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

Amandine Pastor, A Palazzo, P Havlik, H Biemans, Y Wada, M Obersteiner, P Kabat, F Ludwig

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

A. V. Pastor[1,2,3*], A. Palazzo[1], P. Havlik[1], H. Biemans[4], Y. Wada[1], M. Obersteiner[1], P. Kabat[2,5] and F. Ludwig[2]

In the face of meeting Sustainable Development Goals for the water–food–energy–ecosystems nexus, integrated assessments are a great means to measure the impact of global change on natural resources. In this study, we evaluate the impact of climate change with the representative concentration pathway 8.5 scenario and the impact of socioeconomics with the shared socioeconomic pathway 2 scenario on land use, water consumption and food trade under four water regulation policy scenarios (invest, exploit, environment and environment+). We used the Global Biosphere Management Model and constrained it with water availability, environmental flow requirements, and water use from agriculture, industry and households (simulated using the Lund–Potsdam–Jena managed Land model, Environmental Policy Integrated Climate model and WaterGap model). Here, we show that an increase in land use by 100 Mha would be required to double food production by 2050, to meet projected food demands. International trade would need to nearly triple to meet future crop demands, with an additional 10–20% trade flow from water-abundant regions to water-scarce regions to sustain environmental flow requirements on a global scale.

Global water resources are under increasing pressure due to large-scale water abstraction for human needs[1,2]. 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[3]. By 2050, without major policy interventions, human water use and irrigated areas are expected to increase rapidly due to population growth and an increase in food demands[4–6]. In addition, crop yields are projected to decrease by >80% in some areas under the highest-emission climate scenario[6–9]. Climate change could affect 10–45% of current cereal production, while water scarcity is predicted to increase in the coming decades[6,10,11]. However, CO_2 fertilization and optimized crop production could stabilize and/or increase future crop yields under climate change[12,13]. Freshwater abstraction and river fragmentation can be detrimental to freshwater ecosystems[14], and Jagermeyr et al.[15] showed 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 to address future challenges related to climate change and food security[16–18].

Rising demand for water is likely to increase the pressure on riverine ecosystems[19]. To limit biodiversity loss in riverine ecosystems, EFRs have been defined for many river systems around the globe[20,21]. EFRs are needed, inter alia, to preserve connectivity, supply sediments and nutrients for soil fertility, and replenish groundwater aquifers[22]. 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'[23]. The recently developed variable monthly flow (VMF) method[24] 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 $km^3 yr^{-1}$, which is equivalent to 7% of total runoff (much lower than in previous assessments[25,26]).

Integrated assessment models have been developed to evaluate the interactions between socioeconomic developments, climate change and bioenergy scenarios, and their effects on land-use dynamics[27,28]. Integrated assessment models are classified into computable general equilibrium models and partial equilibrium models[29]. Computable general equilibrium models require general production/cost functions for all sectors, whereas partial equilibrium models involve a more comprehensive description of agricultural technologies. In this study, we used the Global Biosphere Management Model (GLOBIOM)—a partial-equilibrium integrated assessment 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), and investigate the impacts 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. 2 and Supplementary Table 1). Table 1 shows that water use for irrigation increases by 20% between 2000 and 2050 in the invest scenario (the least water-restrictive scenario), while water use decreases by 30–38% by 2050 in the environment and environment+ scenarios (under EFR restrictions). Under the invest scenario, the increase in crop production comes from a large expansion of cropland (50% irrigated and 50% rain fed), assuming large-scale investments in water infrastructure. The invest scenario results in the highest water use and the lowest international trade (Table 1 and Fig. 3). Under the exploit scenario (local water restrictions), the increase in crop production comes mainly from an increase in rain-fed area in Latin America and Southeast Asia (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 environment

[1]International Institute for Applied Systems Analysis, Laxenburg, Austria. [2]Water Systems and Global Change Group, Wageningen University, Wageningen, the Netherlands. [3]Centre for Ecology, Evolution and Environmental Changes, Climate Change Impacts, Adaptation and Modelling, Faculty of Sciences of the University of Lisbon, Lisbon, Portugal. [4]Climate Change and Adaptive Land and Water Management Group, Wageningen University and Research, Wageningen, the Netherlands. [5]World Meteorological Organization, Geneva, Switzerland. *e-mail: amandine.pastor22@gmail.com

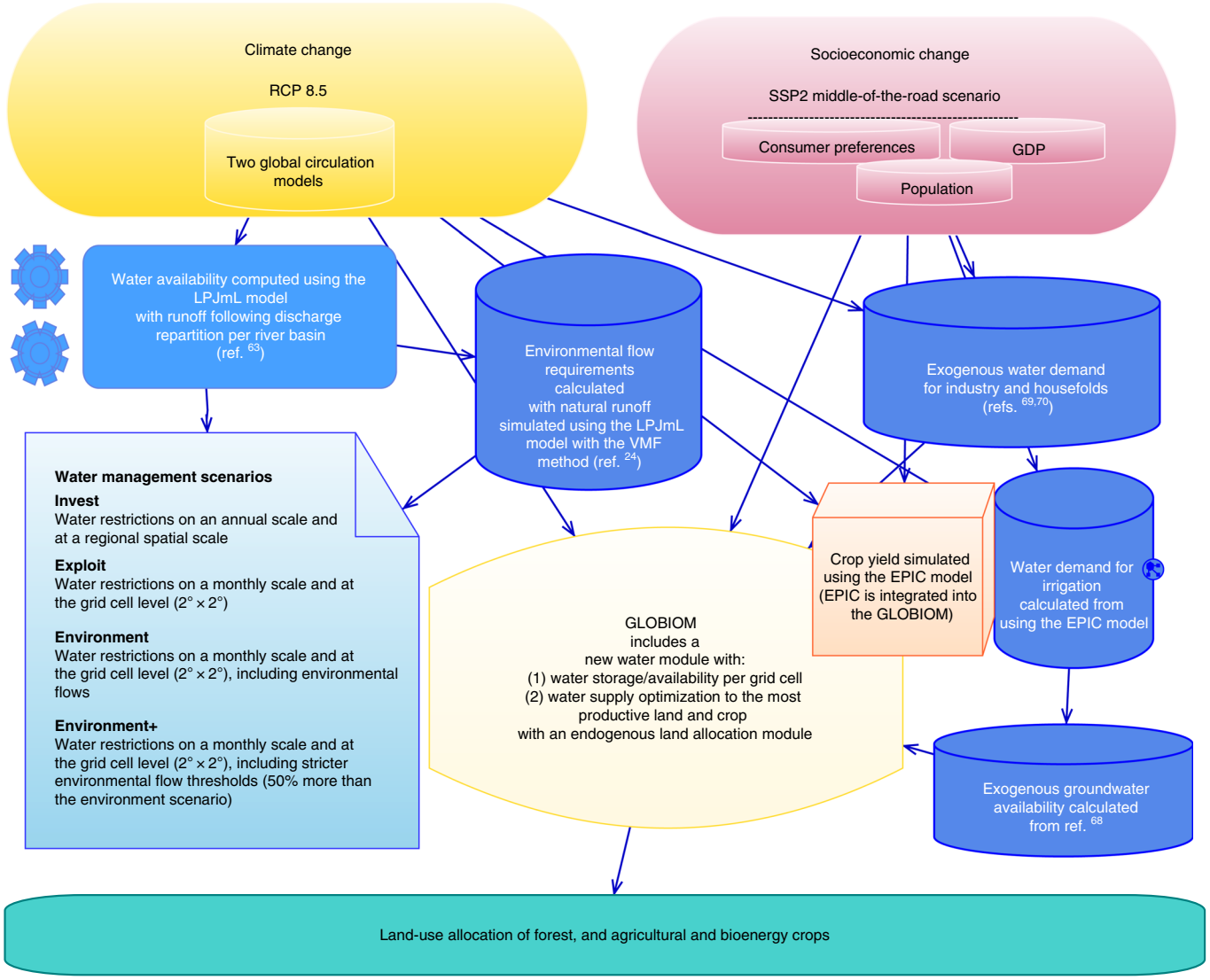

Fig. 1 | Conceptual framework for the inclusion of water dynamics and climate scenarios in the GLOBIOM model. LPJmL, Lund–Potsdam–Jena managed Land.

and environment+ scenarios result in a reduction of irrigated area in China and India by 2050, with a reallocation of cropland in the tropics (Fig. 4 and Supplementary Figs. 3–5). Between 2000 and 2050, international trade would need to nearly triple to meet future crop demands, with an additional 15% to compensate for water restrictions from EFRs (Supplementary Table 5). Crop area would expand from 17–20% in all scenarios, with an increase of high-input rain-fed cropping systems by up to 25% (Fig. 3 and Supplementary Fig. 9). In the ENV scenarios, a conversion of up to 60 Mha of irrigated cropland to rain-fed cropland would be required to meet EFRs (Supplementary Fig. 2).

Future regional changes in land use under water restrictions

In 2050, the increase in agricultural crop production under the invest scenario would be achieved mostly by a 20% expansion of total irrigated and rain-fed crop area (Fig. 4 and Supplementary Table 5), while implementing EFRs (that is, the environment scenario) would imply a regional increase in rain-fed 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 Asia (for example, China) and South Asia (for example, India), while under the environment and environment+ scenarios, by 2050, irrigated area could be reduced from 220 Mha to 161 Mha, mainly in East Asia and South Asia (Fig. 3 and Supplementary Table 5). Climate change alone would lead to an increase in irrigated land in North America and Southeast Asia, including Indonesia, and a decrease in irrigated land in the Middle East and North Africa (MENA) region, as well as an expansion of rain-fed area in Latin America (Fig. 4 and Supplementary Table 5).

Consequences for future crop production

At present, 40% of crop production comes from irrigated areas (Fig. 3 and Supplementary Table 6). We show that by 2050, under EFR restrictions, only 20% of crops could be produced on irrigated land, compared with 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 region 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 and Supplementary Tables 5–7).

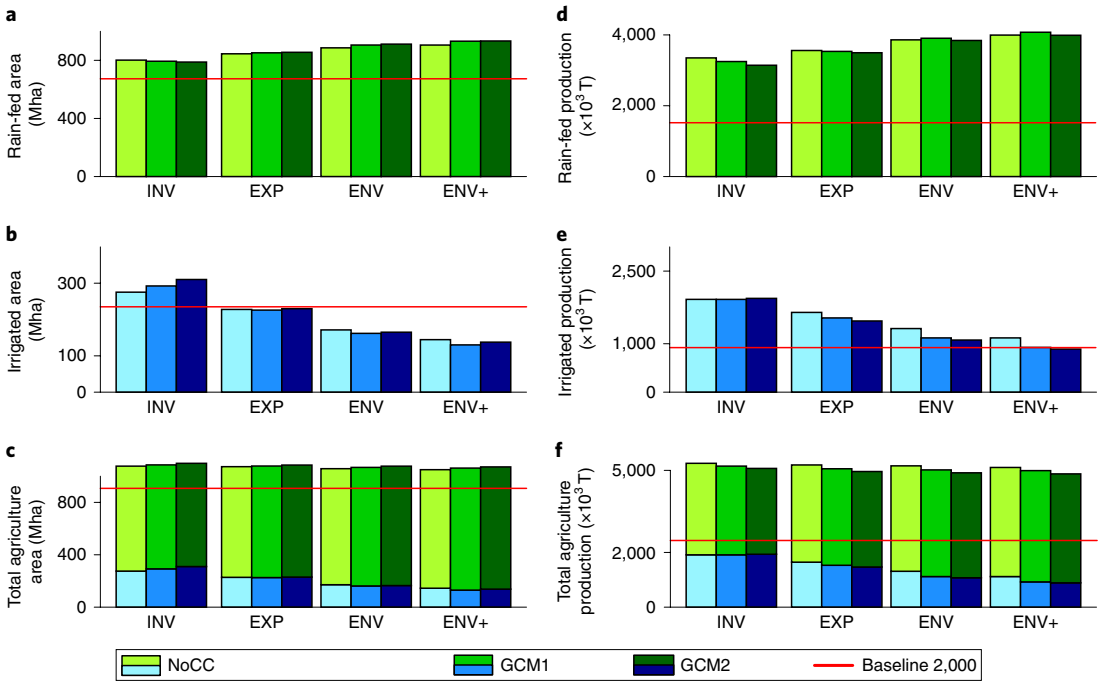

Fig. 2 | Total crop area and production under water management scenarios. **a**–**f**, Global rain-fed crop area (**a**), irrigated crop area (**b**), total agricultural crop area (**c**), rain-fed crop production (**d**), irrigated crop production (**e**) and total crop production (**f**) under four different water management scenarios with increasing restrictions on water availability. Blue shades represent irrigated area and green shades represent rain-fed area.

Pathways to sustain environmental flows

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

International trade by region

The results indicate that bilateral trade needs to increase by: 5% to compensate for climate change alone; 10–13% to compensate for EFRs alone; and 17–20% to compensate for combined climate change and EFRs (Fig. 5 and Supplementary Fig. 5). In general, trade flow increases from water-abundant regions such as Latin America and Southeast Asia to water-scarce regions such as China and the MENA region (Fig. 5). Water-scarce regions need to import more agricultural products under the environment scenarios than under the exploit and invest scenarios (Fig. 5 and Supplementary Figs. 3–5). Climate change further increases imports of agricultural products to China and South Asia (including India), although 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 rain-fed cropland (Supplementary Table 7 and Fig. 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 an increase in food demand, with more than 60% of the increase coming at the expense of forests. In total, 50–60% 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; 12–21% 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 Figs. 2–9 and the Supplementary Data.

Discussion

Our results indicate that, 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 actual deficit in EFRs[15]. In addition to the change in land use, increased inter-regional 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 rain-fed land and a regional reallocation of rain-fed 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 with a business-as-usual scenario (invest). The main increase in exports could come from Latin America (+70%) and Southeast Asia; for example, Indonesia (+22%), while increased dependency on imports would take place mainly in China (+38%), India (+33%) and the MENA region (+19%). In addition, with climate change, we observe that water use for irrigation is lower than

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

Scenarios	NoCC	CC
Baseline 2000	2,516	2,516
INV 2050	2,983	2,911
(% change from baseline 2000)	19	16
EXP 2050	2,461	2,261
(% change from baseline 2000)	−2	−10
ENV 2050	1,774	1,561
(% change from baseline 2000)	−30	−38
ENV+2050	1,440	1,219
(% change from baseline 2000)	−43	−52

All units are in $km^3 yr^{-1}$. NoCC, no climate change; CC, climate change; INV, invest scenario; EXP, exploit scenario; ENV, environment scenario; ENV+, environment+ scenario.

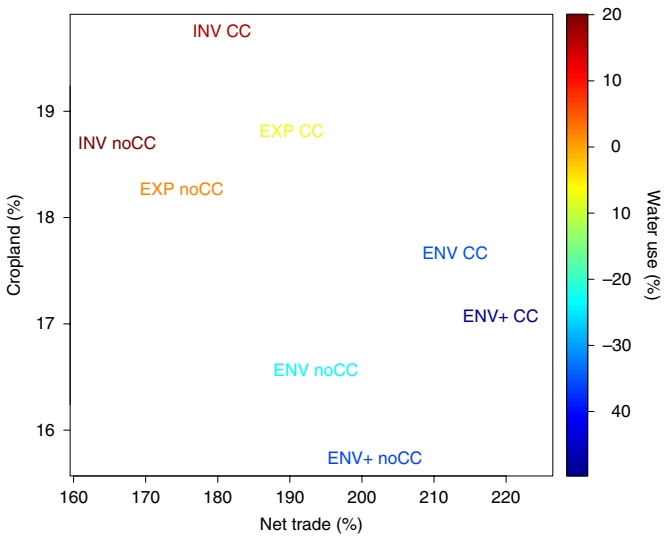

Fig. 3 | Relative percentage changes in land use, water use and trade between 2000 and 2050 under different water management and climate change scenarios. Plots indicate trade-offs between land use, water use and trade. Each scenario follows three directions compared with baseline 2000. Depending on the scenario, trade increases from 200–270% (*x* axis), land use increases from 23–28% (left *y* axis) and water use changes from −60 to +30% (coloured bar).

without climate change (Table 1). This is mainly due to low water availability in water-scarce countries, and the combined increase in water demand for agriculture, industry and households, and EFRs (for the environment and environment+ scenarios). Therefore, in water-scarce regions such as the MENA, the rise in marginal water prices 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 is shown in ref. [30], 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 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 areas 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 Figs. 8 and 9). Tilman et al.[31] 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.[32] 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 the 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 (for example, by using extra nutrients and/or pesticides), which can also have a large impact on freshwater biodiversity[33].

Our results indicate that an increase in trade is necessary to adapt to global change and allocate more water to the environment. Similarly, Dalin and Rodríguez-Iturbe[30] showed that trade can reduce global agricultural water use. In addition, Martinez et al.[34] showed that the 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[35]. However, at present, trade in agriculture is still limited with respect to other commodities due to high freight costs and protective laws and regulations[30,33]. Dalin and Rodríguez-Iturbe[30] 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 (as was the case in 2007) as it can increase food insecurity for the poor and malnourished[36]. Although international trade can help supply food in times of regional shortages, there are also environmental trade-offs such as increasing deforestation and/or agricultural land expansion in Latin America and Southeast Asia. For example, ref. [37] reveals 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 (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 and Supplementary Fig. 5). Currently, both India and China have developed policies for securing food supply through high self-sufficiency ratios[38]. 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[39] in the importing countries and for the 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

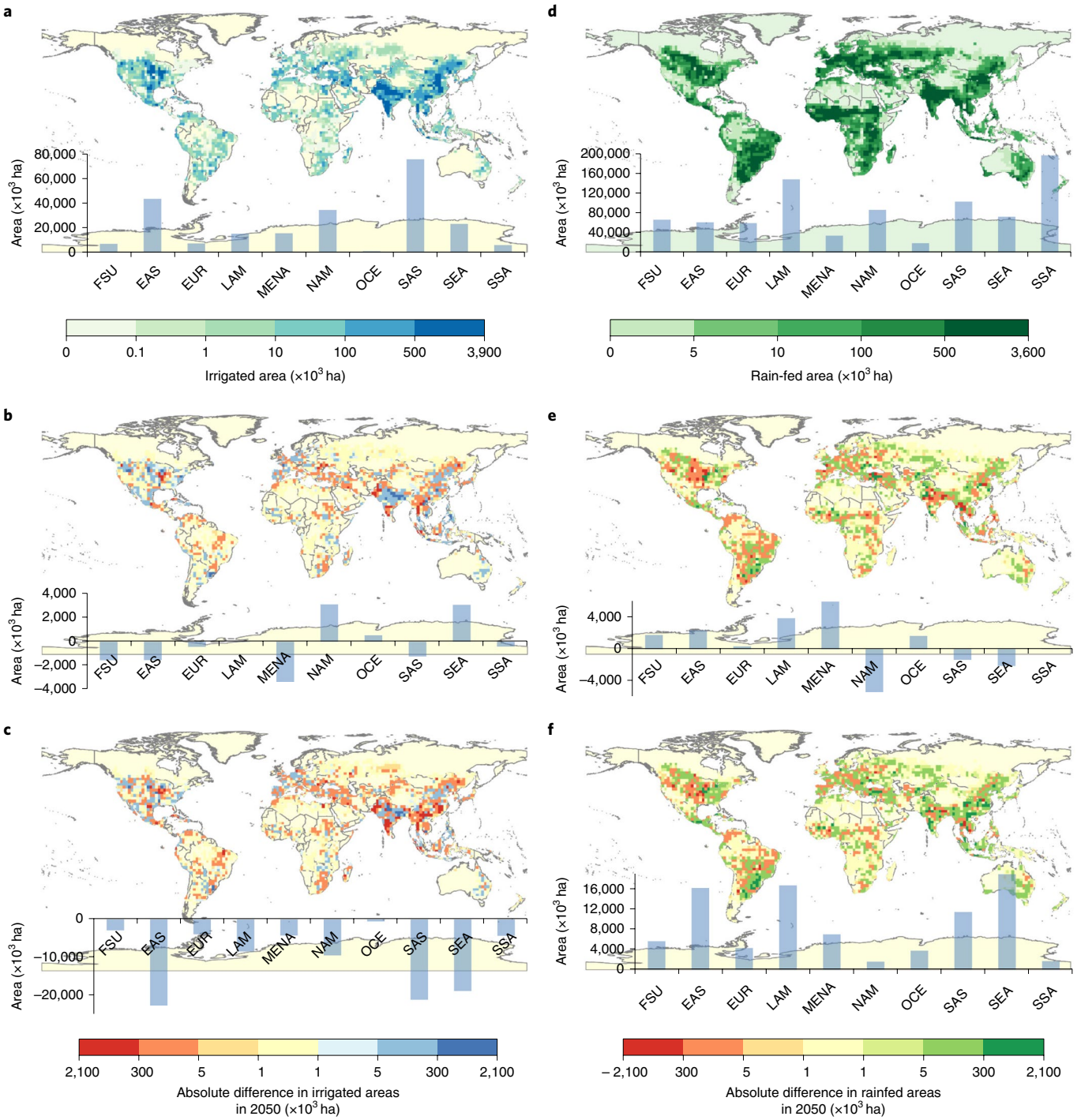

Fig. 4 | Impact of climate change and implementation of EFRs on cropland distribution. a,**d**, Spatial distribution of irrigated (**a**) and rain-fed (**d**) agricultural areas for the exploit scenario in 2050 assuming no climate change. **b**,**e**, Impact of climate change only on the distribution of irrigated (**b**) and rain-fed (**e**) agricultural areas in 2050 (that is, exploit CC minus exploit noCC). **c**,**f**, Combined impact of EFRs and climate change on the distribution of irrigated (**c**) and rain-fed (**f**) agricultural areas (that is, the difference between the environment CC and exploit noCC scenarios). FSU, former Soviet Union; EAS, East Asia; EUR, Europe; LAM, Latin America; MENA, Middle East and North Africa; NAM, North America; OCE, Oceania; SAS, South Asia; SEA, Southeast Asia; SSA, Sub-Saharan Africa.

impact on local agriculture production, local natural resources and the rural economy. In contrast, preserving EFRs can favour 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 the reallocation and loss of terrestrial ecosystems. Alternative solutions must be proposed to compensate for 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 (for example, ref. [40]).

The results show that reaching Sustainable Development Goals on a global scale remains a challenge, especially in the context of the

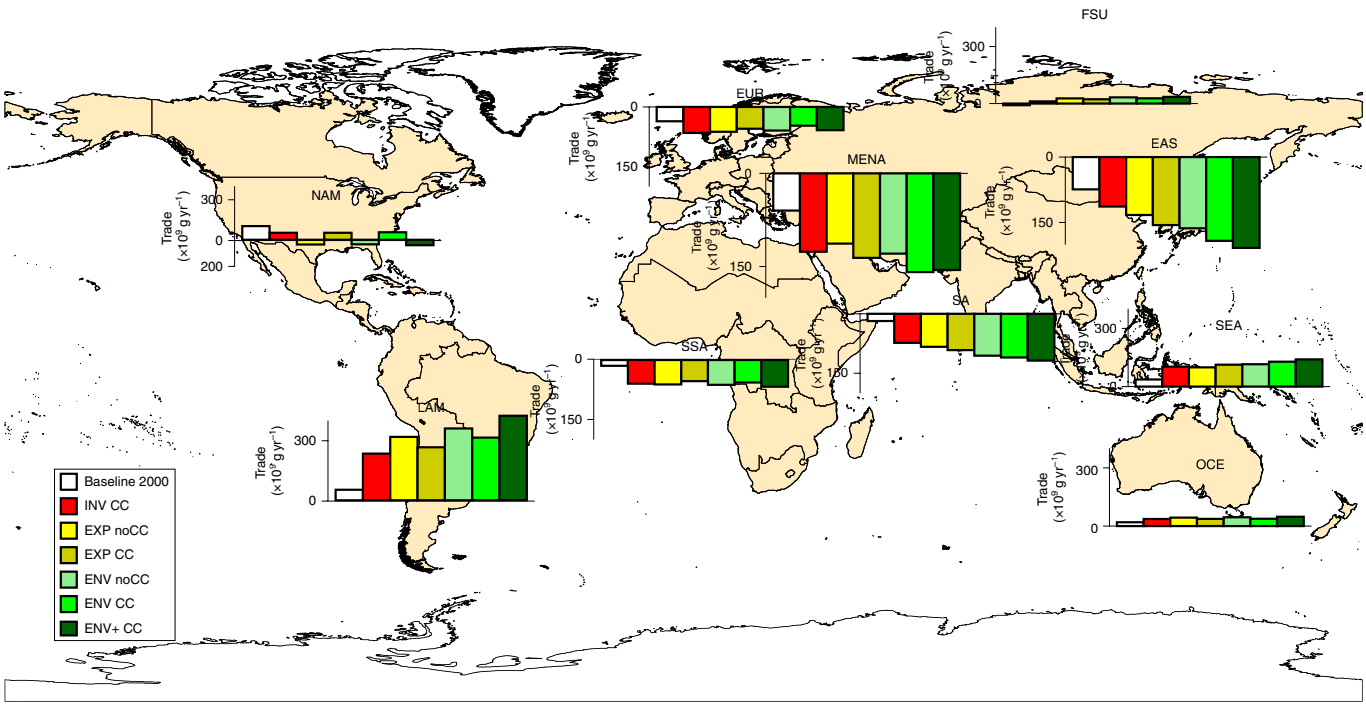

Fig. 5 | Impact of climate change and respective EFRs on net trade in agricultural products. The net trade in terms of crop dry matter for ten global regions under baseline 2000 and the four water management scenarios are shown. Positive numbers indicate net exports and negative numbers indicate net imports of agricultural products.

water–food–energy–ecosystem nexus, in which each component has a target to be respected without compromising the environment[41]. 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[42]. This study highlights how land-use systems could be adapted to meet water and food demands 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 and conversion of irrigated land to rain-fed 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 the model parameters and decreased the uncertainty of our results using multiples models and scenarios. Supplementary Fig. 1 shows the different sources of uncertainty that were tackled in previous studies. In this study, we performed parametric uncertainty analysis by testing the limits of our system to the impacts of: (1) climate change (using the highest-emission scenario: representative concentration pathway 8.5 (RCP 8.5); (2) two different climate models (structural uncertainty; Fig. 3); (3) three levels of water restriction for environmental flows (that is, no restriction, medium and high restrictions (Fig. 3)); and (4) two different trade scenarios (that is, constrained and unconstrained (Supplementary Table 6)). For socioeconomic scenarios, we used shared socioeconomic pathway (SSP2), which is the average scenario. Uncertainties and ranges of socioeconomic scenarios have been addressed in previous studies showing the impact of different SSPs on future land use[43,44]. However, Schmitz et al. (2014) showed that the shift from SSP2 to SSP3 would imply a change of <1% in the total agricultural area in the 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. 3). We also show that 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 Figs. 4–6) on land use. Complementary to refs. [45,46], 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, rain-fed area would be 20% higher than with the SSP2 yield growth assumption (Supplementary Fig. 8). Finally, if we assume that water demand for other users would remain constant between 2000 and 2050 (Supplementary Fig. 8), our results indicate that irrigated area could increase by up to 15% (with a low impact on rain-fed crop area). We also tested the impact of decreasing groundwater storage by 50% (Supplementary Fig. 8) and show that it would decrease the total global irrigated area by about 10%. At the 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 of our scenarios that irrigation use efficiency will increase according to the technological projections of SSP2 (2% per decade); if irrigation use efficiency were to remain constant over the time period (Supplementary Fig. 8), the irrigated area would decrease by 10%. Similar results can be found in ref. [43], which shows that land-use expansion for crop and pasture would respectively increase by 40 and 20% from the baseline year by 2100, and that the crop yield rate increase would range from 0.3–1.2 until 2050, with highly variable change in crop yield due to climate change and a doubling of crop yield due to technological improvement[47] (Supplementary Fig. 6b). We hope that 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[48]. Finally, Springmann et al.[49] showed that the major contribution to mitigating the environmental impacts of

rising food demand is technological improvement (50%), followed by reducing food waste (20%), shifting diet (20%) and finally shifting to the 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 the GLOBIOM and an extension of the intercomparison models designed for the Agriculture Model Intercomparison and Improvement Project[27].

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 Sustainable Development Goals 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 rain-fed 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, to anticipate global change and meet food and water requirements for humanity.

Methods

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

GLOBIOM. The 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°×2°, and food demand is defined for 30 world regions (Supplementary Fig.1). The GLOBIOM includes agriculture, bioenergy and forest modules to optimize land-use allocation[50,51]. 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 steps). Food demand projections follow the projections from the Food and Agriculture Organization (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. The GLOBIOM allows the optimization of land use through several adaptations: the reallocation of crops to more productive areas; a shift to crops that are less expensive and demand less input; and a change from extensive rain-fed systems to intensive rain-fed and irrigated systems[52]. Yields of 18 crops were simulated with the Environmental Policy Integrated Climate (EPIC) model, which is a connected module of the GLOBIOM[53]. For further information on model parametrization and yield calculation in the GLOBIOM and EPIC models, refer to the Supplementary Fig. 1.

Socioeconomic scenarios. Future socioeconomic development, including population, gross domestic product (GDP) and technological change, was based on SSP2[54–56]. Details on the translation of SSPs into the GLOBIOM can be found in Supplementary Tables 3 and 4. SSPs were developed by a community of scientists and economists over the past ten 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 3,000 kcal person^{-1} d^{-1} based on FAO projections for 2030[56–58]. The narrative of the SSP2 scenario is as follows: "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"[54].

LPJmL (hydrological) model. Water availability was simulated with the LPJmL model, which is a dynamic global vegetation model that simulates water and carbon cycles[59–61]. The water module was developed with a river routine and the implementation of reservoir operation[60,62]. Water availability was simulated with the LPJmL model from 2000–2050 at a spatial resolution of 0.5°×0.5°. We calculated the average monthly water availability for every ten-year time step from 2000–2050 to be used as an input for the GLOBIOM. The mean monthly runoff estimated by LPJmL was redistributed according to the average discharge rates in each river basin to allow good spatial representation of water availability within the GLOBIOM[63]. Water availability was aggregated from 0.5–2.0° to fit the land unit ID of the GLOBIOM, with a total of 4,845 simulation units. EFRs were calculated using the VMF method[24].

Description of EFR calculations. EFRs were estimated using the VMF method[24]. 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% is available 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[24]. 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 were estimated using the EPIC model and adjusted according to GDP[53,64]. 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[65] based on the econometric relationship between historical yields and GDP growth[65]. All crop yield simulations were 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 the GLOBIOM builds on the work presented in ref. [66] by defining spatially explicit irrigation demand, irrigation source and seasonality of water, as well as examining the impact of climate change. The GLOBIOM calibrates spatially explicit water demand for irrigation (that is, irrigated water demand (IWD)) in the initial year (2000), using the irrigated cropland area dataset available from SPAM[67] and EPIC estimates of crop irrigation water requirements, to match the FAO AQUASTAT statistics for water withdrawn for irrigation[52]. For this study, simulations from the GLOBIOM were adjusted from an annual to a monthly time step to account for the seasonality of water availability and demand.

Calibration of monthly irrigation demand with seasonality. The annual IWD estimated by EPIC was rescaled to a monthly time step using a coefficient of seasonal irrigation (CSI) defined for every grid cell. The CSI was based on the monthly irrigated water withdrawal from the LPJmL model via equation (1):

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

where c is the cell of the LPJmL model, m is the month, MID is the monthly irrigation demand and AID is the annual irrigation demand. For simulations of the impact of climate change, the annual IWD was estimated using EPIC, which considers the potential crop yields while taking into account the local climate[53,64].

Representation of water sink in the GLOBIOM. After calculating water availability using the LPJmL model, as explained above, the data were entered as exogenous variables in the GLOBIOM. The 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 environment and environment+ 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 ref. [68] 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 non-renewable sources is assumed to remain constant over time:

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

, where m is the month and lu is the land unit at 2° × 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 and the change in the spatially explicit IWD. To calculate the scarcity cost of water, the 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 ref. [66]. Future industrial and domestic water consumption was based on refs. [69,70]. In addition, EFRs 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, the LPJmL model was run with the bias-corrected output of two commonly used global climate models (MPI-ESM-LR and HadGEM2-A0) using the highest-emission scenario (RCP 8.5)[71]. Climate-forcing data were extracted from the ISIMIP database[72,73].

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

(1) The invest scenario 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 are calculated on an annual time step, and water allocation is constrained on a regional scale.
(2) The exploit scenario assumes that all freshwater from rivers and groundwater aquifers can be used up to full depletion in each land unit (2°×2°). Water use for agriculture is constrained by local water availability and 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.
(3) The environment scenario 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 VMF method[24].
(4) The environment+ scenario is the same as the environment scenario, 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 analysed with and without climate change (Supplementary Fig. 1).

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.

(1) Under the constrained trade scenario, regional bilateral trade flows are set according to the reference scenario (exploit scenario without climate change) with SSP2 yield projections and no increases in irrigation use efficiency.
(2) Under the unconstrained trade scenario, regional bilateral trade flows follow the default setup, for which trade is optimized according to bilateral trade policies and assumptions about trade costs.

Data availability

The data that support the findings of this study are available from the corresponding author on request. General correspondence and requests for source data and materials should be addressed to A.V.P. Requests for access to code should be addressed to A.V.P and A.P. (palazzo@iiasa.ac.at) following institutional rules.

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Author contributions

A.V.P. and A.P conceptualized the model, wrote the Methods section and performed the model simulations. All authors developed the concepts and ideas. A.V.P. prepared the data input, performed the data analysis and wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to A.V.P.

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