The global nexus of food-trade-water sustaining environmental flows by 2050

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Abstract

In face of meeting Sustainable Development Goals (SDGs) for water-food-energy-ecosystems nexus, integrated assessments are great means to measure the impact of global change on natural resources. In this study, we evaluate the impact of future climate change scenarios (RCP8.5) and future shared-socioeconomic Pathways (SSP2) on land use, water consumption and food trade under water regulation policy scenarios (INVEST-EXPLOIT-ENVIRONMENT). We have used the land use model GLOBIOM, and constrained it with water availability, environmental flow requirements (EFRs) and water use from agriculture and industry and households (simulated with LPJml, EPIC and WaterGap models). Here, we show that an increase in land use by 100Mha would be required to double food production by 2050, in order to meet projected food demand. International trade would need to nearly triple to meet future crop demand, with an additional 10-20% trade flow from water-abundant regions to water-scarce regions to sustain EFRs on a global scale.

Keywords: food production, agricultural area, environmental flow requirements, international trade

1. Introduction

Global water resources are under increasing pressure due to large-scale water abstraction for human needs (Loh et al. 2010; WWF/ZSL 2016). About 70% of the water that is abstracted from freshwater systems is used for irrigation and about 40% of our food is produced on irrigated lands (Wada et al. 2013). By 2050, without major policy interventions, human water use and irrigated area are expected to increase rapidly due to population growth and an increase in food demand (Elliott et al. 2014; Molden 2007; Alexandratos and Bruinsma 2012). In addition, crop yields are projected to decrease by more than 80% in some areas under the highest-emission climate scenario (Elliott et al. 2014; Rosenzweig et al. 2014; Schlenker and Roberts 2009; Ray et al. 2013). Climate change could affect 10 to 45% of current cereal production while water scarcity is predicted to increase in the coming decades (Elliott et al. 2014; Osborne, Rose, and Wheeler 2013; Haddeland et al. 2014) However, CO_2 fertilization and optimized crop production could stabilize and/or increase future crop yields under climate change (de Vrese, Stacke, and Hagemann 2018; Tester and Langridge 2010). Freshwater abstraction and river fragmentation can be detrimental to freshwater ecosystems (Poff and Zimmerman 2010), and Jagermeyr et al. (2017 have shown that under current conditions, 30% of irrigated crop production comes at the expense of environmental flow requirements (EFRs). The use of trade and/or “climate-smart food systems” was proposed in order to address future challenges related to climate change and food security (Kummu et al. 2014; Qureshi, Hanjra, and Ward 2013; Wheeler and Von Braun 2013).

Rising demand for water is likely to increase the pressure on riverine ecosystems (Falkenmark, Rockström, and Karlberg 2009). To limit biodiversity loss in riverine ecosystems, EFRs have been defined for many river systems around the globe (Declaration 2007; Tharme 2003). EFRs are needed, *inter alia*, to preserve connectivity, supply sediments and nutrients for soil fertility, and replenish groundwater aquifers (Richter 2010). Until recently, on a global scale, most of the methods used to define EFRs were applied to single river basins or estimated with a “rule of thumb” (A. V Pastor et al. 2013). The recently developed Variable Monthly Flow Method (VMF) (A. V. Pastor et al. 2014) was designed with refined spatial and temporal scales to be applied globally. Using this method, the planetary boundary for freshwater resources was estimated at 2,800 km^3 yr^{-1}, equivalent to 7% of total runoff and much lower than in previous assessments (D. Gerten et al. 2013; Steffen et al. 2015).

Integrated Assessment (IA) models have been developed to evaluate the interactions between socioeconomic developments, climate change and bioenergy scenarios and their effects on land-use dynamics (Lampe et al. 2014; Verburg et al. 2004). IA models are classified into computable general equilibrium (CGE) models and partial equilibrium (PE) models (Robinson et al. 2014). CGE models require general production/cost functions for all sectors, whereas PE models involve a more comprehensive description of agricultural technologies. In this study, we used the PE integrated assessment model GLOBIOM (Global Biosphere Management Model) to optimize the allocation of future cropland and water withdrawals and find trade-offs between future crop production and sustainable water withdrawals. We evaluate how a redistribution of cropland could result in more sustainable water use (Fig. 1). This is the first integrated global assessment that evaluates the impact of climate change, socioeconomic change and the implementation of EFRs on the future distribution of cropland and food production.

In this study, we show that crop production needs to be doubled by 2050 under any of the water management policy scenarios (Fig. 3 and Supplementary Table 8). Table 1 shows that water use for irrigation increases by 20% between 2000 and 2050 in the INVEST scenario (the less water restrictive scenario), while water use decreases by 30-38% by 2050 in the ENV and ENV+ scenarios (under EFRs restrictions). Under the INVEST scenario, the increase in crop production comes from a large expansion of cropland (50% irrigated/50% rainfed), assuming large scale investments in water infrastructure. The INVEST scenario results in the highest water use and the lowest international trade (Table 1, Fig. 2). Under the EXPLOIT scenario (local water restrictions), the increase in crop production comes mainly from an increase in rainfed area in Latin America and in South-East Asia (SEA; Figs. 4 and 5). The EXPLOIT scenario results in the largest increase in land use, with intermediate trade and water use. To comply with EFRs, the ENV and ENV+ scenarios result in a reduction of irrigated areas in China and India by 2050 with a reallocation of cropland in the tropics (Fig. 4 - Supplementary Fig. 3-4-5). Between 2000 and 2050, international trade would need to nearly triple to meet future crop demand, with an additional 15% to compensate for water restrictions from EFRs (Table A5). Crop area would expand from 17% to 20% in all scenarios, with an increase of high-input rainfed cropping systems by up to 25% (Fig. 3; Supplementary Figure 9). In the ENV scenarios, a conversion of up to 60 Mha of irrigated cropland to rainfed cropland would be required to meet EFRs (Supplementary Figure 2).

Future regional changes in land use under water restrictions

In 2050, the increase in agricultural crop production under the INVEST scenario would be mostly achieved by a 20% expansion of total irrigated and rainfed crop area (Fig. 4 and Table A5), while implementing EFRs (ENVIRONMENT scenario) would imply a regional increase in rainfed area and a large reduction in irrigated area, especially in Asia (Fig. 4). For example, we show that under the INVEST scenario, irrigated area could expand from about 220 Mha in 2000 to 300 Mha in 2050, mainly in East of Asia (EAS, e.g. China) and South Asia (SA, e.g. India), while under the ENV and ENV+ scenarios, by 2050, irrigated area could be reduced from 220 Mha to 161 Mha, mainly in EAS and SA (Fig. 3, Table A5). Climate change alone would lead to an increase in irrigated land in North America (NAM) and Southeast Asia (SEA), including Indonesia, and to a decrease in irrigated land in the Mediterranean and North-African (MENA) region and to an expansion of rainfed area in Latin America (LAM; Fig. 4, Table A5).

Consequences for future crop production

At present, 40% of crop production comes from irrigated areas (Fig.3, Supplementary Table 6). We show that by 2050, under EFRs restrictions, only 20% of crops could be produced on irrigated land, compared to 38% for the INVEST scenario (Supplementary Table 7). Under the EXPLOIT and INVEST scenarios, part of the irrigated production comes at the expense of EFRs, especially in the MENA and in China and India, while, under the ENV scenarios, irrigated area would be reduced by about 50% in these regions representing more than 30 Mha (Fig. 4, Supplementary Tables 7-8).

Pathways to sustain environmental flows

Our results show that there are three main mechanisms that compensate for the loss of irrigated agriculture in order to meet EFRs (Fig. 2). The first is a conversion of irrigated and natural areas to rainfed areas (Figs. 3 & 4, Supplementary Figure 2 and Table 5-6), the second is an increase in global crop trade (Fig. 5, Supplementary Figures 3-4-5), and the third is a shift to more intensive cropping systems and less water-demanding crops (Supplementary Figure 9, Supplementary Data). In 2050, the difference between scenarios in total crop area remains relatively small (Fig. 2). The additional crop production would come from regional shifts in land use, cropping systems and modes of production. Conversion of irrigated area to rainfed area takes place in productive croplands with sufficient rainfall (Supplementary Figure 2). To compensate for this loss of cropland area in China, India and in the MENA, our results show that an expansion of cropland area by up to 20 Mha in Latin America, Africa and Russia would be required (Fig. 4, Supplementary Table 2).

International trade by region

Results indicate that bilateral trade needs to increase by 5% to compensate for climate change alone, by 10-13% to compensate for EFRs alone and by 17-20% to compensate for combined climate change and EFRs (Fig. 5, Supplementary Figure Fig. A5). In general, trade flow increases from water-abundant regions such as Latin America and Southeast Asia to water-scarce regions such as China and MENA (Fig. 5). Water-scarce regions need to import more agricultural products under the ENVIRONMENT scenarios than under the EXPLOIT and INVEST scenarios (Fig. 5, Supplementary Figure 3-4-5). Climate change further increases imports of agricultural products to China and South Asia (including India), though the impact of climate change on global crop trade remains lower than the effect of implementing EFRs.

Changes in land use and expansion

Under climate change and water limitations, part of the additional crop production would come from converting grasslands, forests and other natural vegetation into productive rainfed cropland

(Supplementary Table 7 and Figure 2). Globally, agricultural expansion into natural land and primary forest is expected to be about 300 Mha (100 Mha cropland and 200 Mha grassland) between 2000 and 2050 due to increase in food demand, with more than 60% of the increase coming at the expense of forests. Fifty to sixty percent of this conversion would occur in Latin America, where managed land would expand into forest and other natural land. On a global scale, the impact of EFRs alone could lead to 15% more conversion of grassland to cropland, 12 to 21% more conversion of natural land to cropland and up to 9% more conversion of forest to cropland (Supplementary Table 7). Additional results on cropping system shifts, agriculture intensification and sensitivity analyses on crop yields, crop area and water supply are available in supplementary results (Supplementary Figures 2 to 9, Supplementary Data).

Discussion

Our results indicate that in order to protect freshwater by meeting EFRs and supply sufficient food for future generations, irrigated areas should be reduced by 30% relative to the current situation, which correspond to the compromised EFRs found in Jägermeyr et al. (2017). In addition to the change in land use, increased interregional trade in agricultural products is needed to supply the world's population with sufficient food (three times more than in 2000). Interestingly, our results indicate that the primary cause of land use expansion is the increase in food demand, whereas, to meet EFRs, our assessment shows that what is needed is a large-scale conversion of irrigated land to intensive rainfed land and a regional reallocation of rainfed area, especially in Latin America and the Pacific Islands. The combined impact of climate change and EFRs would increase net trade by up to 15% globally compared to a business-as usual scenario (INVEST). The main increase in exports could come from Latin America (+70%) and Southeast Asia, e.g. Indonesia (+22%), while increased dependency on imports would take place mainly in China (+38%), India (+33%) and MENA countries (+19%). In addition, with climate change, we observe that water use for irrigation is lower than without climate change (Table 1), this is mainly due to a low water availability in water-scarce countries and due to a combined increase in water demand for agriculture, industry and households and EFRs (for ENV and ENV+ scenarios). Therefore, in water scarce regions such as MENA, the rise in marginal water price leads to a partial abandonment of irrigated area. Stricter EFRs would not entirely be a win-win scenario for the world, since regional reallocation of agricultural land would have consequences such as the loss of agricultural area and expansion into natural lands and forests up to 9% (Supplementary Table 7). As it is shown in Dalin et al. (2016), the environmental impact of water trade is beneficial as long as the exporter's water productivity is higher than that of the importer, however, this latter should not deplete non-renewable water, pollute freshwater and/or lead to the collapse of other terrestrial ecosystems. In addition, it is important to consider that the expansion of agricultural area to natural areas can release stored carbon, fragment species habitat, and alter the hydrological cycle.

Our results show that it is possible to double agricultural production with a 20% increase in cropland. This assumes a significant reduction in the crop yield gap through intensification, technological improvements and a rapid uptake of improved technologies, especially in Africa, Asia and Latin America (Supplementary Figures 8-9). Tilman et al. (2011) provided similar estimates and found that crop production can be doubled with a relatively small rise in agricultural area if a number of adaptation measures are implemented to intensify agricultural production. However, a study by Wirsenius et al. (2010) estimated a required increase in agricultural area of 1,600 Mha by 2030, which is much higher than our projections. This difference is partly due to less-flexible trade flows between regions and a less-flexible scheme for change in land use with respect to our study. Agricultural intensification can also have major effects on the environment, including freshwater ecosystems, due to increased use of agrochemicals. Our study explicitly focuses on the water quantity aspects of protecting freshwater habitats, but this should not come at the expense of water quality (e.g. by using extra nutrients and/or pesticides), which can also have a large impact on freshwater biodiversity (Turner and Rabalais 2003).

Our results indicate that increase in trade is necessary to adapt to global change and allocate more water to the environment. Similarly, a study from Dalin and Rodríguez-Iturbe (2016) showed that trade can reduce global agricultural water use. In addition, a study from Martinez et al. (2017) shows that agricultural trade market reduces the impact of climate change and crop yield reduction on food provision. Therefore, it is important to include infrastructures and water trade flows in future freshwater planetary boundary assessments (Konar et al. 2016). However, at present, trade in agriculture is still limited with respect to other commodities due to high freight cost and protective laws and regulations (Turner and Rabalais 2003; Dalin and Rodríguez-Iturbe 2016). Dalin and Rodríguez-Iturbe (2016) also show that increased trade can have other negative consequences, such as decreased terrestrial biodiversity and local socioeconomic changes. Trade liberalization can potentially increase the environmental impact in countries where environmental protection laws are less restrictive and should be used with caution. Trade can also be a risky tool in times of food crisis or drought, such as in 2007, increasing food insecurity for the poor and malnourished (Suweis et al. 2015). Although international trade can help supply food in times of regional shortages, there are also environmental tradeoffs such as increasing deforestation and/or agricultural land expansion in LAM and SEA. For example, DeFries et al. (2012) reveal a direct, positive linear relationship between forest loss in Asia and Latin America and net agricultural trade. To reduce the negative effects of agricultural expansion policies, exporting countries could establish expansion limits for agricultural land dedicated to export crops, intensification policies (in order to avoid expansion), and subsidies to sell crops locally at a lesser price and thus reduce exports.

Our results show the trade-offs between land use, water use and crop production versus trade. Increase in food demand reduces national self-sufficiency ratios especially in Asia and the MENA region, and this result is worsened by EFRs and climate change (Fig. 5, Supplementary Figure 5). Currently, both India and China have developed policies for securing food supply through high self-sufficiency ratios (Yu and Lu 2006). Our analyses show that it is possible on a macroeconomic scale to provide food and water for all, However, on a regional scale, reducing regional irrigation water use would have significant consequences for regional crop production leading to increased imports and this could have negative consequences for food security (Margulis 2013) in the importing countries and for environment in the exporting countries. It is important for a regime with more agricultural trade to be combined with policies guaranteeing food access and affordability because sufficient production does not guarantee access to food for all. Importing more food into a country that is limited in natural resources (land and/or water) can have a negative impact on local agriculture production, local natural resources and on the rural economy. In addition, preserving EFRs can on one side favor ecosystems, replenish groundwater, provide downstream populations with sufficient water and prevent desalinization. However, this should not come with too many compromises on population habits and reallocation and loss of terrestrial ecosystems. Alternative solutions must be proposed to compensate the reduction in irrigation water use such as crop diversification in semi-arid areas (this study) and the introduction of drought-resistant crops and aquaculture such as in Romo-leon et al., (2014).

The results show that reaching SDGs on a global scale remains a challenge, especially in the context of the Water-Food-Energy-Ecosystem Nexus, in which each component has a target to be respected without compromising the environment (Bazilian et al. 2011). For example, on a regional level, finding trade-offs between water, food and energy remains a challenge in Southeast Asia, where conflicts between downstream and upstream water users may exist and where increasing the water use efficiency remains a priority (Rasul 2014). This study highlights how land-use systems could be adapted to meet water and food demand for humans and ecosystems in the face of global change. The reallocation of crops to the most productive and water-abundant regions, intensification of cropping systems, conversion of irrigated land to rainfed land are suggested, mainly in Asia and shifting to less water-intensive crops in water scarce regions would ease plant growth and crop production.

To make our results more robust, we performed a sensitivity analysis of model parameters and decreased the uncertainty of our results by using multiples models and scenarios. The Supplementary Figure 1 shows the different sources of uncertainty that were tackled in previous studies. In this study, we mainly performed parametric uncertainty analysis by testing the limits of our system to the impact of climate change (using the highest emission scenario: RCP8.5), the impact of two different climate models (structural uncertainty, Fig. 3), the impact of three levels of water restrictions for environmental flows: no restriction, medium and high restrictions (Fig. 3), and the impact of two different trade scenarios: constrained and unconstrained (Supplementary Table 6). For socio-economic scenarios, we used SSP2 which is the average scenario. Uncertainties and ranges of socioeconomic scenarios (SSPs) are addressed in the previous studies showing the impact of different SSPs on future land use (Fujimori et al. 2017; Schmitz et al. 2013). However, in Schmitz et al. (2014), it is shown that the shift from SSP2 to SSP3 would imply a change of less than 1% in total agricultural area in GLOBIOM. From a global perspective, our results show a higher impact of EFRs on food production than the sole impact of climate change and climate models (Fig. 2). We also show that a constrained trade could reduce food production from -6 to -12% (with increasing water restrictions). We performed a sensitivity analysis to examine the effects of our crop-yield growth assumptions, water demand for other users (domestic and industrial), groundwater resources and irrigation use efficiency (Supplementary Figure Figs. 4-6) on land use. Complementary to Leclère et al. (2014) and Fuss et al. (2011), our results show that crop area is sensitive to crop yield volatility (SSP2 crop-yield growth assumptions versus constant crop yields). With a constant yield assumption, rainfed area would be 20% higher than with the SSP2 yield-growth assumption (Supplementary Figure 9a). Finally, if we assume that water demand for other users would remain constant between 2000 and 2050 (Supplementary Figure 9b), our results indicate that irrigated area could increase by up to 15% (with a low impact on rainfed crop area). We also tested the impact of decreasing groundwater storage by 50% (Supplementary Figure 9c) and show that it would decrease irrigated area by about 10%. At regional level, the MENA and South Asia regions, which are highly dependent on irrigation, would be affected more than the rest of the world and imports would be mandatory for their populations' food requirement. Finally, we assumed in all our scenarios that irrigation use efficiency will increase according to the technological projections of SSP2 (2% per decade); if irrigation use efficiency remained constant over the time period (Supplementary Figure 9d), irrigated area would decrease by 10%. Similar results can be found in Fujimori et al. (2017) showing that land use expansion for crop and pasture would respectively increase by 40% and 20% from the baseline year by 2100 and that crop yield rate increase would range from 0.3 to 1.2 until 2050 with highly variable change in crop yield due to climate change and a doubling of crop yield due to technological improvement (Palazzo et al. (2017); Supplementary Figure 6b). We hope future studies will also address the impact of extreme events with this framework because global warming and climate variability are likely to increase in the coming decades (Field et al. 2014). Finally, a study from Springmann et al. (2018) shows that the major contribution to mitigate environmental impacts of rising food demand is technological improvement (50%) followed by reducing food waste (20%), shifting diet (20%) and finally shifting to SSP1 scenario (10%). Our study is a first step in conceptualizing the analytical framework and solutions for the potential trade-offs between future food security and freshwater use. This framework should be further expanded to test the robustness of our results, for example, through a stochastic version of GLOBIOM and through an extension of the inter-comparison models done for the Agriculture Model comparison: AgMip (Lampe et al. 2014).

In conclusion, our results show that it is possible to meet both global agricultural demand and the water needs of the environment with an increase in total cropland of 20% by 2050. However, this should come with substantial improvements in agriculture and water management, with an increase in crop yields through technological improvements, and with the selection of less water-intensive crop varieties. It would also be necessary to reallocate irrigated crop production from water-scarce regions to water-abundant regions but with the considerations of externalities. Our analyses show that if trade is not allowed to compensate for crop production losses, it will be more difficult to meet future crop demand while sustaining environmental flows. Increase in trade and trade liberalization is often mentioned as having a negative impact on the environment and on access to food by disadvantaged communities, but our results show that an increase in global trade can also help meet future SDGs in terms of food security and water preservation for the environment. This study also addresses the adaptations required, such as crop shifting, reallocation of land use, and improvement in crop and agriculture management, and the corresponding negative externalities, such as the expansion of rainfed land into natural and forest areas, to meet future food demand and preserve freshwaters. Finally, policies and regulations should encourage climate and socioeconomic adaptation pathways on a regional level in order to anticipate global change and meet food and water requirements for humanity.

Methods

Modelling framework

A modelling framework was developed (Fig. 1, Supplementary Figure Fig. A1) to measure the impact of meeting EFRs on global water use, future crop production strategies and land use allocation. The framework links the Global Biosphere Management Model (GLOBIOM) to a water module fed by runoff and EFRs calculated with the hydrological model LPJmL (more information in Supplementary Figure B).

GLOBIOM model

GLOBIOM is an economic partial equilibrium integrated assessment model that allocates agricultural crops and commodities based on an endogenous price balance between demand and supply. The spatial unit used here for food supply is 2 by 2 deg. and food demand is defined for 30 world regions (Supplementary Figure Table 1). GLOBIOM includes agriculture, bioenergy and forest modules to optimize land-use allocation (Havlík et al. 2014, 2011). The model optimizes food and livestock production at a minimum cost under socioeconomic and biophysical constraints. The baseline year is

2000, and the model is recursively dynamic (10 year time-step). Food demand projections follow the projections from the FAO up to 2030, but the demand is partly endogenous. Regional crop prices vary with food demand, which is driven by population and per capita income. Prices are endogenous to the model and depend on technology, natural resources and consumer preferences. GLOBIOM allows the optimization of land use through several adaptations: reallocation of crops to more productive areas, a shift to crops that are less expensive and demand less input, and a change from extensive rainfed systems to intensive rainfed and irrigated systems (FAO 2016). Yields of 18 crops were simulated with the Environmental Policy Integrated Climate (EPIC) model which is a connected module of the GLOBIOM model (Williams et al. 1989). For further information on model parametrization and yield calculation in the GLOBIOM and EPIC models, refer to the Supplementary Figure B.

Socioeconomic scenarios

Future socioeconomic development, including population, gross domestic product (GDP) and technological change, was based on the Shared Socioeconomic Pathway 2 (SSP2) (O'Neill et al. 2015; Samir and Lutz 2014; Popp et al. 2017). Details on the translation of SSPs into GLOBIOM can be found in Supplementary Tables 3-4. SSPs were developed by a community of scientists and economists over the last 10 years to provide plausible scenarios based on past trends in economic and biophysical drivers. In this study, the SSP2 scenario, known as the middle-of-the-road scenario, assumes moderate adaptation and mitigation challenges, with a medium growth of the population to 9 billion people and a dietary requirement of 3000kcal/person/day based on Food and Agriculture Organization (FAO) projections for 2030 (Samir and Lutz 2014; Kriegler et al. 2012; Fricko et al. 2017). The narrative of the SSP2 scenario is the following: "The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Land use change is incompletely regulated, i.e. tropical deforestation continues, although at slowly declining rates over time. Rates of crop yield increase decline slowly over time, but low-income regions catch up to a certain extent. Caloric consumption and animal calorie shares converge slowly towards high levels. International trade remains to large extent regionalized (O'Neill et al. 2015)."

LPJmL model – hydrological model

Water availability was simulated with the Lund-Potsdam-Jena managed Land model (LPJml), which is a dynamic global vegetation model that simulates water and carbon cycles (Sitch et al. 2003; Dieter Gerten et al. 2004; Rost et al. 2008). The water module was developed with a river routine and the implementation of reservoir operation (Rost et al. 2008; Biemans et al. 2011). Water availability was simulated with LPJmL from 2000 to 2050 at a 0.5° by 0.5° spatial resolution. We calculated average monthly water availability for every 10 year time-step from 2000 to 2050 to be used as an input for GLOBIOM. The mean monthly runoff estimated by LPJmL was redistributed according to the average discharge rates in each river basin to have a good spatial representation of water availability within GLOBIOM (Schewe et al. 2014). Water availability was aggregated from 0.5 deg. to 2 deg. to fit the Land Unit ID (LUID) of GLOBIOM, with a total of 4,845 simulation units. EFRs were calculated with the Variable Monthly Flow (VMF) method (A. V. Pastor et al. 2014) .

Description of Environmental Flow Requirement (EFRs) calculations

Environmental Flow Requirements (EFRs) were estimated using the Pastor et al. (2014) Variable Monthly Flow (VMF) method. The VMF method follows the natural variability of river discharge by adjusting EFRs according to the flow season. The VMF method was designed to improve the protection of freshwater ecosystems during low-flow seasons. In the VMF method, the EFRs are set to 60% of the mean monthly flow during the dry (low-flow) season and 30% during the wet (high-flow) season. Thus, in the simulations in which the VMF method for EFRs is implemented, 40% of the river water is available to other users during the dry season and 70% in the wet season. The VMF method was previously validated with 11 local case studies, where EFRs were calculated based on local ecological and hydrological parameters (Pastor et al. 2014). For the simulations, EFRs were calculated based on the 15 previous years before the year 2000 of simulated natural runoff.

Description of crop yield calculations

Yields of 18 different crops are estimated using the Environmental Policy Integrated Climate (EPIC) model and are adjusted according to GDP (Liu et al. 2007; Williams et al. 1989), Future crop yield projections were based on SSP2 yield assumptions that consider the potential technical advancements in agriculture that could occur under projected growth in GDP (Dellink et al. 2015) based on the econometric relationship between historical yields and GDP growth (Dellink et al. 2015). All crop yield simulations are calculated with and without climate change. The scenarios with climate change assume CO_2 fertilization.

Calibration of annual irrigation demand

The inclusion of water use for irrigation in GLOBIOM builds on the work presented in [1] Sauer et al. (2010) by defining spatially explicit irrigation demand, irrigation source and seasonality of water, as well as examining the impact of climate change. GLOBIOM calibrates spatially explicit water demand for irrigation, Irrigated Water Demand (*IWD)*, in the initial year 2000 using the irrigated cropland area dataset available from SPAM (Liu et al. 2013) and EPIC estimates of crop irrigation water requirements in order to match the FAO AQUASTAT statistics for water withdrawn for irrigation (FAO 2016). For this study, simulations from the GLOBIOM model were adjusted from an annual to a monthly time-step in order to account for the seasonality of water availability and demand.

Calibration of monthly irrigation demand with seasonality

The annual irrigated water demand estimated by EPIC was rescaled to a monthly time-step using a coefficient of seasonal irrigation (CSI) defined for every grid cell. CSI is based on the monthly irrigated water withdrawal from LPJmL via Equation (1).

$$CSI(c,m) = \sum_{i=1}^{m}\left(\frac{mid(c,m)}{aid(c,a)}\right) \quad (1)$$

c is the cell of the LPJmL model, *m* is the month, *mid* is monthly irrigation demand and *aid* is annual irrigation demand. For simulations of the impact of climate change, the annual irrigated water requirements were estimated using EPIC, which considers the potential crop yields while taking into account the local climate (Liu et al. 2007; Williams et al. 1989).

Representation of water sink in GLOBIOM

Water availability is calculated with the LPJmL model as explained in the above section and is entered as an exogenous variable in the GLOBIOM model. GLOBIOM has a fixed amount of available water within a watershed. In each simulation unit, the water can be supplied to industry, households and irrigation in the EXPLOIT scenario and reserved to freshwater ecosystems in the ENV and ENV+ scenarios, if the water is not used, it is stored. If water is not available for allocation, a change in land use will occur. Concerning the INVEST scenario, water is available at the regional scale (and economic scarcity is the main factor determining its use). In this study, we divided irrigation water demand into three categories: irrigation sourced from surface water (SWD), irrigation sourced from groundwater (GWD), and irrigation sourced from non-renewable sources (NR). We used the spatially explicit map of irrigated areas sourced from groundwater from Siebert et al. (2010) to determine the share of IWD sourced from groundwater (Equation 2). Non-renewable withdrawals were calculated as the water deficit that cannot be compensated for by surface water or groundwater in 2000. The amount of water withdrawal from groundwater and nonrenewable sources is assumed to remain constant over time.

$$IWD_{m,lu} = SWD_{m,lu} + GWD_{m,lu} + NR_{m,lu} \quad (2)$$

To determine the irrigation sourced from surface water, we determined the surface water available, under the assumption that agriculture is the residual user of water, behind industry, households, and in certain scenarios, the environment.

Biophysical and economic water scarcity

In the simulations, the biophysical scarcity at the pixel level and the economic scarcity of water from the water supply curve take into account the growing demand for surface water, as well as the effects of climate, including the change in the quantity of surface water available (WA) and the change in the spatially explicit water demand for irrigation (*IWD)*. To calculate the scarcity cost of water, GLOBIOM uses a supply function for the total volume of water withdrawn (the regional-level *IWD*) and a marginal price, which increases as water becomes scarce, as well as the regional, crop, and pixel-specific irrigation costs per hectare developed by Sauer et al. 2010. Future industrial and domestic water consumption was based on Flörke et al. (2013) and Wada et al. (2014). In addition, Environmental Flow Requirements were added to some of the scenarios for the time period and further restrict the water available for agriculture.

Climate-change scenarios

For the climate-change scenarios, LPJmL was run with the bias-corrected output of two commonly used Global Climate Models (MPI-ESM-LR & HadGEM2-A0) using the highest emission scenario (Representative Concentration Pathway, RCP 8.5) (Van Vuuren et al. 2011). Climate-forcing data was extracted from the ISIMIP database (Warszawski et al. 2014; Hempel et al. 2013).

Water management policy scenarios

To measure the impact of EFRs restrictions on future land and water use, agricultural production and trade, four water management policy scenarios were developed, with three levels of restrictions in water use compared to an unlimited water supply scenario:

- The Water Investment Scenario (INVEST or INV) assumes large-scale development of irrigation infrastructure and water reallocation. This scenario assumes that all freshwater within a region can be used and reallocated to optimize irrigation on the basis of economic constraints such as crop demand and does not consider EFRs. In this scenario, water demand and supply is calculated on an annual time-step and water allocation is constrained on a regional scale.
- The Maximum Exploitation Scenario (EXPLOIT or EXP) assumes that all freshwater from rivers and groundwater aquifers can be used up to full depletion in each land unit (2 by 2 deg.). Water use for agriculture is constrained by local water availability and by local water demand from other sectors (industrial and domestic) at a monthly time step. EFRs are not considered. This scenario is referred to as the business-as-usual scenario.
- The Environmental Flow Requirement scenario (ENVIRONMENT or ENV) assumes that water needs to be allocated to the environment first. Water use for irrigation is restricted by water demand from other sectors (industrial and domestic) at the land unit level. EFRs are estimated using the Pastor et al. (2014) VMF method (A. V. Pastor et al. 2014).
- The High Environmental Flow Requirement scenario (ENVIRONMENT+ or ENV+) is the same as ENV, but with 50% greater EFR demand. This scenario tests the sensitivity of the

system to higher EFRs and sets a high priority on attaining good ecological status of the rivers.

All water use restriction scenarios were analyzed with climate change (CC) and without climate change (noCC) (Supplementary Figure Fig. A1).

Description of trade scenarios

We designed trade scenarios to evaluate how markets (through bilateral trade) compensate for water scarcity at local levels caused by biophysical limitations, climate change, and reduced water availability due to EFRs.

- Constrained Trade (Con_T): regional bilateral trade flows are set according to the reference scenario (EXPLOIT without climate change) with SSP2 yield projections and no increases in irrigation use efficiency.

- Unconstrained Trade (Unc_T): regional bilateral trade flows follow the default setup, in which trade is optimized according to bilateral trade policies and assumptions about trade costs.

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Author contributions

Data input preparation, analysis and writing were done by A.V.P., concepts and ideas were developed by all authors, model conceptualization, writing and simulations were performed by A.M.P and A.V.P.

Competing interests

The authors declare no competing interests.

Data availability

The data that support the findings of this study are available from the corresponding author upon request. Correspondence and requests for source data and materials should be addressed to lead author A.V.P. and access to code should be addressed to A.V.P and A.M.P. following institutional rules.

Table 1. Water withdrawal for agriculture (irrigation) under different climate change and water management scenarios.

Scenarios	**noCC**[a*]	**CC** [a*]
Baseline 2000	2516	2516
INV 2050	2983	2911
(% change from baseline 2000)	19	16
EXP 2050	2461	2261
(% change from baseline 2000)	-2	-10
ENV 2050	1774	1561
(% change from baseline 2000)	-30	-38
ENV+ 2050	1440	1219
(% change from baseline 2000)	-43	-52

[a] noCC stands for no climate change, CC stands for climate change

[b] INV stands for INVEST scenario (No water constrain), EXP stands for EXPLOITATION scenario (water limited locally), ENV(+) for ENVIRONMENT(+) scenarios (water constrained locally and by environmental flows)

* The units are $km^3 yr^{-1}$.

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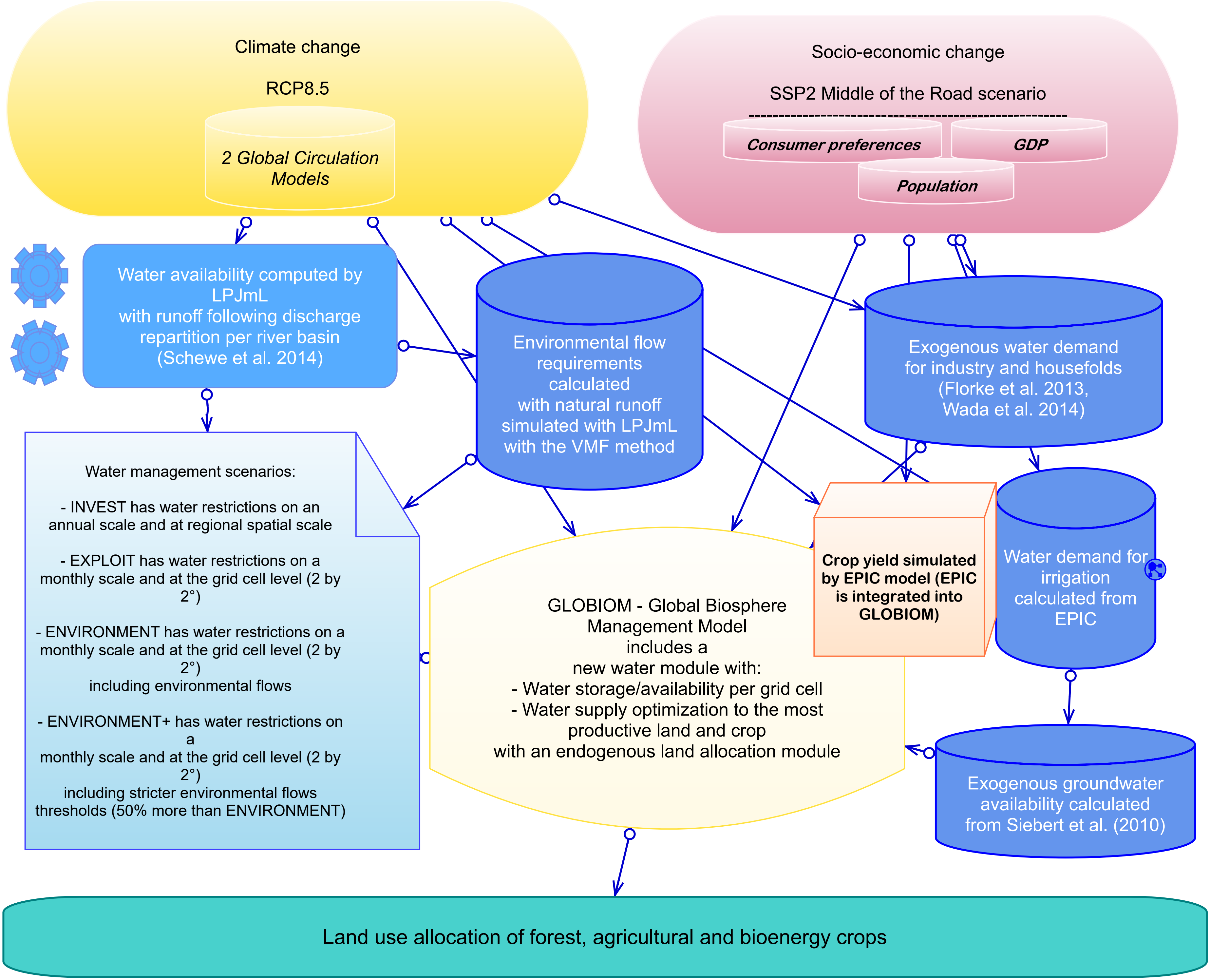


Climate change

RCP8.5

2 Global Circulation Models

Socio-economic change

SSP2 Middle of the Road scenario

Consumer preferences

GDP

Population

Water availability computed by LPJmL with runoff following discharge repartition per river basin (Schewe et al. 2014)

Environmental flow requirements calculated with natural runoff simulated with LPJmL with the VMF method

Exogenous water demand for industry and housefolds (Florke et al. 2013, Wada et al. 2014)

Water management scenarios:

- INVEST has water restrictions on an annual scale and at regional spatial scale
- EXPLOIT has water restrictions on a monthly scale and at the grid cell level (2 by 2°)
- ENVIRONMENT has water restrictions on a monthly scale and at the grid cell level (2 by 2°) including environmental flows
- ENVIRONMENT+ has water restrictions on a monthly scale and at the grid cell level (2 by 2°) including stricter environmental flows thresholds (50% more than ENVIRONMENT)

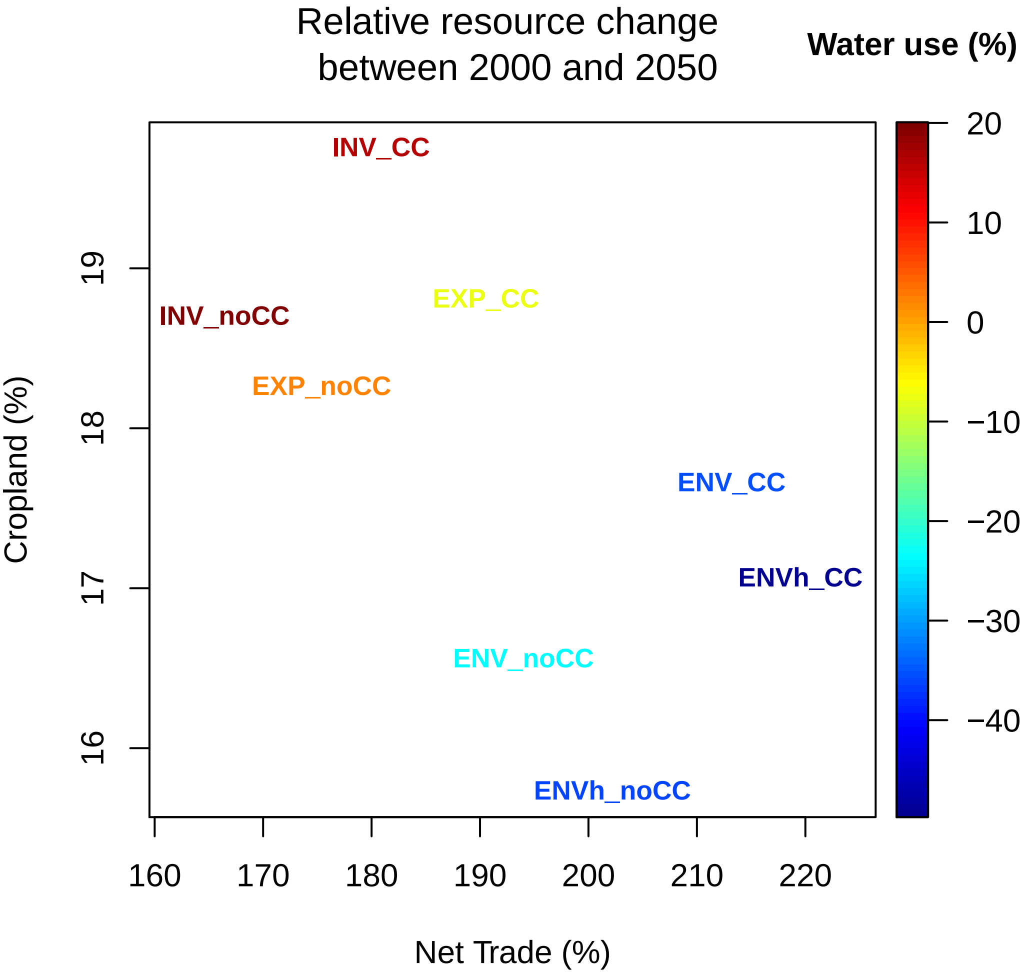
GLOBIOM - Global Biosphere Management Model includes a new water module with:
- Water storage/availability per grid cell
- Water supply optimization to the most productive land and crop with an endogenous land allocation module

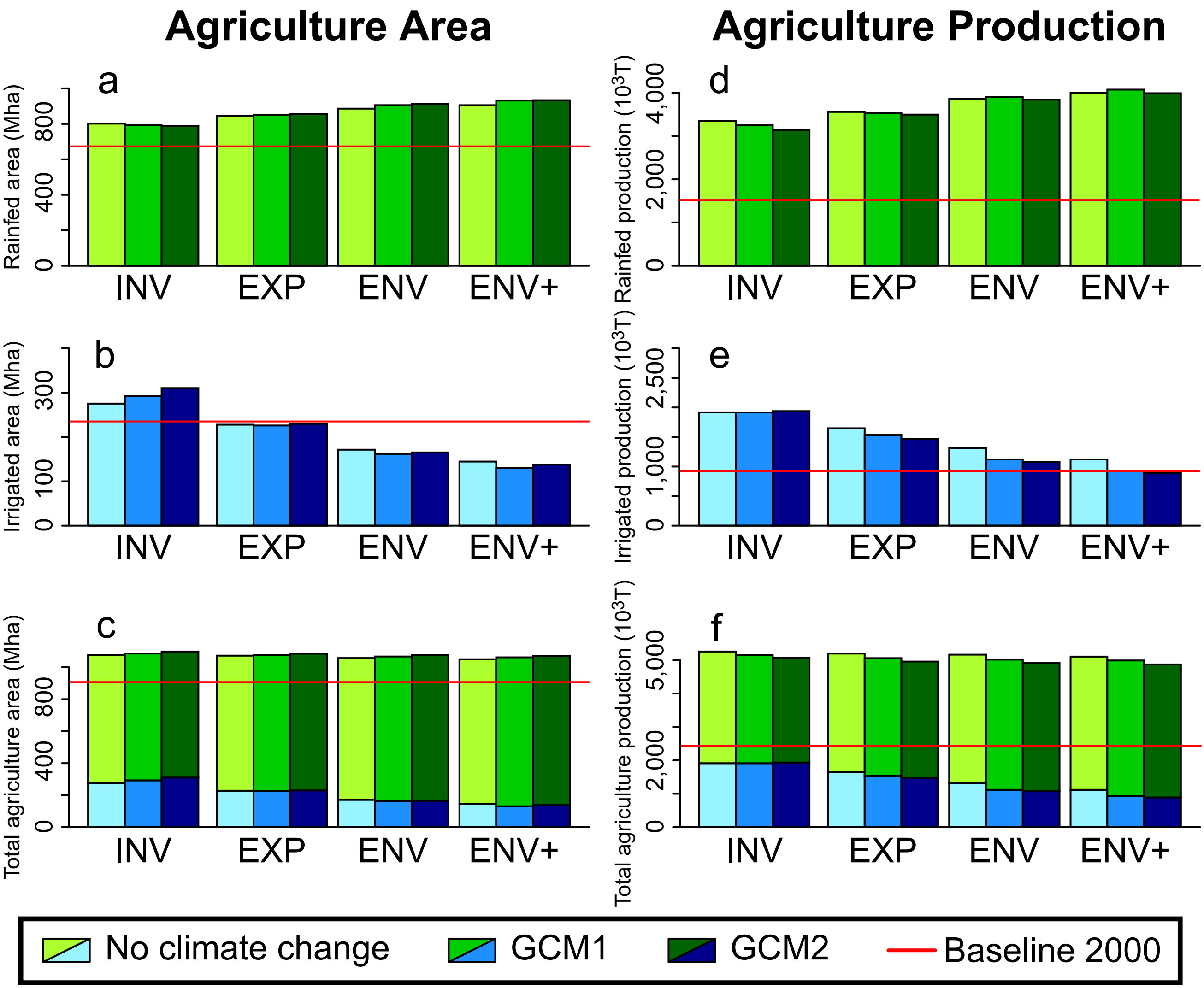
Crop yield simulated by EPIC model (EPIC is integrated into GLOBIOM)

Water demand for irrigation calculated from EPIC

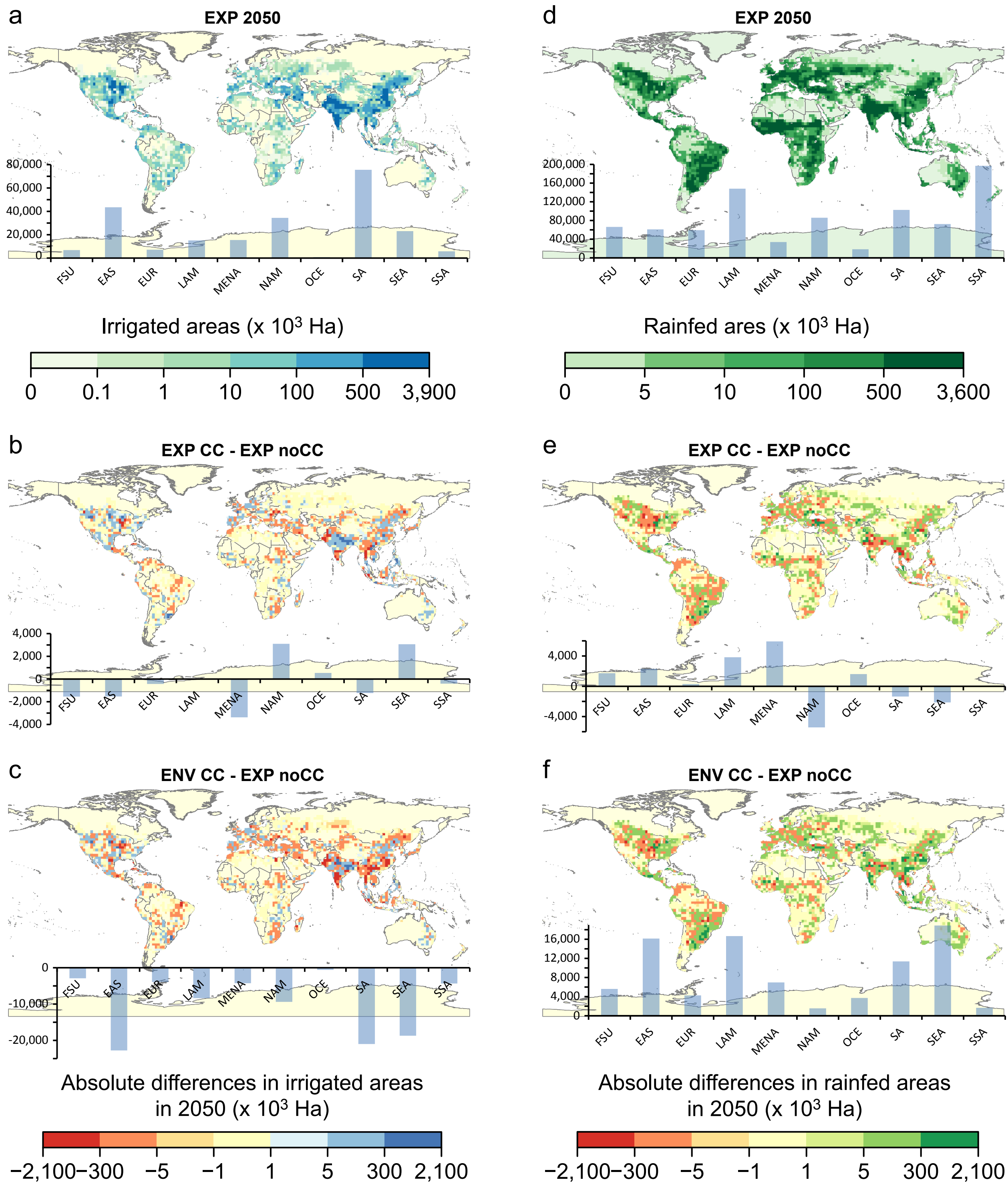
Exogenous groundwater availability calculated from Siebert et al. (2010)

Land use allocation of forest, agricultural and bioenergy crops

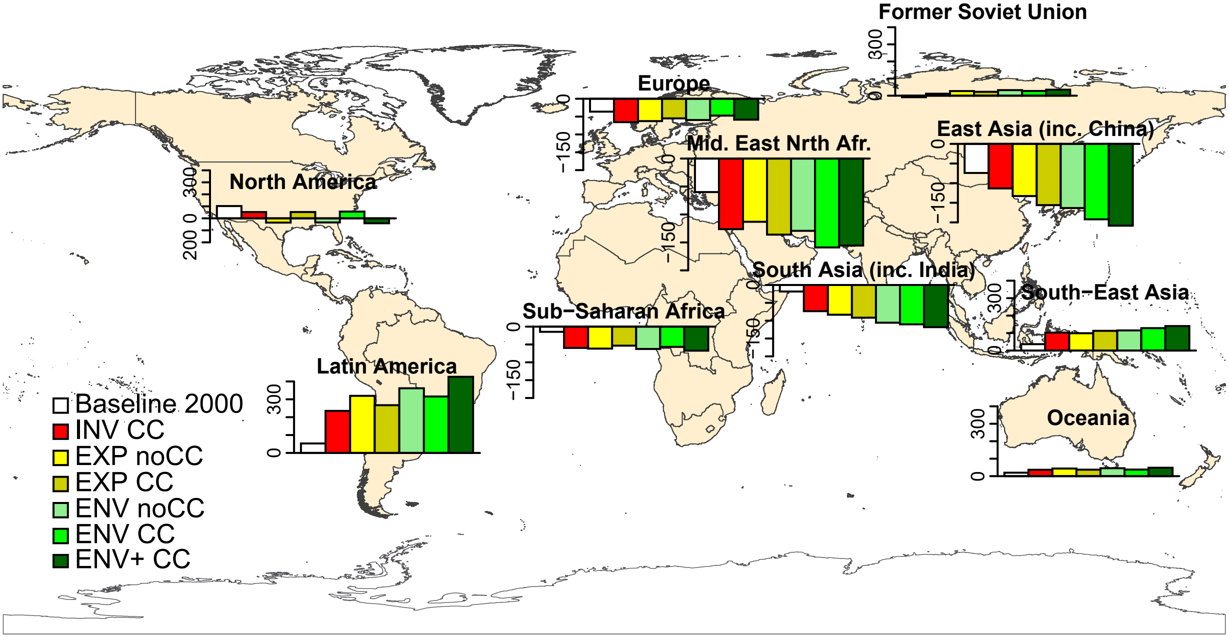

Relative resource change
between 2000 and 2050
Water use (%)
20
10
0
−10
−20
−30
−40
INV_CC
INV_noCC
EXP_CC
EXP_noCC
ENV_CC
ENVh_CC
ENV_noCC
ENVh_noCC
Cropland (%)
19
18
17
16
160
170
180
190
200
210
220
Net Trade (%)



Agriculture Area
Agriculture Production
a
b
c
d
e
f
Rainfed area (Mha)
Irrigated area (Mha)
Total agriculture area (Mha)
Rainfed production (10^3T)
Irrigated production (10^3T)
Total agriculture production (10^3T)
0
400
800
100
300
0
1,000
2,500
2,000
4,000
5,000
INV
EXP
ENV
ENV+
No climate change
GCM1
GCM2
Baseline 2000



a
EXP 2050
80,000
60,000
40,000
20,000
0
FSU
EAS
EUR
LAM
MENA
NAM
OCE
SA
SEA
SSA
Irrigated areas (x 10³ Ha)
0
0.1
1
10
100
500
3,900
d
EXP 2050
200,000
160,000
120,000
80,000
40,000
0
FSU
EAS
EUR
LAM
MENA
NAM
OCE
SA
SEA
SSA
Rainfed ares (x 10³ Ha)
0
5
10
100
500
3,600
b
EXP CC - EXP noCC
4,000
2,000
0
-2,000
-4,000
FSU
EAS
EUR
LAM
MENA
NAM
OCE
SA
SEA
SSA
e
EXP CC - EXP noCC
4,000
0
-4,000
FSU
EAS
EUR
LAM
MENA
NAM
OCE
SA
SEA
SSA
c
ENV CC - EXP noCC
0
-10,000
-20,000
FSU
EAS
EUR
LAM
MENA
NAM
OCE
SA
SEA
SSA
f
ENV CC - EXP noCC
16,000
12,000
8,000
4,000
0
FSU
EAS
EUR
LAM
MENA
NAM
OCE
SA
SEA
SSA
Absolute differences in irrigated areas in 2050 (x 10³ Ha)
−2,100
−300
−5
−1
1
5
300
2,100
Absolute differences in rainfed areas in 2050 (x 10³ Ha)
−2,100
−300
−5
−1
1
5
300
2,100


Former Soviet Union
300
0
Europe
0
−150
North America
300
0
200
Mid. East Nrth Afr.
0
−150
East Asia (inc. China)
0
−150
South Asia (inc. India)
0
−150
South−East Asia
300
0
Sub−Saharan Africa
0
−150
Latin America
300
0
Oceania
300
0
□ Baseline 2000
🟥 INV CC
🟨 EXP noCC
▨ EXP CC
🟩 ENV noCC
🟩 ENV CC
🟩 ENV+ CC