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Agriculture and resource availability in a changing world: The role of irrigation

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[1] Fertile land and freshwater constitute two of the most fundamental resources for food production. These resources are affected by environmental, political, economic, and technical developments. Regional impacts may transmit to the world through increased trade. With a global forest and agricultural sector model, we quantify the impacts of increased demand for food due to population growth and economic development on potential land and water use until 2030. In particular, we investigate producer adaptation regarding crop and irrigation choice, agricultural market adjustments, and changes in the values of land and water. In the context of resource sustainability and food security, this study accounts for the spatial and operational heterogeneity of irrigation management to globally assess agricultural land and water use. Agricultural responses to population and economic growth include considerable increases in irrigated area and water use but reductions in the average water intensity. Different irrigation systems are preferred under different exogenous biophysical and socioeconomic conditions. Negligence of these adaptations would bias the burden of development on land and water scarcity. Without technical progress, substantial price adjustments for land, water, and food would be required to equilibrate supply and demand.

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1. Introduction

[2] Global population is projected to grow by about 65% within the next 50 years. At the same time, average per capita income is expected to rise [*Wallace*, 2000]. Together, these two developments imply a substantial increase in demand for water and food – not only because of more people, but also because of trends toward more water-intense lifestyles and diets. Water resources are an important economic driver in many regions because they may constrain food production, energy generation, and activities in other economic sectors. The complex interdependencies between water resources and food production have been referred to in recent studies as an evolving global food crisis [*Hightower and Pierce*, 2008; *Lundqvist et al.*, 2008].

[3] The future supply of food and water faces several challenges. First, technical progress in agriculture may be subject to decreasing rates because of biophysical limits [*Beadle and Long*, 1985; *Bugbee and Salisbury*, 1988]. Second, future land expansion may be restricted because of physical limits and conflicting demands. Furthermore, the productivity of existing cropland may decline because of soil degradation and expansion of other sectors on fertile agricultural land [*Foley et al.*, 2005; *Ramankutty et al.*, 2002]. Third, environmental and human health regulations may constrain agricultural management and put limits to intensification [*Rockstroem et al.*, 2004; *Tilman et al.*, 2001; *Van Hofwegen*, 2006]. Fourth, continued growth in domestic and industrial sector water consumption will decrease the available water volume for agriculture [*Bouwer*, 2000; *Rosegrant et al.*, 2002]. Fifth, climate change is likely to change the productivity of agricultural systems. These impacts will differ across locations and involve both improvements and deteriorations [*Lobell et al.*, 2008; *Milly et al.*, 2008; *Ramankutty et al.*, 2002]. While the above mentioned challenges may differ locally, their net impact is likely to affect all countries as agricultural commodities are internationally traded.

[4] The global dimension of agricultural water use is evident from the fact that agriculture accounts for more than 70% of anthropogenic water withdrawals. Furthermore, about 20% of total arable cropland is under irrigation, producing about 40% of the global harvest [*Bruinsma*, 2003]. With continuing population growth and limited potential to increase suitable cropland, irrigation becomes an increasingly important tool to ensure sufficient global supply of food in the future [*Wichelns and Oster*, 2006].

[5] Increasing levels of irrigation will raise the cost of water and in some regions this may have severe consequences. As

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water scarcity increases, inefficient allocation of water causes higher costs to society. Missing property rights and inadequate water pricing are major causes of such inefficiencies. Preventing these externalities from growing out of proportion is therefore in societies' best interest. However, national and international policymakers need scientific guidance to adequately regulate water use. In particular, appropriate assessments of agricultural water use need to consider (1) the heterogeneity of natural and farming conditions, (2) international commodity markets especially for agricultural products, (3) agricultural and land use related environmental policies, and (4) synergies and trade-offs between different land use related externalities [*Cowie et al.*, 2007; *Khan et al.*, 2007].

[6] In this study, we investigate global interactions between agricultural production and the availability of land and water resources, focusing on irrigation as the major tool and determinant to affect both agricultural productivity and environmental resources. A first attempt to integrate crop and site-specific irrigation methods into a global partial equilibrium model for the land use sectors is presented, in which we quantitatively analyze how irrigation decisions respond to different development scenarios.

2. Background

[7] Investigations dealing with the amount, distribution, and availability of agricultural water are often unique regarding method, scope, and scale. A brief review of global assessments of the distribution and variability of water supply is given by *Oki and Kanae* [2006]. More integrated approaches investigate interactions between economic development, water demand, and potential water stress by linking hydrological projections of climate change impacts on freshwater availability with population growth or socioeconomic development scenarios among the broader context of global change [*Alcamo et al.*, 2003; *Arnell*, 1999, 2004; *Simonovic*, 2002; *Voeroesmarty et al.*, 2000]. Other studies put a more detailed emphasis on the manifold impacts of land and water use changes on the natural environment [*Foley et al.*, 2005; *Hussain*, 2007; *Tilman et al.*, 2001]. Finally, there are some comprehensive assessments, which integrate global change scenarios with supply and demand of water. These assessments depict trends and limits of future water resource development in a global all-sector context [*Bouwman et al.*, 2006; *Molden*, 2007; *Rosegrant et al.*, 2002]. The common objective across studies is to provide reasonable projections of future water use and to assess potential for achieving sustainable food security.

[8] The estimates of land and water required for irrigation may differ, subject to the particular research methods and the underlying scenario assumptions. Furthermore, future demand for cropland and irrigation water also depends on changes in obtainable yield and water use efficiency, and thus may be significantly affected by technological progress and water management. With regard to agricultural water management, future improvements are likely to be related to efficiency gains in the use of green water [*Liu et al.*, 2009; *Rijsberman*, 2006; *Rockstroem et al.*, 2009].

[9] Most existing empirical studies that explicitly predict or simulate the adoption of agricultural irrigation practices stay at farm or basin scales. A few global assessments of irrigation distribution and impacts exist but mainly within disciplinary boundaries, that is, within physical geography or economics. These studies, however, do not account for site-specific differences between alternative irrigation systems and usually reduce and simplify decisions to a choice between rain-fed and irrigated agriculture. Global integrated land use models accounting for multisectoral competition and limitations of land and water resources are rare [*Heistermann et al.*, 2006].

[10] Our analysis aims to assess future pathways of global land use and their sustainability, on the basis of scenarios of population and economic development and their impact on demand for food and other agricultural and forest commodities. We want to quantify the complex feedbacks that occur across different scales between irrigation decisions, technologies, agricultural markets, and resources.

[11] To achieve this, crop and site-specific irrigation methods are integrated into a global economic partial equilibrium model for the land use sectors. Irrigation concerns are depicted by biophysically constrained and economically motivated choices between alternative irrigation systems, each representing individual technical, environmental, and economic characteristics.

[12] The model enables an integrated assessment of global agricultural land and water use, and of the interrelations with irrigation management that takes place on smaller scales, accounting for resource economics, commodity markets, and international trade. Analyses explicitly consider regional capacities of irrigation system applicability, performance, and distribution based on respective geographic constraints and crop requirements. The model output shows the impacts of political, technical, environmental, and market developments on agricultural management decisions and their effects on scarcity of land and water, agricultural commodity supply and prices, and environmental externalities. These externalities include greenhouse gas emissions, soil sediment losses, and nitrogen leaching.

[13] The primary objective of this study is to gain insights about global interactions among economic development, resource scarcity, and irrigation decisions. We consider the diverse set of agricultural water use options within a global economic partial equilibrium model analysis. The depiction of different irrigation methods is relevant to integrated global irrigation assessments because of major differences in suitability and cost. Previous global studies have neglected system differences. Owing to data limitations, our approach applies several simple assumptions. Model results thus have to be interpreted with care.

3. Materials and Methods

[14] This section is structured as follows. We portray the model and basic components of the irrigation module, followed by a more detailed description of the determinants of irrigation choice. For each of these elements we describe the methods used to derive parameter values, and the assumptions made on how the depicted elements are constituted and interlinked. Finally, we briefly explain the computation of total irrigation costs.

3.1. Global Forest, Agriculture, and Biomass Sector Model: GLOBIOM

[15] We apply a mathematical programming-based global recursive dynamic partial equilibrium model integrating the

Table 1. Study World Regions

Region	Abbreviation
North America	NAM
Western Europe	WEU
Pacific OECD[a]	PAO
Central and East Europe without Former Soviet Union	EEU
Former Soviet Union	FSU
Planned Asia with China	CPA
South Asia	SAS
Other Pacific Asia	PAS
Middle East and North Africa	MEA
Latin America and Caribbean	LAM
Sub-Saharan Africa	AFR

[a]Organisation for Economic Co-operation and Development.

agricultural, bioenergy, and forestry sectors: Global Biomass Optimization Model (GLOBIOM). The agricultural and forest market equilibrium is computed by choosing land use and processing activities to maximize the sum of producer and consumer surplus subject to resource, technological, and policy constraints, as described by *McCarl and Spreen* [1980]. The market equilibrium reveals commodity and factor prices, levels of domestic production and consumption, export and import quantities, resource usage, and environmental impacts for 28 world regions, which are here for ease of presentation further aggregated to 11 regions (Table 1). A detailed description of GLOBIOM including an algebraic model description giving information on the contained parameters, variables, and equations can be found in the work of *Havlík et al.* [2010]. In what follows, we only briefly present the aspects most relevant for this article.

[16] GLOBIOM is a bottom-up model with a detailed representation of the supply side based on the spatially explicit description of land resource endowments through a system of Simulation Units (SimU). A Simulation Unit is the spatial aggregate of 5 arc min pixels, which are homogenous with respect to weather, soil, topographical, and land cover characteristics, and which are within the same 30 arc min pixel and within the same country boundaries (R. Skalský et al., Geo-bene global database for bio-physical modeling v. 1.0: Concepts, methodologies and data, Global Earth Observation–Benefit Assessment: Now, Next, and Emerging, Laxenburg, Austria, available at http://www.geo-bene.eu/?q=node/1734, 2008). In total, we define more than 200,000 SimUs covering the globe. Their size varies between approximately 10 × 10 km and 50 × 50 km. Crop, forest, and energy biomass production technologies are specified as fixed input-output ratios calculated for each relevant SimU. The flexible model structure enables to aggregate the SimU specific parameters over one or more dimensions of homogeneity to reduce the size of the final program to solve. For the application in this article, we aggregated the SimUs over the 30 arc min grid dimension.

[17] Crop production accounts for 18 of the globally most important crops: barley, cassava, chickpeas, cotton, dry beans, groundnuts, maize, millet, oil palm fruits, potatoes, rapeseed, rice, sorghum, soybeans, sugarcane, sunflower seed, sweet potatoes, and wheat. The average yield level for each crop in each country is taken from FAOSTAT [*Food and Agriculture Organization* (*FAO*), 2007a]. For 17 crops, fertilization and irrigation management specific yields are simulated with the biophysical process model Environmental Policy/Integrated Climate (EPIC) [*Williams*, 1995] at the level of SimUs. (Oil palm is not simulated with EPIC. Only country level parameters based on FAOSTAT are used.) These 17 crops together represent about 75% of the 2007 harvested area as reported by *FAO* [2007a]. Four management systems are considered (irrigated, high input–rain-fed, low input–rain-fed, and subsistence management systems) corresponding to the International Food and Policy Research Institute (IFPRI) crop distribution data classification [*You and Wood*, 2006].

3.2. Irrigation Module

[18] We compute irrigation water consumption at the field (SimU) level, which accounts for the beneficial water use by the crops, and the application efficiency of the particular irrigation system. We do not compute gross water use in terms of actual water withdrawals from surface waters or groundwater. Thus we do not consider the efficiency of water delivery from source to field, which would account for return flows and water potentially available for reuse.

[19] The model portrays four major types of irrigation systems: surface systems including basin and furrow irrigation, localized drip, and sprinkler irrigation. The suitability of these systems depends on various factors, which influence crop suitability, water demand, energy requirement, labor intensity, and overall cost, and thus affect motivation-based decision making that aims at individual as well as societal welfare maximization. The interdisciplinary range of factors that determine irrigation decisions in our model is shown in Table 2.

[20] For each irrigation method we evaluate biophysical and technical suitability to exclude inappropriate system applications. Among the biophysical determinants of irrigation system choice, the model enables us to take directly into account the slope, soil, and crop types. For the purpose of this study, we further disaggregated the first slope class considered in the basic SimU delineation (0–3 degrees) into five subclasses (Table 3). The new slope classes were defined with respect to threshold values that determine the applicability of the different irrigation methods [*Brouwer et al.*, 1988]. In combination with the soil type (Table 3), the slope class determines the suitability to apply a particular irrigation system as well as the appropriate choice of flow

Table 2. Biophysical, Technical, and Economic Determinants of Irrigation Choice

Factor Type	Factors
Biophysical	Crop characteristics (water tolerance, rain-fed and irrigated yields, and irrigation demand), soil infiltration rate, slope inclination, length of growing period, and water resource availability
Technical	Water application efficiency, operation time per irrigation event, level of pressurization (energy and labor requirement), and coverage per irrigation system unit
Economic	Crop market prices, investment capital cost, energy prices, labor cost, and land and water prices (resource economics)

Table 3. Classifications for Slope Inclination and Soil Texture

	Classes
Slope intervals (deg)	0–0.35, 0.35–1, 1–1.6, 1.6–2.25, 2.25–3, 3–6, 6–10, 10–15, 15–30, 30–50, >50
Soil texture	sandy, loamy, clay, stony, peat

rate, which is a parameter to compute operation costs. However, the slope class representation in our model does not enable to account for elements like terraces. Since in some regions such elements make up a nonnegligible fraction of the total cropland and hence create incompatibilities between the slope maps and crop distribution maps, we adjusted the suitable area for surface irrigation methods with respect to these areas.

[21] Not all crop types may be irrigated by all irrigation systems [*Brouwer et al.*, 1988]. Besides the restrictions due to slope and soil type, the suitability of a particular irrigation method is determined by the crop-specific tolerance toward moisture, the characteristic planting and harvesting techniques, the specific physical habit of the crop, and its economic market value (i.e., low market value crops are excluded from being irrigated by high-cost drip irrigation). For all irrigation system constraints related to crop and soil type, see Table 4.

[22] Unlike for land resources, irrigation water availability is not defined at SimU level yet. In the model, irrigation water use is currently constrained through an artificial supply function, representing the relative water scarcity through its increasing marginal cost. The upper limit on irrigation water availability is computed by considering the sustainably exploitable internal renewable water amount, and water demands from other sectors (domestic, industry, livestock, submitted environmental flow) [*FAO Land and Water Development Division*, 2008; *Rosegrant et al.*, 2002].

[23] Consumptive irrigation water requirements by irrigation system are calculated under consideration of system-specific field application efficiencies in addition to the beneficial-use crop irrigation demands. The application efficiency varies by region and is determined by considering regional climatic factors [*International Institute for Applied Systems Analysis*, 2000] and indicators of sociodemographic development [*United Nations Development Programme*, 2000] (Table 5).

[24] The model chooses the extent of a particular irrigation system considering irrigation cost per spatial unit for all appropriate combinations of regional geographic background, crop type, and irrigation system. Specific irrigation system characteristics are portrayed in Table 6.

3.3. Parameterization: Energy Requirement

[25] Energy use is computed as a function of irrigated area, water amount, pressure requirement, and total irrigation time [*Buchanan and Cross*, 2002]. On-farm irrigation scheduling is affected by geographic and technical properties (Table 2). We use a simplified but consistent approach to represent these interdependencies through a generalized irrigation scheduling. In this context, the application depth per irrigation event is an important parameter to calculate cost-effective energy demand. A stepwise approach to determine application depth is used, based on the simplifying assumption of fixed operation times per irrigation event (Table 7).

[26] The irrigation schedules assume constant application depths during the entire growing season. Information on soil infiltration rate, suitable slope, the acceptable range of flow rate by soil type at optimal slope, and corresponding size of irrigated area are taken from *Brouwer et al.* [1988].

[27] In a first step we calculate maximum number of events with respect to length of growing period [*Fischer et al.*, 2002] and common application frequencies [*Brouwer et al.*, 1988; *Buchanan and Cross*, 2002]. Using the total irrigation water demand over the complete vegetation period, we determine application depth per event by region, crop, and method. Second, we calculate the maximum application depth by soil type with respect to recommended flow rates and particular soil infiltration rates, at slopes that are reported to be most suitable for the particular irrigation method [*Brouwer et al.*, 1988].

[28] To account for slope effects on surface irrigation performance, we modify the application depths for basin irrigation, using ratios of recommended to minimum flow rate as multiplier while assuming proportionality of irrigation depth and flow rate. Then we derive slope-related basin-size coefficients, which depict the maximum basin area by slope class in percent of the basin area at optimum slope when flow rate remains constant (Table 8). For this, we assume quadratic basins and a linear relationship between slope and basin size. These slope coefficients were applied to previous soil-indexed optimal-slope application depths.

[29] Regarding furrow irrigation, we consider soil and slope influences on maximal furrow length and their implications for acceptable flow rate according to numbers given by *Brouwer et al.* [1988]. We translate furrow lengths to area per furrow and determine application depth per furrow (by region, crop, soil type, and slope) for maximal area, under consideration of operation time:

$$AD_{\mathrm{slope,soil}} = OT^{*}FR\ \max_{slope}/A\ \max_{slope,soil}, \tag{1}$$

where $AD_{slope,soil}$ is application depth per irrigation event for furrow irrigation by slope class and soil type in millimeters, OT is operation time per irrigation event for furrow irrigation in seconds, $FR\ \max_{slope}$ is maximum flow rate per furrow by

Table 4. Irrigation System Suitability by Soil and Crop Type[a]

	Sandy Soil	Loamy Soil	Clay Soil
Barley	F/S	B/F/S	F/S
Cassava			
Chickpeas	F/D/S	B/F/D/S	F/D/S
Cotton	F/D/S	F/D/S	F/D/S
Dry beans	F/D/S	F/D/S	F/D/S
Groundnuts	F/D/S	F/D/S	F/D/S
Maize	F	F	F
Millet	F/S	B/F/S	F/S
Oil palm fruits	F/D	F/D	F/D
Potatoes	F/S	F/S	F/S
Rapeseed	F/S	F/S	F/S
Rice	B/F	B/F	B/F
Sorghum	F/S	B/F/S	F/S
Soybeans	F/D/S	B/F/D/S	F/D/S
Sugarcane	F/S	B/F/S	F/S
Sunflower seed	F/D	F/D	F/D
Sweet potatoes	F/S	F/S	F/S
Wheat	F/S	B/F/S	F/S

[a]B, basin irrigation; F, furrow irrigation; D, drip irrigation; S, sprinkler irrigation.

Table 5. Water Application Efficiency by Irrigation System and Region

World Region	Water Application Efficiency by Irrigation System[a] (%)			
	Basin	Furrow	Drip	Sprinkler
North America	53	48	93	85
Western Europe	55	50	93	86
Pacific OECD	38	33	86	71
Central and East Europe	55	50	93	86
Former Soviet Union	55	50	93	86
Planned Asia with China	45	40	89	79
South Asia	35	30	84	68
Other Pacific Asia	40	35	88	75
Middle East and North Africa	25	20	80	60
Latin America and Caribbean	40	35	88	75
Sub-Saharan Africa	30	25	82	64

[a]Estimates are based on information by *Clemmens and Molden* [2007], *International Institute for Applied Systems Analysis* [2000], and *United Nations Development Programme* [2000].

slope class in l/s, and $A\ \max_{slope,soil}$ is maximum area per furrow by slope class and soil type in m^2. After modifying the surface application depths we recalculate the number of annual irrigation events on the basis of total water requirements and determine the application depth per event.

[30] Energy use for irrigation is determined by underlying pressure requirements. Total pressure requirement is the sum of sprayer pressure (for nonsurface systems) and static head pressure to bridge elevation differences. Information on sprayer pressure and static head pressure calculation was obtained from *Buchanan and Cross* [2002] and the Natural Resources Conservation Service (Energy Consumption Awareness Tool: Irrigation, available at http://ipat.sc.egov.usda.gov/Help.aspx, U. S. Department of Agriculture, Washington, D. C., 2007).

3.4. Parameterization: Labor Requirement

[31] Labor requirement is the number of irrigation events times the estimated work hours per event as taken from *Turner and Anderson* [1980], who were cited by *Buchanan and Cross* [2002] (Table 9). To depict variations in labor intensity by crop type, we use crop-specific cost data [*Paul*, 1997; Agricultural Electronic Bulletin Board (AgEBB), Missouri, SEMO Crop Budget 2006, Missouri Irrigation Economics, University of Missouri, Extension Southeast Missouri, available at http://agebb.missouri.edu/irrigate/economics/index.htm] to calculate a labor multiplier (Table 10).

3.5. Irrigation Cost

[32] We apply an economic optimization approach dealing with trade-offs between competing land use types. Within the optimization procedure, trade-offs in terms of cost-benefit comparisons are dealt with from a sectoral perspective, and on behalf of maximized welfare across the modeled sectors. In the agricultural sector, farmers are the prior agents of decision making, which are also assumed to act driven by economic motivation. However, for the optimization the surplus of the agricultural sector as a whole is relevant. From such a macroeconomic (national) accounting point of view we consider total expenditures for irrigation, and we neglect public cost recovery and subsidies for irrigation facilities or water delivery to farmers for reasons of simplification. This is done with respect to the global scale and the relative coarse temporal, spatial, and sectoral resolution of our partial equilibrium model.

[33] Irrigation costs include capital costs and costs for operation and maintenance (O&M). Operation costs are composed of pressure-related energy costs in terms of energy prices by source [*Metschies*, 2005; Energy Information Administration, International Energy Annual (IEA) 2004: Long-term historical international energy statistics, Department of Energy, Washington, D. C., available at http://www.eia.doe.gov/iea/, 2006], and labor costs in terms of average agricultural wages per hour [*International Monetary Fund*, 2007; *World Bank*, 2006]. For a schematic overview of the determination of total irrigation costs, see Figure 1.

[34] Nonlabor capital and maintenance costs differ between systems but are assumed to be globally identical despite the fact that they may substantially differ between regions [*Rosegrant et al.*, 2002]. Using average discounted annual capital costs per spatial unit for sprinklers (D. Reinbott, Irrigation investment and ownership cost, Missouri Irrigation Economics, University of Missouri, Extension Southeast Missouri, AgEBB, Missouri, available at http://agebb.missouri.edu/irrigate/economics/index.htm, 2005) and additional information on technical and economic comparisons of sprinkler, drip, and surface irrigation systems [*Phocaides*, 2000], we determine cost ratios to derive average capital cost per year for each irrigation method. Maintenance cost was set to 5% of capital cost for nonsurface and furrow irrigation, and to 3% for basin irrigation [*Paul*, 1997; *Phocaides*, 2000].

4. Scenario Description

[35] Population growth and economic development affect the agricultural sector on the commodity markets through increased demand for food, and indirectly also through increased demand for wood. Economic development additionally affects food demand qualitatively via shifts in consumption patterns and increasing demand for water-intense commodities. For the simulation of future food demand, we use regional projections of per capita food intake levels differentiated in animal and crop calories from *Alexandratos et al.* [2006], and the regional population projections from the IIASA GGI B2 baseline scenario (International Institute for Applied Systems Analysis, GGI Scenario Database, available at http://www.iiasa.ac.at/Research/GGI/DB/, 2008). In regions with increasing rates of economic development, expected dietary shifts are represented by a growing fraction of livestock products among the daily calorie intake.

[36] Population and economic growth will put supplementary pressure on land and water availability through

Table 6. Specific Characteristics of Different Irrigation Systems

	Basin	Furrow	Drip	Sprinkler
Functional type	gravity	gravity	pressurized	pressurized
Irrigation system category	surface irrigation	surface irrigation	localized irrigation	sprinkler irrigation
Capital cost	low	low	high	medium
Energy demand for operation	none	none	low	high
Maintenance and labor intensity	low	high	medium	medium

Table 7. Assumed Fixed Operation Times per Irrigation Event by Irrigation Method

Irrigation Method	Estimated Number of Operation Hours per Irrigation Event[a]
Basin irrigation	48
Furrow irrigation	48
Drip irrigation	48
Sprinkler irrigation	60

[a]Estimated guide values are by *Buchanan and Cross* [2002].

increased demand for these resources in other sectors, especially residential/domestic and industry sectors. The additional pressure on water availability for irrigation is calculated by reducing the basic water availability for agriculture by projected increases in livestock, domestic, and industry water consumption. These increases are calculated proportional to population and imposed on basic water consumption levels in these sectors as reported by the *FAO Land and Water Development Division* [2008]. For the calculation of the additional pressure on land availability from the residential sector, we assume that residential land growth takes the form of urban expansion. We use the population density data from Demographia (World Urban Population Density by Country and Area, available at http://www.demographia.com/db-intlua-area2000.htm, 2006) and assume that residential expansion eliminates cropland.

[37] We present results for two scenarios: "No pressure from domestic and industry sectors" and "Pressure from domestic and industry sectors." The former scenario ignores the additional land and water demand from nonagricultural sectors but considers commodity market effects. For both scenarios, we implement projections on the development of bioenergy and biofuels according to the POLES simulation results corresponding to an updated version of *Russ et al.* [2007].

[38] The base year distribution of irrigation systems is calibrated to closely reproduce system distribution as derived from FAOSTAT, AQUASTAT, and ICID databases [*FAO*, 2000, 2004, 2007b; *FAO Land and Water Development Division*, 2008; International Commission on Irrigation and Drainage, ICID Database, available at http://www.icid.org/, 2008] (Table 11).

5. Results

[39] This section summarizes the simulated trends of irrigated area, system distribution, and water use at global level. Subsequently, we discuss projected developments with regard to drivers and mechanisms of agricultural decisions.

Table 8. Basin Irrigation: Coefficients for the Adjustment of Application Depth to Higher Slopes, Accounting for Relationships Between Slope Inclination, Soil-Dependent Flow Rates, and Maximum Basin Area

Slope Class (deg)	Basin-Slope Coefficient
0–0.35	0.875
0.35–1	0.092
1–1.6	0.013
1.6–2.25	0.006
>2.25	not convenient for basin irrigation

Table 9. Estimated Work Hours per Acre and Irrigation Event

Irrigation Method	Estimates of Labor Required[a] (Hours per Acre per Event)
Basin irrigation	0.5
Furrow irrigation	0.7
Drip irrigation	0.07
Sprinkler irrigation	0.1

[a]Based on guide values given by *Buchanan and Cross* [2002].

[40] Rising demands for food lead to increasing crop, land, and water prices. Irrigation water use in the model is constrained through a price sensitive supply function. This marginal cost function passes through the observed/estimated price quantity pair of irrigation water. The curvature of the supply function is defined by employing a constant price elasticity. The water price is not an observed market price but rather a calibrated estimate of all costs of getting the water. Thus, it depicts the internal value of water rather than the real price of irrigation water, which actually does not exist in many regions. Technological progress affecting productivity is not considered in the model runs. The resulting global water price indexes are presented in Figure 2.

[41] Irrigation water requirements strongly depend on biophysical conditions, crop type, and water use efficiencies. As explained in section 3.2, we depict consumptive irrigation water use at field level rather than gross irrigation water withdrawals that include water losses between source and field.

[42] The simulation results on global irrigation water use project a moderate increase in the first decade of the simulation period. The increase in total water use is relatively high during the second decade but declines thereafter (Figure 3). Note that the water endowment constraints implemented for each model region were not binding in the examined scenarios.

[43] Changes in the water volume for irrigation can be decomposed into changes in water consumptions per hectare and changes in the area under irrigation. Our simulations project the highest absolute increase in irrigated area to occur in South Asia (SAS). Highest relative increases of irrigation area expansion are found for the former Soviet Union (FSU), Central and East Europe (EEU), North America (NAM), and Latin America and the Caribbean (LAM). In Sub-Saharan Africa (AFR), a considerable expansion of irrigated area starts with a delay if seen in relation to population growth. The global trend of irrigated land expansion is depicted in Figure 4.

[44] Global water use intensity more or less remains constant in the first 10 years of the simulation period; later it decreases at growing rates (see Figure 5). Whereas water

Table 10. Labor Multiplier by Crop Type and Irrigation Method

Crop Type	Crop Labor Multiplier by Irrigation Method[a]			
	Basin	Furrow	Drip	Sprinkler
Rice	2.3	2.3	–	–
Vegetables (all)	1	1.5	1	1
All other crops	1	1	1	1

[a]Estimates are based on information by the Agricultural Electronic Bulletin Board, Missouri (available at http://agebb.missouri.edu/irrigate/economics/index.htm, 2006), and by *Paul* [1997].

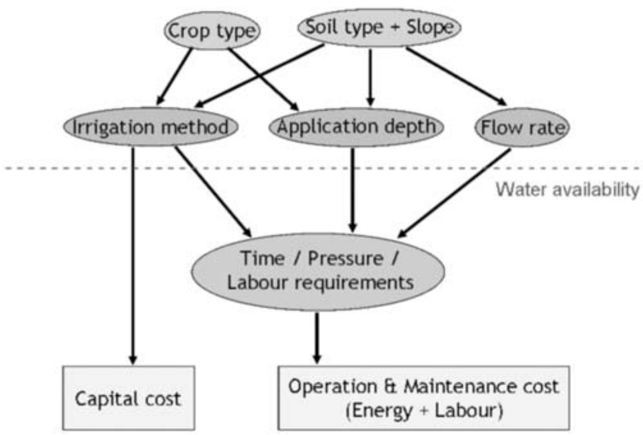

Figure 1. Scheme for determining total irrigation costs.

intensity remains constant in CPA and LAM, it substantially decreases in Africa and, to a lesser extent, in SAS, despite high rates of population growth and high increases of per capita calorie intake. Globally, a general trend of combined expansion and extensification of irrigated agriculture can be identified.

[45] Shifts in regional irrigation management toward improved water use efficiency are triggered in correspondence with increasing rates of population growth, with respect to our population scenarios. Before that, efficiency improvement is progressing at comparably low rates.

[46] We will face a general trend of irrigated area expansion to sufficiently meet changing food demands. Additional water pressure simultaneously triggers an extensification of management practices in terms of decreasing water use intensity, and consequently approves water-efficient irrigation methods or crop types with lower irrigation demands.

[47] Food demand–induced incentives for irrigation expansion may lead to more water-efficient irrigation methods. A growing trend toward an application of more costly but also more water-efficient methods can be detected (see Figure 6 for global trends).

[48] On a global scale, a progressive substitution of surface methods by sprinkler systems appears first, before eventually also the share of micro-irrigation methods such as drip irrigation significantly starts to grow. In developed regions such changes appear earlier and more gradual than in less developed regions. However, technological standards and cost recovery for investment and O&M may also play a role to affect such developments.

[49] According to these results, shifts to more efficient management of water use seem an inevitable consequence of growing populations and economic development. The depicted option of changing the irrigation technique is one of many and implies the importance of putting integrated concepts on today's agenda to ensure a timely mitigation of tomorrow's resource problems.

6. Discussion

[50] Global projections of agricultural land and water use are rare. Comparisons between projections have to be interpreted with caution because of differences in scenario assumptions, analysis scope and resolution, and modeling approach [*Heistermann et al.*, 2006]. In general, existing studies may be distinguished regarding the dominating analysis technique in bottom-up and top-down studies, regarding the system dynamics in static, recursive dynamic, and fully dynamic specifications, and regarding the resolution and scope with respect to space and economic sectors. Furthermore, projections of changes in crop area and water demand are influenced by specific assumptions on population, economic, and policy development and their associated impacts to agricultural commodity demand and relevant resource endowments, climate change and its effect on agricultural productivity, and technical progress rates including crop yield improvements.

[51] To place this study in perspective, we compare our irrigation water projections with previous global assessments by *Döll and Siebert* [2002], *Molden* [2007], *Postel* [1998], *Rosegrant et al.* [2002], and *Seckler et al.* [1998] (Table 12). If only values of water withdrawals are given, we approximate consumption data using average ratios from studies that provide values on both items.

[52] However, crop coverage in our analysis is restricted to the crops listed in section 3.1. To evaluate our baseline and simulation results this always must be considered. For a more detailed review of global water resource assessments and modeling approaches, we refer one to the works by *Simonovic* [2002] and *Wallace and Gregory* [2002].

[53] Our base year irrigated area is 257 million hectares (Mha). This estimate is in line with data on actual irrigated areas for the period of 1995–2000 covering a range from 210 to 340 Mha [*FAO*, 2007b; *Gardner*, 1998; *Gleick*, 2000; *Molden*, 2007; *Rosegrant et al.*, 2002; *Siebert and Doell*, 2007].

[54] Comparing consistent information on total water withdrawals for irrigation, consumptive irrigation water use, and beneficial crop irrigation water use, as given by *Döll and Siebert* [2002] and *Rosegrant et al.* [2002], we find that on average about 25% of the globally withdrawn water for irrigation is actually taken up by the crops, 56% is not consumed and available for subsequent use, and 19% is unproductively lost.

[55] Existing estimates of global consumptive irrigation water use vary between 900 km^3 [*Postel*, 1998] and about 1700 km^3 [*Shiklomanov*, 2000] per year for the period of 1995–2002. Other reference values to be mentioned are 1287 km^3 [*Döll and Siebert*, 2002] and 1435.5 km^3 [*Rosegrant et al.*,

Table 11. Baseline Irrigation System Distribution by Region

World Region	Assumed Fraction of Irrigation Methods on Total Irrigated Area[a] (%)		
	Basin and Furrow	Drip	Sprinkler
North America	47.48	6.59	45.93
Western Europe	33.97	17.95	48.08
Pacific OECD	79.71	5.04	15.25
Central and East Europe	38.50	2.62	58.88
Former Soviet Union	58.30	0.05	41.65
Planned Asia with China	97.00	1.00	2.00
South Asia	95.64	0.20	4.16
Other Pacific Asia	100	0	0
Middle East and North Africa	87.60	1.40	11.00
Latin America and Caribbean	86.66	2.50	10.84
Sub-Saharan Africa	69.51	4.73	25.76

[a]Estimates are based on information by the Food and Agriculture Organization (2000–2008) and the International Commission on Irrigation and Drainage (ICID Database, available at http://www.icid.org/, 2008).

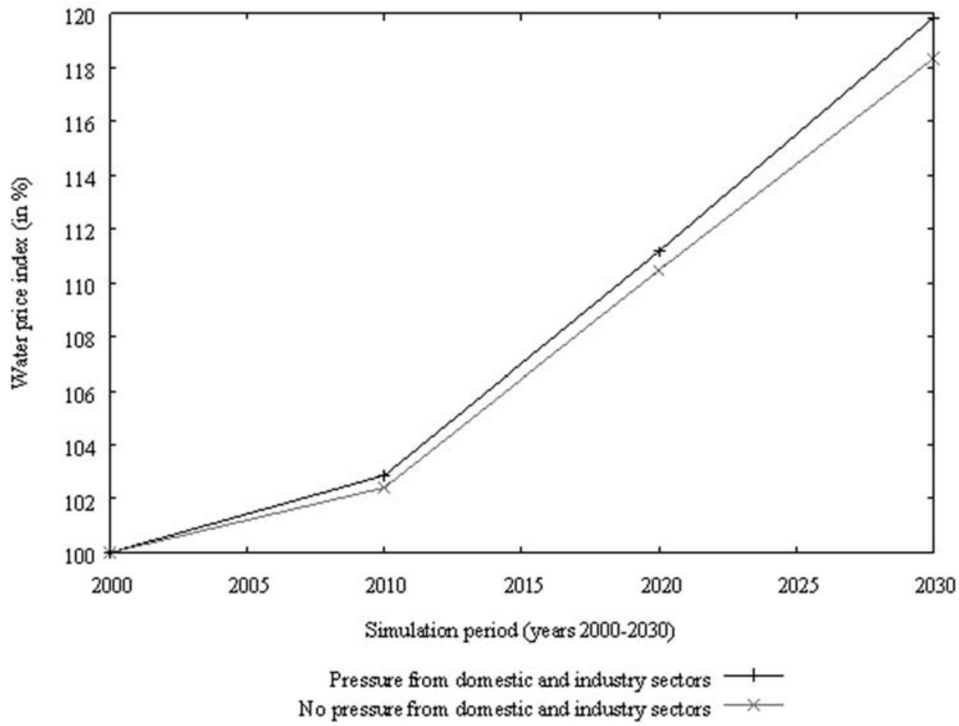

Figure 2. Water price index.

2002]. In contrast, total withdrawal for irrigation is estimated to be in the range of 2000–3000 km^3 per year worldwide [*Siebert and Doell*, 2007]. Overall, these values are of comparable magnitude with our consumptive irrigation amount of about 1155 km^3 for the represented crops in 2000.

[56] Table 12 compares average global values across all crops and irrigation methods (see remarks on the restricted crop coverage of our analysis). Differences in base-year numbers may not only be due to different assumptions and techniques in the estimation of irrigation area and corresponding irrigation water requirements, but also due to different refer-

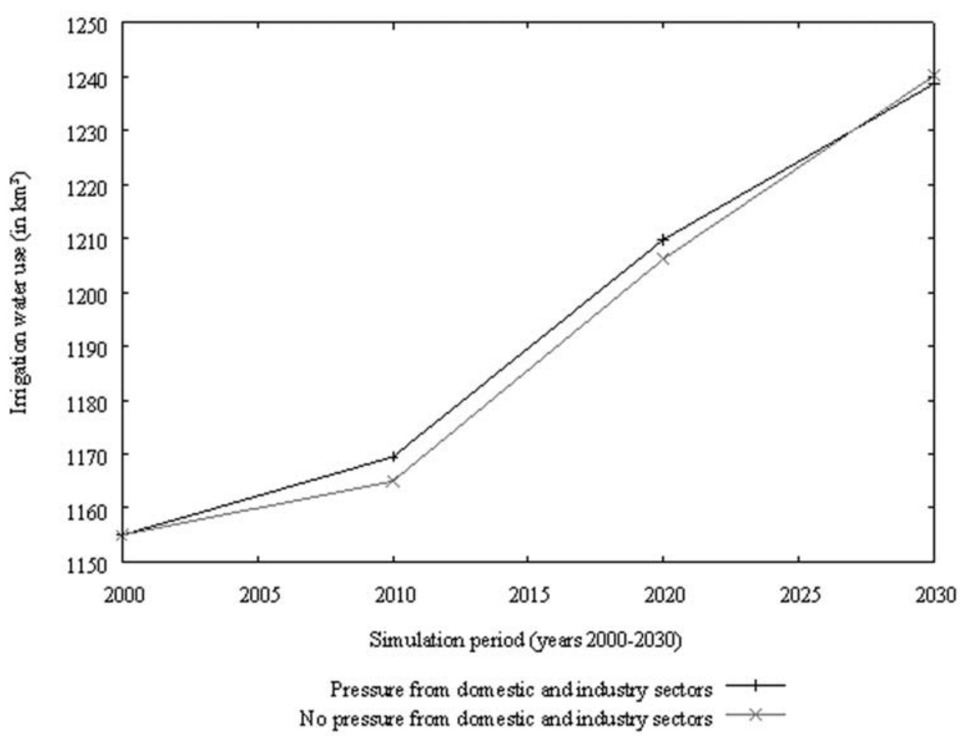

Figure 3. Global irrigation water use.

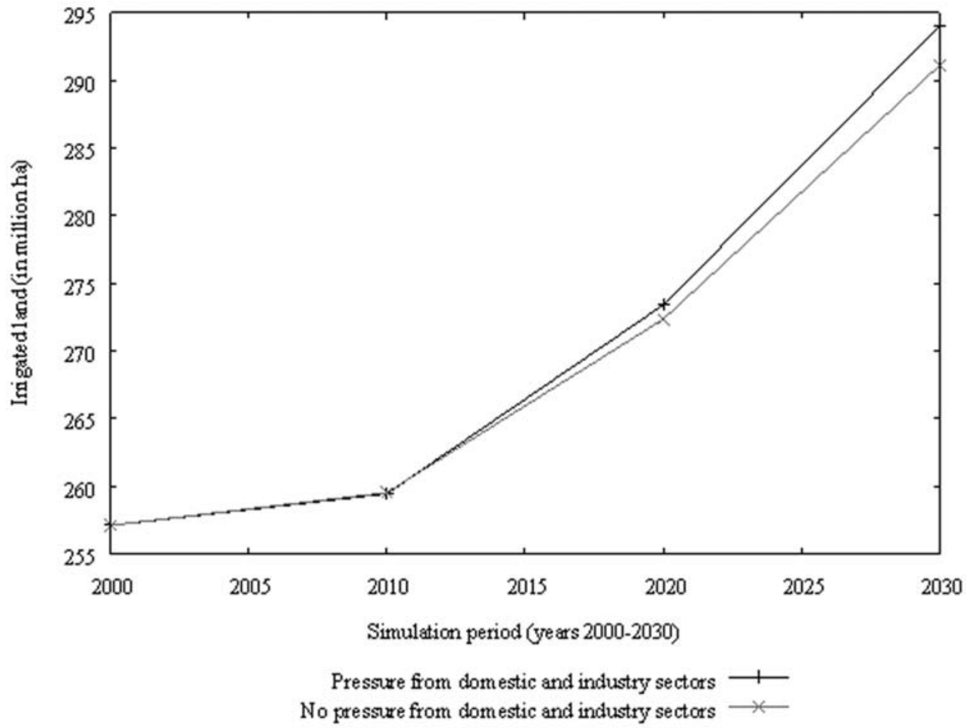

Figure 4. Global irrigated land.

ence periods or dissenting definitions of irrigation itself (with respect to surface irrigation using rainwater). Future projections are further subject to the model-endogenous process of crop allocation, which in our analysis considers international agricultural market interactions.

[57] The comparisons show that the relative increase of irrigation water use is highest for *Postel* [1998] with about 227% and lowest at our study (7%) and for *Rosegrant et al.* [2002], respectively (ranging from a decrease of 17% to an increase of 22% depending on the scenario). Importantly, with regard to average global water use intensity, *Seckler et al.* [1998] and *Molden* [2007] project an intensification of irrigation practices whereas our results indicate an extensification. The different projections discussed are likely

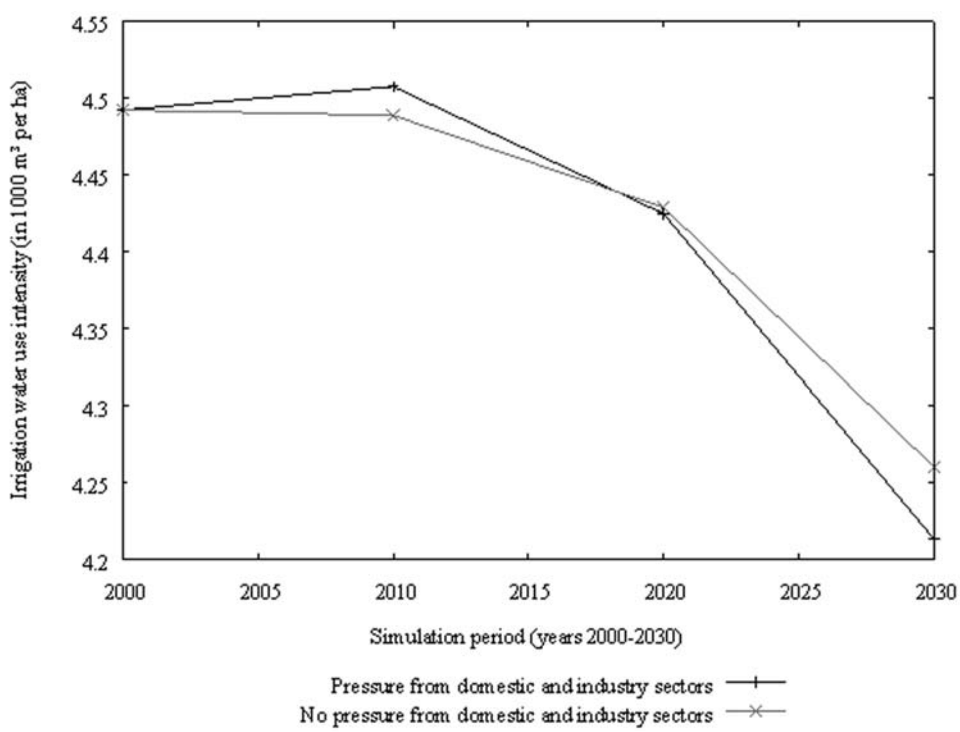

Figure 5. Global agricultural water use intensity.

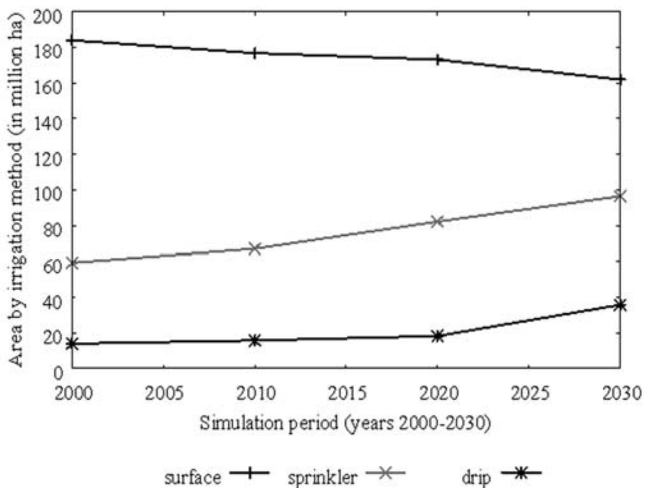

Figure 6. Irrigation methods (global).

caused by different assumptions on water productivity, trends of resource degradation, and water use efficiencies underlying the projection of consumptive water use. Our food demand and resource projections for 2030 suggest that an expansion of irrigated area by 14% and an increase in consumptive irrigation water by 7% are likely required when considering irrigation method based efficiency shifts.

[58] *Rijsberman* [2006] cites several studies projecting required increases in total cropland (rain-fed and irrigated) of 29% to 34% to meet the food demands in 2025. As already mentioned, existing trajectories of consumptive irrigation water use until 2025 under business-as-usual scenarios vary between increases of 22% and 227% [*Postel*, 1998; *Rosegrant et al.*, 2002; *Siebert and Doell*, 2007]. However, more optimistic scenario assumptions on productivity growth and water use efficiency may lead to completely different projections. For example, assuming an average yield increase of 40% by 2025 relative to 2000 for the main crop types, *Rosegrant et al.* [2002] project a much smaller increase in crop area. These investigations result in a total combined increase of only about 10% for both irrigated and rain-fed land with a simultaneous increase in irrigation water amount of only 4% to meet world food demand in 2025. In this assessment we regard population growth and economic development as the most important primary drivers of global land use change and water use.

[59] Population growth leads to an increased demand for food in general, with an expected increase in total agricultural water use. Besides, population growth is connected to increasing pressures on land and water resources from the residential and domestic sectors in terms of land demands for settlement and water demands for drinking and sanitation. In simplified relative terms this means that more food has to be produced on less land – a goal that implies an increasing share of irrigated farming – as well as less water is available for agriculture, which implies the need for improved water use efficiency. Real options are more diverse and include the expansion on marginal lands as well as trade-offs between the different land use sectors.

[60] Consequently, one major research question is whether an intensification or extensification of land use practices is appropriate to mitigate problems of resource scarcity. We approach this question by focusing on the role of alternative irrigation methods and the related potentials to achieve sustainable food security. The quantitative results are presented in the foregoing paragraphs. However, a deeper look at the underlying relations by further decomposing the term of irrigation water use seems adequate for policy support, as well as with respect to the scientific contribution of the study.

[61] Economic growth is assumed to enhance per capita income. Higher per capita income increases the demand for water owing to changes in lifestyle and diets. Concerning agriculture, the demand for more water-intense commodities like, for example, livestock products, is assumed to increase. These tendencies consequently put additional pressure on water resources and, in conjunction with population-based developments, underline the need for improvements of water use efficiency. But increased per capita income also enables higher investments in agricultural water management and irrigation systems. Concluding, a rise in per capita income may have significant effects on (1) the net total and agricultural water demands, as well as on (2) the gross irrigation water demand. Our study predicts an increase in the absolute net water demand, but also an improvement in the efficiency of irrigation water use.

[62] Thus, per capita income can be regarded as the major driver of changes in the chosen irrigation method as it drives both, the incentive for water efficiency improvements due to increased water demands, and the feasibility of necessary monetary investments in advanced systems or in research that enhances technological progress. The latter point, however, is

Table 12. Comparison of Irrigation Water Use Projections

	Döll and Siebert [2002]	*Rosegrant et al.* [2002]	*Postel* [1998]	*Seckler et al.* [1998]	*Molden* [2007]	This Study (Restricted Crop Coverage)
Projection period	2000	1995–2025	1995–2025	1990–2025	1995–2050	2000–2030
Base year: area actually irrigated (Mha)	250	-	249.5	245.07	339.66	257
Base year: irrigation consumptive water (km^3)	1287	1435.5	900	1272[a]	1426	1155
End of projection period: area actually irrigated (Mha)	-	-	-	392.11	394	293
End of projection period: irrigation consumptive water (km^3)	-	1196–1745[b]	2950	1910–2639[a,b]	2039[a,c]	1236

[a]Available data refer to withdrawal (not consumption): Estimated ratio of consumption/withdrawal = 0.54 for base year and 0.69 for end of projection period, respectively.
[b]Range of data for different scenario simulations.
[c]Available data refer to total agricultural water use: Assumed livestock fraction of 27 km^3 [*Döll and Siebert*, 2002] was subtracted to obtain irrigation amount.

only of theoretical nature as in our model there is no link between economic indicators and irrigation investments.

[63] Important key factors to guide these developments are respective policies that explicitly consider water pricing. The need to treat water as an economic good becomes more obvious with growing economic competition for adequate water resources and rising problems of water scarcity. However, the agricultural share on total economic production and labor force in industrialized countries is expected to decrease [*Lotze-Campen et al.*, 2005] despite the growing absolute demand for agricultural commodities and an expected increasing global share of irrigation on total water use. Explanations for such a declining economic importance of the agricultural sector may be found in other preferences and priorities among the lifestyle changes that accompany economic welfare. In turn, this promotes a more efficient allocation of agricultural input resources such as land and water in several respects, as the competition for these resources is not only exacerbated but also shifted for the benefit of the more viable economic sectors.

7. Conclusions

[64] Our study integrates alternative irrigation systems into a global agricultural and forest model (GLOBIOM) to estimate regional adaptations in agricultural water use for different development scenarios. The new model combines the heterogeneity of irrigation systems and natural resources with micro and macroeconomic drivers. The innovation of integrating explicit irrigation systems in their particular biophysical, economic, and technical context into a global partial equilibrium model of the agricultural and forestry sectors improves large-scale land use change assessments. The model evaluates interdependencies between socioeconomic development and policies as well as land use related externalities, resource availability, and food supply. The analysis shows that agricultural responses to population and economic growth include considerable increases in irrigated area and agricultural water use, but reductions in the average water use per irrigated hectare.

[65] Furthermore, we show that irrigation is a complex decision beyond the binary decision of adopting irrigation or not. Different irrigation systems are preferred under different exogenous conditions including biophysical and socioeconomic factors. Negligence of these adaptations would bias the burden of development on land and water scarcity.

[66] Without technical progress in agriculture, a population and income level as predicted under GGI B2 scenario for 2030 would require substantial price adjustments in land and water use to equilibrate the food supply and demand. Our projections suggest that an expansion of irrigated area by 14%, and of consumptive irrigation water use by 7% are likely to be needed when considering irrigation method based efficiency shifts.

[67] To accurately estimate land and water scarcity the likely adaptation of farmers to different irrigation methods needs to be quantified. In particular, we excluded from this analysis institutional and other barriers to an adoption of more advanced irrigation technologies. Furthermore, this work needs to be complemented by more detailed hydrological studies on the physical availability of green and blue water at much finer than regional scale.

[68] This study also underlines the need for integrated approaches to assess the role of water resources and irrigation in the context of future food security and overall socioeconomic welfare. The inclusion of technical and economic aspects of irrigation choice can provide new insights into the interdisciplinary trade-offs between determinants of global land use change. To conclude, let us state that the present article represents only the very beginning of our analysis and the model is being continuously improved so that new, more accurate results can be presented soon.

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