Agriculture, Population, Land and Water Scarcity in a changing World – The Role of Irrigation

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Abstract– **Fertile land and fresh water 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. In particular, we investigate producer adaptation regarding crop and irrigation choice, agricultural market adjustments, and changes in the values of land and water.**

Keywords– **Irrigation, Food supply, Integrated assessment, Water use intensity, Agricultural adaptation, Land scarcity, Partial equilibrium model**

I. INTRODUCTION

Global population is projected to grow by about 65% within the next 50 years. At the same time, average per capita income is also expected to rise[1]. 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 towards more water-intense lifestyles and diets. Water resources are an important economic driver because they 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[2,3].

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[4,5]. 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[6,7]. Third, environmental and human health regulations may constrain agricultural management and put limits to intensification[8-10]. Fourth, continued growth in domestic and industrial sector water consumption will decrease the available water volume for agriculture[11,12]. Fifth, if climate change intensifies, the productivity of agricultural systems will be impacted. However, these impacts will differ across locations and involve both improvements and deteriorations[7,13,14]. While the above mentioned challenges may differ locally, their net impact is likely to affect all countries as agricultural commodities are heavily traded.

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 40% of the global harvest[15]. 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[16]. However, increasing levels of irrigation will increase the cost of water and, in some regions, this may cause severe problems of water scarcity.

As water scarcity increases, inefficient allocation of water causes increasing costs to society. Missing property rights and inadequate water pricing are major causes of such inefficiencies. The magnitude of water-related externalities may further increase as international agreements to mitigate global change put more restrictions on agriculture or land use in general. 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 agricultural water use. In particular, appropriate assessments of agricultural water use need to consider a) the heterogeneity of natural and farming conditions, b) international commodity markets especially for agricultural products, c) agricultural and land use related environmental policies, and d) synergies and tradeoffs between different land use related externalities[17,18]

Many existing studies, which endogenously consider the adoption of irrigation practises, stay at farm or basin scales. A few global assessments of irrigation distribution and impacts exist but mainly within disciplinary boundaries, i.e. 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 rainfed and irrigated agriculture. Global integrated land use models accounting for multi-sectoral competition and limitations of land and water resources are rare[19].

In this study we analyse quantitatively how irrigation decisions in land use systems respond to different development scenarios. Possible irrigation options include four major systems in addition to rainfed agriculture. The suitability of these systems depends on environmental, technological, and economic factors, which influence crop suitability, water use efficiency, energy demand, labour intensity, and overall cost of irrigated agriculture, and thus affect motivation-based decision making that aims at individual or societal welfare maximisation[20].

We present a first attempt to integrate crop and location-specific irrigation methods into a global partial equilibrium model of land use. This model estimates economically motivated decision making subject to site-specific environmental constraints, and heterogeneous, system-specific costs[21]. The model optimises explicitly water and energy use efficiency.

This model can be used to assess the impacts of political, technical, environmental, and market developments on agricultural management decisions and their aggregated impacts on scarcity of land and water, agricultural commodity supply and prices, and impacts on environmental externalities including deforestation, greenhouse gas emissions, soil erosion, and nutrient leaching.

II. MATERIALS AND METHODS

Our paper is structured as follows. We briefly portray the model and basic components of the irrigation module, followed by a more detailed description of the determinants of irrigation choice (crop profitability, resource endowments, water demand, energy demand, labour demand). 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. Then we describe the computation of total irrigation costs, depending on the particular biophysical and economic environment.

In the next sections we introduce the baseline scenarios and discuss first model results.

A. Global Forest and Agricultural Sector Model

We apply a mathematical programming-based, price-endogenous sector model of the agricultural and forestry sectors. The model depicts production, consumption, and international trade in 11 world regions. The agricultural sector is represented by more than 40 crops and an aggregated livestock sector. For crop management, the model can choose between different irrigation systems as described in detail in the following sections. Livestock production and consumption is represented by an aggregate of animal calories and is connected to crop production through fixed feed ratios. Except for the irrigation-related parameters the agricultural part of the model relies on FAO statistics accessible at http://faostat.fao.org. Forestry sector focuses on biomass production for sawnwood and wood pulp and represents also the first transformation level. It is an adapted version of the 4DSM model[22]. The model contains also several bioenergy processing technologies and a complete greenhouse gas accounting, but those are not the focus of the present analysis.

The model simulates the market and trade equilibrium in global agricultural markets. The market equilibrium reveals commodity and factor prices, levels of domestic production, export and import quantities, resource usage, and environmental impacts.

B. Irrigation Module

Four irrigation methods are portrayed: surface irrigation systems including basin and furrow irrigation, localised drip irrigation, and sprinkler irrigation (represented by center-pivot sprinklers). Current cost trends of water delivery infrastructures made us assume 'piped water supply' for all of the systems[23]. For each method we evaluate biophysical and technical compatibility to exclude inappropriate irrigation decisions.

The choice of crop and management type is motivated by profit maximisation subject to resource constraints. Profitability is defined as revenue less production costs. Crop revenue is calculated as the expected yield per spatial unit times the respective market price per unit of yield. Production costs contain all expenses for management and inputs required to reach the respective management-related yield. Crop yields and corresponding irrigation demands are based on exogenous databases[24-26]. Yearly water availability for irrigation considers internal renewable water resources less water requirements of other sectors[27]. Land resources are further classified by slope and soil type[26].

We also considered system application efficiencies to project gross water demands [20]. Actual water use is finally computed considering irrigation cost per spatial unit for all appropriate combinations of geographic background, crop type, and irrigation system.

C. Parameterisation: Energy Requirement

Four energy sources can be used optionally: Electricity, diesel, gasoline, and natural gas. Energy use is a function of irrigated area, water demand, pressure requirement, and total irrigation time[20]. Pressure for pumping is determined by estimated pipe length and lifting height.

On-farm irrigation scheduling is affected by various functional relationships among geographic and technical parameters. We used a simple but consistent approach to represent these interdependencies by means of 'generalised irrigation scheduling'. In this context 'application depth per irrigation event' is an important parameter to calculate cost-effective energy demand. We used a stepwise approach to determine application depth based on the assumption of fixed operating times per event[28]. The schedules assume uniform application depths during complete vegetation period. Guide values on soil infiltration rate, suitable slope, the allowable range of flow rate by soil type at optimal slope, and corresponding size of irrigated area were taken from literature[29]. In a first step we calculated maximum number of events with respect to length of growing period[30] and common application frequencies[20,29]. Using total irrigation water demand, we accordingly determined application depth per event by country, crop, and method. Second, we calculated maximum application depth by soil type on optimal slope with respect to flow rate and soil infiltration rate. To account for slope effects on surface irrigation performance we modified the application depths for basin irrigation using ratios between recommended and minimum flow rate as multipliers, while assuming proportionality of irrigation depth and flow rate. Then we derived 'slope-related basin size factors', which depict the maximum basin area by slope class in percent of the optimum-slope basin area when flow rate is the same. For this we assumed quadratic basins and a linear relationship between slope and basin size. These slope coefficients were applied to previous soil-indexed optimal-slope application depths. Regarding furrow irrigation, we considered soil and slope influences on maximal furrow length and their implications for allowable flow rate[29]. We transformed furrow lengths to 'area per furrow' and determined application depth per furrow (by country, crop, soil type, and slope) for maximal area under consideration of operating time. After modifying the surface application depths we re-calculated yearly numbers of irrigation events based on total water requirements, and determined the 'final' application depth per event.

Energy use for irrigation is determined by underlying pressure requirements. Total pressure requirement is the sum of sprayer pressure (for non-surface systems) and static head pressure to bridge elevation differences. Information on sprayer pressure and static head pressure calculation were obtained from literature[20,31]

D. Parameterisation: Labour Requirement

Labour requirement is the number of irrigation events times estimated labour hours per event[28].

To depict variations by crop type we introduced a 'crop labour factor' as a multiplier, based on costs per spatial unit[32,33], and used the value of maize as benchmark.

E. Irrigation Cost

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[34,35], and labour costs in terms of average agricultural wages per hour[36,37]. For unavailable items we inter- or extrapolated mean trends.

At present stage, capital and maintenance costs by method were assumed to be globally identical, though in fact they may substantially differ between regions[12].We took capital costs per spatial unit for center-pivot sprinklers as reference[38] to determine costs of drip and surface systems, using further technical information on these systems[23]. Maintenance cost was set to 5% of capital cost for non-surface and furrow irrigation, and to 3% for basin irrigation[23,33].

III. BASELINE SCENARIOS

Population growth affects agriculture through increased demand for food. Higher demand for land and water from non-agricultural sectors increases the scarcity of these two resources. Economic development may additionally affect food demand qualitatively and quantitatively via shifts in consumption patterns and increasing demand for water-intense commodities.

We analyse these drivers independently and jointly on a resolution of 11 world regions (Table 1). Increase of population from 2000 to 2030, according to the IIASA GGI A2r baseline scenario calculations, portrays the major driving force for scenario simulation[39]. We estimated future food demand by multiplying regional projections of per capita calorie intake[40] with the increment in regional population according to the GGI scenarios.

Table 1 Model World Regions

World regions [+ no. of contained individual countries/subregions]
North America (NAM) [6]
Western Europe (WEU) [29]
Pacific OECD (PAO) [3]
Central and East Europe w/o former SU (EEU) [12]
Former Soviet Union (FSU) [15]
Planned Asia with China (CPA) [6]
South Asia (SAS) [8]
Other Pacific Asia (PAS) [18]
Middle East and North Africa (MEA) [19]
Latin America and Caribbean (LAM) [38]
Sub-Saharan Africa (AFR) [49]

The average daily calorie intake per head is projected to increase in all regions. Highest rates are assumed for regions that are also predicted to have high population growth (Sub-Saharan Africa, most Asian countries). 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.

Supplementary pressure from population growth in terms of increased residential water and land demand, causing reductions in water and land available for agriculture, were calculated using domestic water consumption[27], and population density data[41]. We assumed that residential land growth takes the form of urban expansion.

Baseline reference data on land and water endowment, and on irrigation distribution was obtained from FAOSTAT, AQUASTAT, and ICID databases[24,25,27,42,43].

IV. RESULTS AND DISCUSSION

We will describe simulated trends of irrigated area and water use intensity to analyse these results in the context of alternative irrigation options.

Rising demands for food lead to increasing crop, land, and water prices. We applied constant supply functions for water. Technological progress affecting productivity is not considered in the model runs.

The effects of the constant water elasticity on regional water prices is presented in Fig. 1.

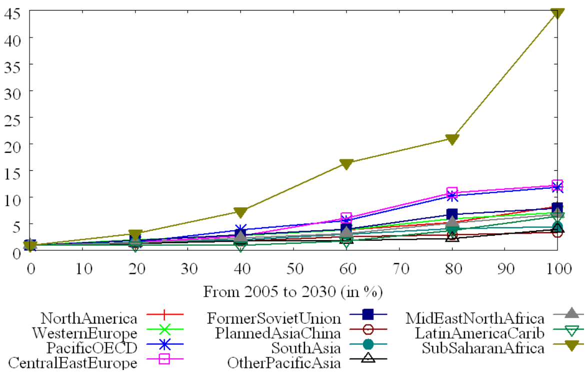

Fig. 1 Results – Water Index by Region

Total water use is going to increase at only slightly varying rates until about 80% of the total increase projected until 2030 has proceeded. From this point increase rates decline accompanied by corresponding prices increases for water (Fig. 2).

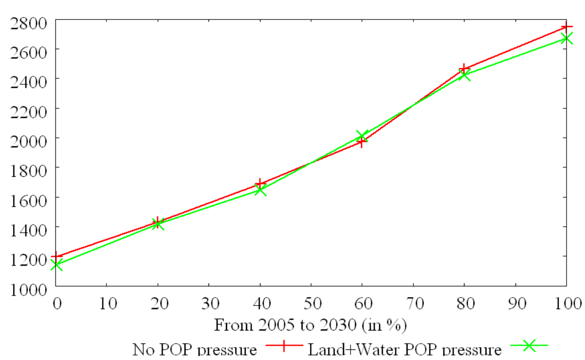

Fig. 2 Results – Global Irrigation Water Use

Simulations indicate highest increase and totals of irrigated area in South Asia (SAS). Increasing rates of irrigated area expansion are also predicted for Latin America and the Caribbean (LAM), Former Soviet Union (FSU), Planned Asia with China (CPA), and Other Pacific Asian states (PAS). After a relatively long period of population growth a stronger expansion of irrigated area is finally also simulated for Sub-Saharan Africa (AFR).

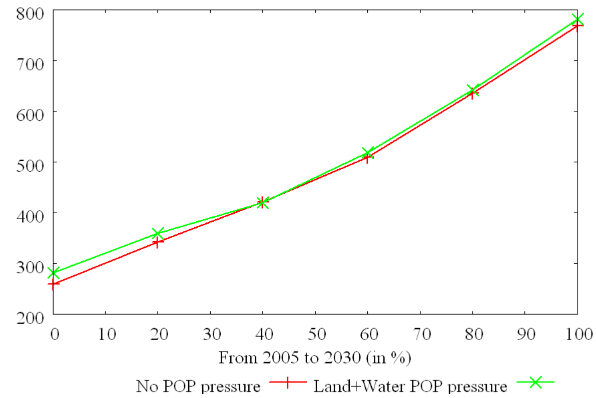

Fig. 3 Results – Global Irrigated Land

Global water use intensity more or less continuously decreases over time. Whereas water intensity remains relative 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.

Critical thresholds to trigger explicit shifts in regional irrigation management towards improved water use efficiency seem to appear when about 60-80% of predicted global population growth until 2030 has taken place. In between 20-60%, water use efficiency improvement is progressing at comparably low rates.

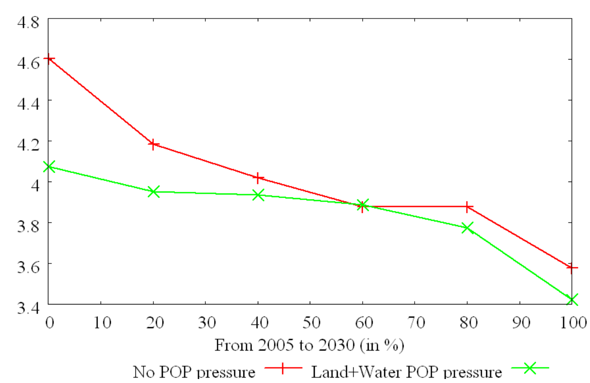

Fig. 4 Results – Global Agricultural Water Intensity

We will face a general trend of irrigated area expansion to sufficiently meet changing food demands. Additional water and land pressure due to residential demands accelerate the increase in irrigated area, but simultaneously trigger an extensification of management practises in terms of decreasing water use intensity.

Residential pressure on land resources seems to force shifts from rainfed to irrigated agriculture to maintain food production, whereas residential pressure on water resources restricts water intensity when water becomes scarce, and consequently approves water-efficient irrigation methods or, respectively crop types with lower irrigation demands.

Food demand-induced needs for irrigation expansion may be met by more water-efficient irrigation methods: Results show that after some time current and additional agricultural production likely shifts to irrigation practises that are more water saving. On long-term a broad application of relative expensive but most water-efficient methods is eventually triggered. On global scale, a progressive substitution of sprinkler irrigation by drip systems appears first, before eventually also surface irrigation decreases in favour of water-efficient pressurized techniques.

In higher developed regions such 'shifting trends' appear earlier and more smoothly than in less developed regions. Besides technological standards, cost recovery for investment and O&M may play a major role.

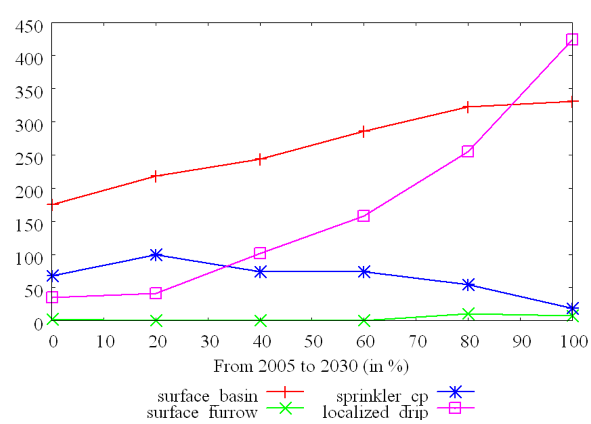

Fig. 5 Results – Irrigation Methods (global)

The timing of the occurrence of 'global irrigation shifts' may be illustrated by simulated global surface irrigation developments. A global dominance of surface methods (especially basin irrigation), which is predicted for the early stages of population development, is likely related to the specific characteristics of rice production, in conjunction with regional population dynamics: As long as water supply is not a limiting factor to irrigation decisions, basin irrigation can be maintained at high levels and further increased as the market price of rice is relatively high, basin irrigation is cheap, and food demand grows. But particularly regions most suitable for rice cultivation also have high rates of population growth (e.g. SAS, CPA), and thus are particularly exposed to occurring problems of water scarcity. A shift away from the combination of high water demands, large areas, and water inefficient irrigation performance leads to considerable water savings per hectare.

V. CONCLUSIONS

The model framework is applicable to evaluate interdependencies between policies on one side, and land use related externalities, water availability, and food supply on the other side.

In this study, we use a global agricultural and forest sector model to evaluate interdependencies between development, food supply, and scarcity of water and land. Our simulations show that agricultural responses to population and income growth include considerable increases in irrigated area and agricultural water use but reductions in the average water use per irrigated hectare.

Irrigation is a complex decision beyond the binary decision of using 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.

Without technical progress in agriculture, a population and income level as predicted under GGI A2r scenario for 2030 would require substantial price adjustments for land, water, and food to equilibrate supply and demand.

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 adopt more advanced irrigation technologies. Furthermore, our work needs to be complemented by more detailed hydrological studies on the physical availability of green and blue water supply.

The study emphasises 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 paper represents only the very beginning of our analysis and the model is being continuously improved so that new, maybe more accurate results, can be presented soon.

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