <u>Variables</u>

3   *x*   level of activity (21 crop activities (ha), 3 livestock activities (ton), 2 land

4   conversion activities (ha), 3 input purchase activities (US$))

5   *yld_tc*   technological change variable

6   <u>Parameters</u>

7   *c*   production costs per activity unit (US$)

8   *tcc*   technological change costs

9   *wat_tc*   water-saving rate ($0 \leq wat\_tc \leq 1$)

10   *d_food*   demand for food energy (GJ)

11   *y_food*   food energy delivery (from crops and livestock) (GJ)

12   *y_feed*   feed energy delivery (from crops and residues) (GJ)

13   *y_fodd*   green fodder energy delivery (from crops) (GJ)

14   *y_land*   land delivery (i.e. from conversion activities) (ha)

15   *y_wat*   water delivery (i.e. from irrigation activities) (m^3)

16   *y_input* variable input delivery (i.e. labor, chemicals, capital) (US$)

17   *req_feed*   feed energy requirement (i.e. per ton of livestock output) (GJ)

18   *req_fodd*   green fodder energy requirement (i.e. per ton of livestock output) (GJ)

19   *req_land*   land requirements (i.e. cropland, pasture) (ha)

20   *req_wat*   water requirements (m^3)

21   *req_input*   variable input requirements (i.e. labor, chemicals, capital) (US$)

1   *req_share*   area to be considered for rotational constraints (ha)

2   *land_const*   available land (cropland, pasture, non-agric.) (ha)

3   *wat_const*   available water discharge for irrigation (m^3)

4   *max_share*   maximum crop share in average rotation (percent)

5   <u>Indices</u>

6   *i*   number of economic regions (10)

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

8   *k*   number of activities (21 crops (*kcr*), 3 livestock (*kli*), 2 land conversion (*klc*), 3 input

9   purchases (*kin*))

10   *l*   number of food energy demand categories (10)

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

12   *n*   number of rotational constraints (10)

13

14   <u>Goal function</u>: Cost minimization (Total costs of production; sum for all *i* regions):

15
$$C = \sum_i \sum_j \sum_k x_{i,j,k} * c_{i,k} + \sum_i yld\_tc_i * tcc_i$$

16   subject to:

17   <u>Global constraints:</u>

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

19
$$\sum_i \sum_j \sum_k x_{i,j,k,l} * y\_food_{i,j,k,l} * yld\_tc_i \geq d\_food_{i,l}$$

20   *(similar for fiber)*

21

1   <u>Regional constraints (for all *i* regions)</u>: (Note: all *k* activities are included in all constraints, in

2   order to reduce the number of indices; however, many of the parameter values may be zero)

3   Minimum trade balance (regional supply $\geq$ regional demand * self-sufficiency rate):

4

$$\sum_{j}\sum_{k} x_{i,j,k} * y\_food_{i,j,k} * yld\_tc_i \geq d\_food_{i,l} * self\_sufficiency_{i,l}$$

5   *(similar for fiber)*

6   Feed energy balance (regional demand $\leq$ regional supply)

7

$$\sum_{j}\sum_{k} x_{i,j,k} * \left(req\_feed_{i,k} - y\_feed_{i,j,k}\right) * yld\_tc_i \leq 0$$

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

9

$$\sum_{j}\sum_{k} x_{i,j,k} * \left(req\_fodd_{i,k} - y\_fodd_{i,j,k}\right) * yld\_tc_i \leq 0$$

10   Input purchase balances (regional demand $\leq$ regional supply; for all *kin* inputs)

11

$$\sum_{j}\sum_{k} x_{i,j,k} * \left(req\_input_{i,k,kin} - y\_input_{i,j,k,kin}\right) \leq 0$$

12   <u>Cellular constraints (for all *j* cells)</u>:

13   Land constraints (for initially available cropland and pasture):

14

$$\sum_{k} x_{i,j,k} * \left(req\_land_{i,k,m} - y\_land_{i,j,m}\right) \leq land\_const_{i,j,m}$$

15   Land conversion constraint (for non-agricultural land to be potentially

16   converted into cropland and pasture):

17

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

18   Rotational constraints (for all *n* constraint types):

19

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

1   Water constraints:

2
$$\sum_{k} x_{i.j,k} * \left(req\_wat_{i,k} - y\_wat_{i,j} \right) / \left(1 + \left(yld\_tc_i * wat\_tc \right) \right) \le wat\_const_{i,j}$$

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

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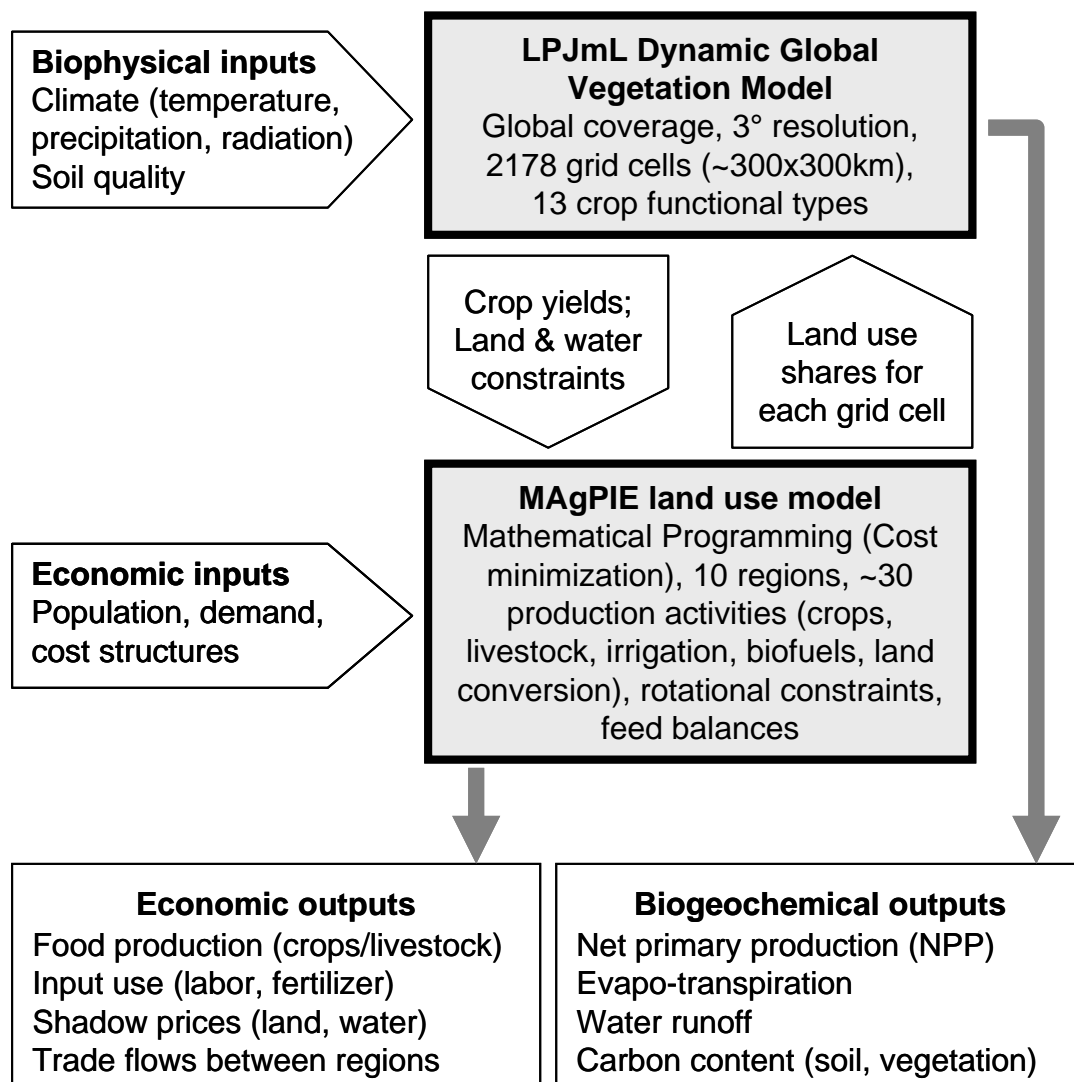
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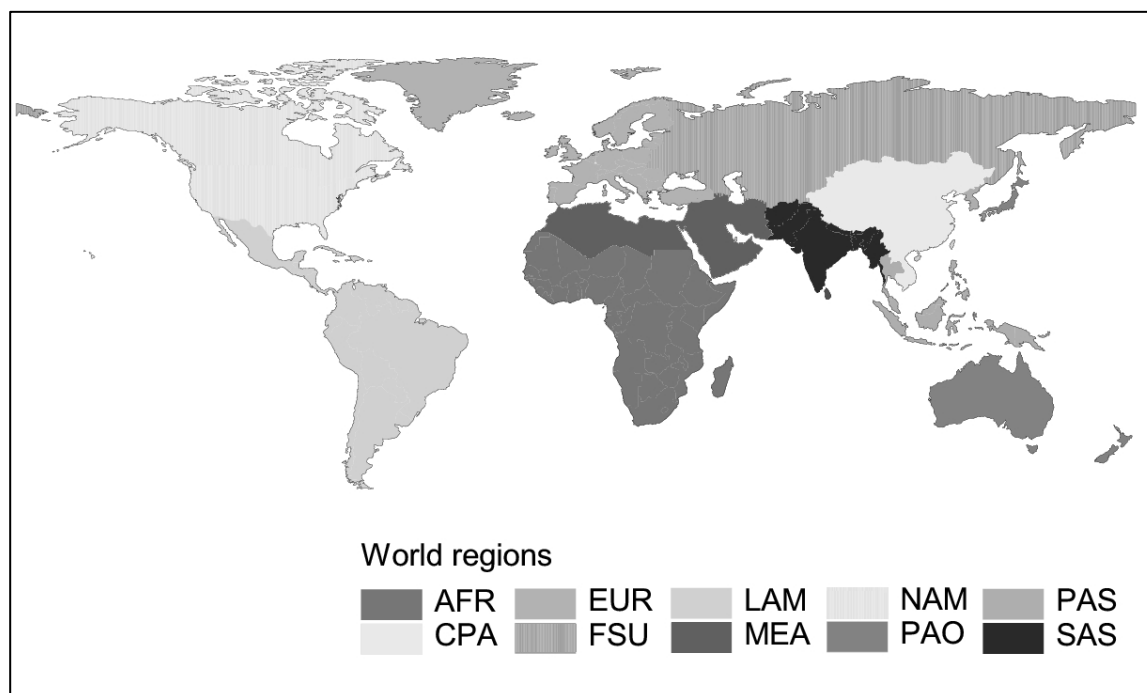24   results and prospects to 2025. Water International, 27(2): 170-182.

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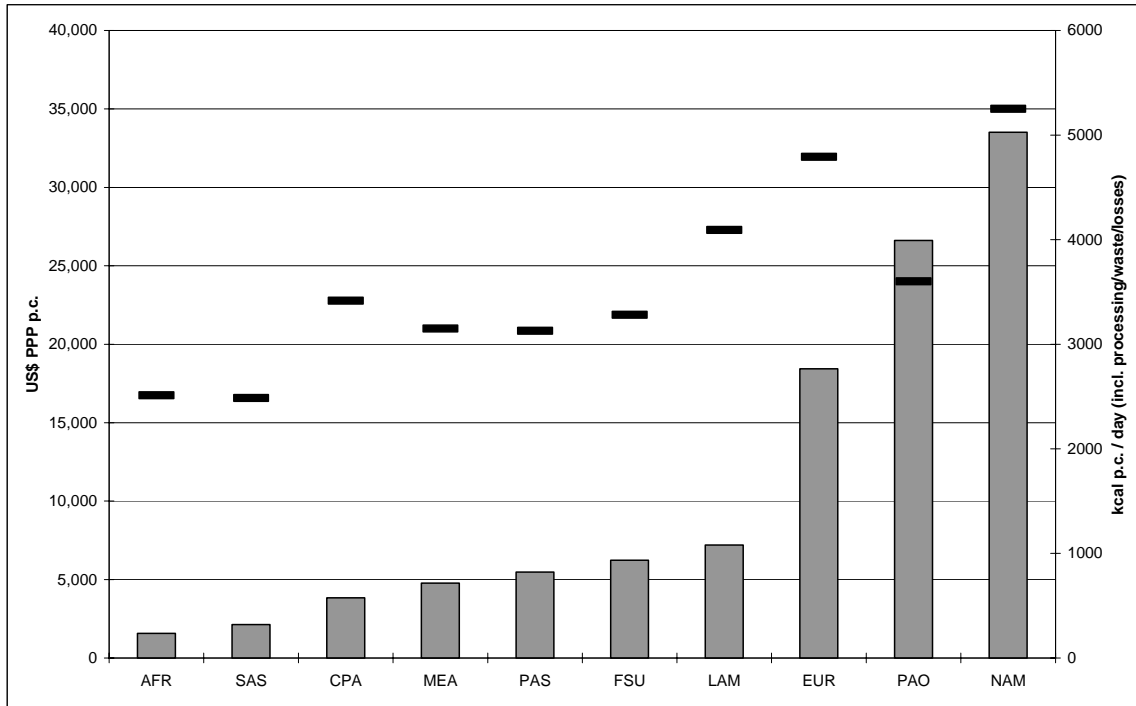
1   **11. Figure captions**

2

3   Figure 1: Information flow within the coupled modeling system

4   Figure 2: Model regions

5   Figure 3: Structure of model regions: Gross Domestic Product per capita (red column) and

6   calorie demand (blue dash) in 1995

7   Figure 4: Regression of calorie intake against income (Gross Domestic Product per capita)

8   based on data for 105 countries (in 1990 and 2000) ($R^2 = 0.66$)

9   Figure 5: Observed (a) and simulated (b) cropland shares in total area (percent) for 1970

10   Figure 6: Cropland shares in total area (percent) in individual grid cells for each model region

11   in 1970 (Simulation results against data from Ramankutty and Foley (1999))

12   Figure 7: Individual crop shares in total cropland for all model regions in 1970 (Simulation

13   results against data from FAOSTAT (2005))

14   Figure 8a: Annual technological change rates between 1970 and 1995 for all model regions

15   (Simulation results against data from FAOSTAT (2005))

16   Figure 8b: Changes in total cropland area between 1970 and 1995 for all model regions

17   (Simulation results against data from FAOSTAT (2005))

18   Figure 9: Shadow price for irrigation water (US$/m3) in 1995 (Simulation results)

19   Figure 10: Required annual yield increases (percent) over the period 1995-2055, baseline

20   scenario plus scenarios with low water-saving rate and cropland expansion (see text for

21   explanation). As a matter of orientation, the dashed line is set at 1.4 which is the rate of

22   change equivalent to a doubling of yield in 50 years time.

1 **Figure 1**
2
3
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Biophysical inputs
Climate (temperature, precipitation, radiation)
Soil quality

LPJmL Dynamic Global Vegetation Model
Global coverage, 3° resolution, 2178 grid cells (~300x300km), 13 crop functional types

Crop yields; Land & water constraints

Land use shares for each grid cell

MAgPIE land use model
Mathematical Programming (Cost minimization), 10 regions, ~30 production activities (crops, livestock, irrigation, biofuels, land conversion), rotational constraints, feed balances

Economic inputs
Population, demand, cost structures

Economic outputs
Food production (crops/livestock)
Input use (labor, fertilizer)
Shadow prices (land, water)
Trade flows between regions

Biogeochemical outputs
Net primary production (NPP)
Evapo-transpiration
Water runoff
Carbon content (soil, vegetation)

1   **Figure 2**

2
3

Acro-nym	Name	Population (mio in 1995)	Cropland share in total area	Number of 3-degree grid cells	Share of grid cells with cropland
AFR	Sub-Saharan Africa	553	8%	262	74%
CPA	Centrally Planned Asia (incl. China)	1281	17%	143	85%
EUR	Europe (incl. Turkey)	554	26%	175	71%
FSU	Former Soviet Union	276	15%	462	59%
LAM	Latin America	452	9%	266	87%
MEA	Middle East/ North Africa	278	4%	130	39%
NAM	North America	292	14%	428	37%
PAO	Pacific OECD (Japan, AUS, NZL)	134	5%	136	49%
PAS	Pacific Asia	383	16%	104	67%
SAS	Southern Asia (incl. India)	1270	37%	72	94%

1   **Figure 3**
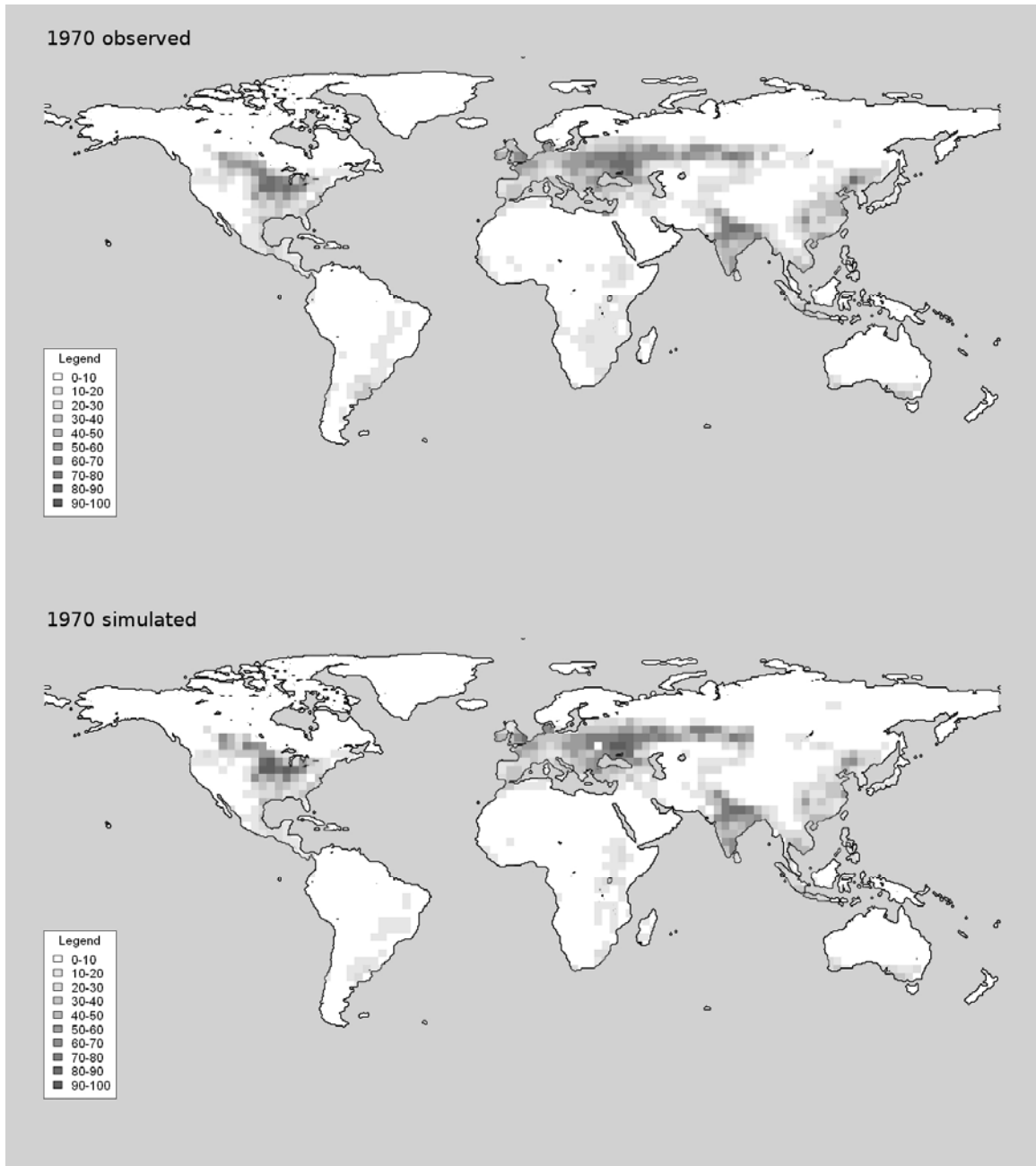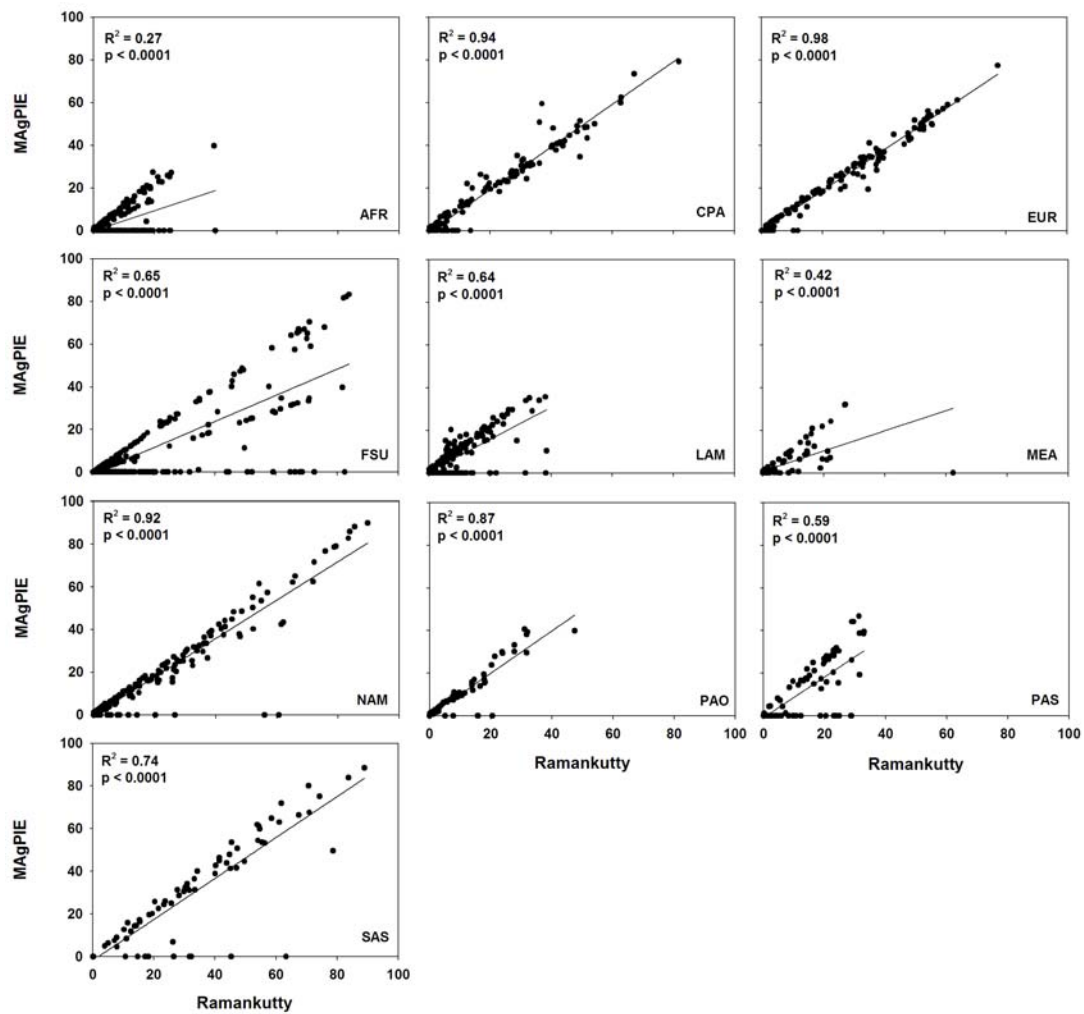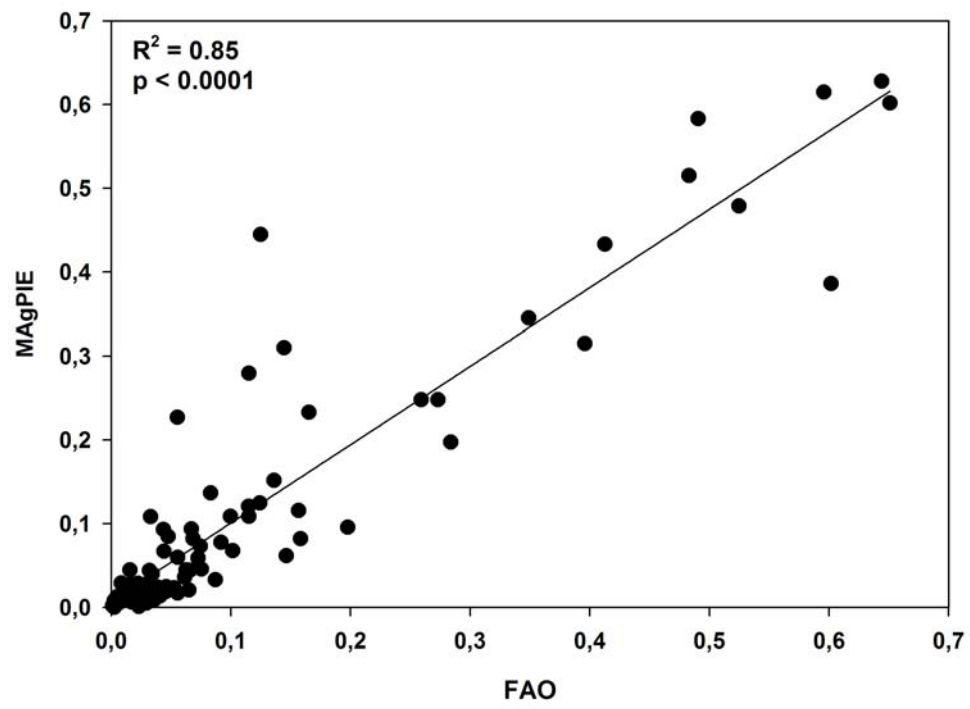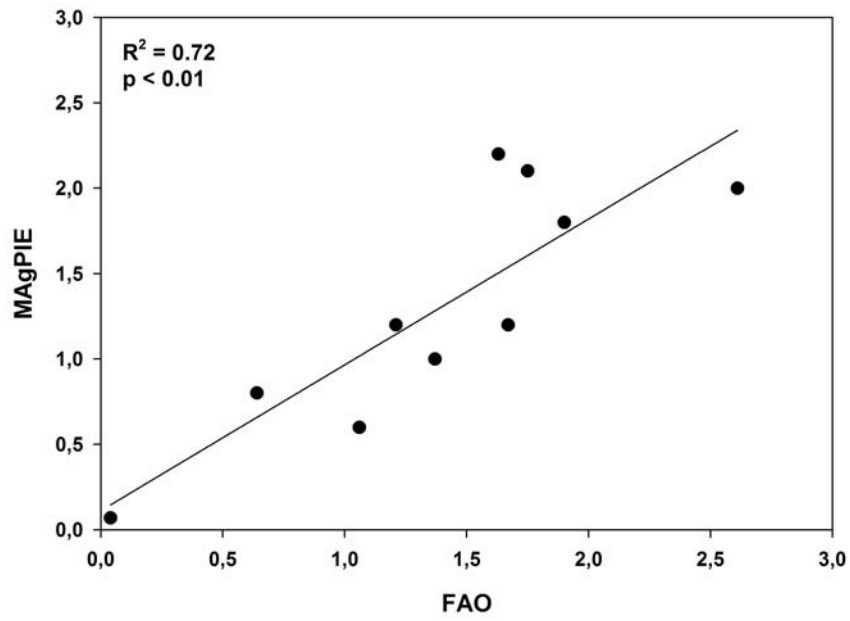

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1   **Figure 4**
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1 **Figure 5**

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1970 observed

Legend
- 0-10
- 10-20
- 20-30
- 30-40
- 40-50
- 50-60
- 60-70
- 70-80
- 80-90
- 90-100

3

1970 simulated

Legend
- 0-10
- 10-20
- 20-30
- 30-40
- 40-50
- 50-60
- 60-70
- 70-80
- 80-90
- 90-100

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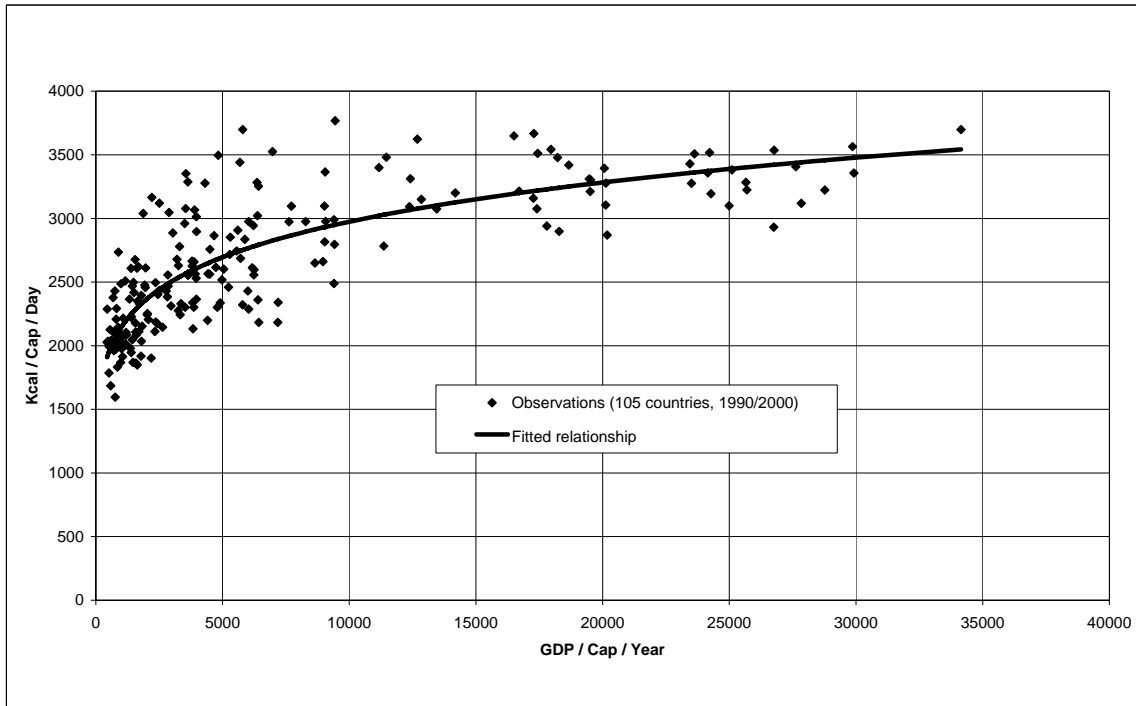
1 **Figure 6**
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1 **Figure 7**
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1   **Figure 8a**

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4   **Figure 8b**
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6

1 **Figure 9**
2

Water Shadow Price

Legend
- 0
- >0.0-1.0
- >1.0-2.0
- >2.0-5.0
- >5.0

3

1 **Figure 10**
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