Economically Efficient and Environmentally Sustainable Irrigation Potentials: a Spatially Explicit Global Assessment

Felicitas Dorothea Beier[1], Benjamin Leon Bodirsky[1], Jens Heinke[1], Kristine Karstens[1], Jan Philipp Dietrich[1], Christoph Müller[1], Fabian Stenzel[1], Patrick José von Jeetze[1], Alexander Popp[1], and Hermann Lotze-Campen[1]

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Abstract

To satisfy increasing global agricultural demand, the expansion of irrigation is an important intensification measure. At the same time, unsustainable water abstractions and cropland expansion pose a threat to biodiversity and ecosystem functioning. Irrigation potentials are influenced by local biophysical irrigation water availability and competition of different water users. Because water abstractions for various human uses along the river divert the river flow, it is also important to consider competing water uses when estimating irrigation potentials. Using a novel river routing routine that considers economic criteria of water allocation via a productivity ranking of grid cells and both land and water sustainability criteria, we estimate global irrigation potentials at a halfdegree spatial resolution. We show that there are considerable potentials to expand irrigation without harming the environment, but not necessarily at the places where irrigation is taking place today. In terms of potentially irrigated areas on current cropland, 711 Mha could be sustainably irrigated when only considering biophysical criteria. Of these, only 254 Mha have a yield value gain of more than 500 USD/ha and would be economically viable to be irrigated. The open-source data processing routine is a valuable aggregation and disaggregation tool for the use of hydrological inputs within land-system models that do not have a highly resolved representation of land use. The potentials can be aggregated to different simulation level units (e.g. basin level or country level) while maintaining biophysical and economic consistency.

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Key Points:

- We find considerable potential to sustainably expand irrigation, but not necessarily in currently irrigated areas
- Our data processing routine provides a hydrological input aggregation tool to global land-system models
- Globally, 476 Mha of all suitable agricultural land could be economically efficiently and sustainably irrigated

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Abstract

To satisfy increasing global agricultural demand, the expansion of irrigation is an important intensification measure. At the same time, unsustainable water abstractions and cropland expansion pose a threat to biodiversity and ecosystem functioning. Irrigation potentials are influenced by local biophysical irrigation water availability and competition of different water users. Because water abstractions for various human uses along the river divert the river flow, it is also important to consider competing water uses when estimating irrigation potentials. Using a novel river routing routine that considers economic criteria of water allocation via a productivity ranking of grid cells and both land and water sustainability criteria, we estimate global irrigation potentials at a 0.5 °spatial resolution. We show that there are considerable potentials to expand irrigation without harming the environment, but not necessarily at the places where irrigation is taking place today. In terms of potentially irrigated areas on current cropland, 711 Mha could be sustainably irrigated when only considering biophysical criteria. Of these, only 254 Mha have a yield value gain of more than 500 USD ha^{-1} and would be economically viable to be irrigated. The open-source data processing routine is a valuable aggregation and disaggregation tool for the use of hydrological inputs within land-system models that do not have a highly resolved representation of land use. The potentials can be aggregated to different simulation level units (e.g. basin level or country level) while maintaining biophysical and economic consistency.

Plain Language Summary

Irrigation plays an important role for food production. Global crop demand is expected to grow due to the growing world population and increasing role of bioenergy to avoid climate change. Irrigation can contribute to meet this increasing demand by facilitating higher yields per hectare of agricultural land. In this study, we quantify areas across the globe that can be irrigated given economic and environmental constraints. We determine how much area and which areas can be irrigated globally given local water availability; how much of these can be irrigated sustainably; and what is the economic benefit of irrigation in different locations. We find that 2492 Mha of all land that is suitable for agricultural production could be irrigated. 1578 Mha could be irrigated sustainably. In reality, many of these areas might not be irrigated for economic reasons. Where the gain through irrigation is small, farmers might not install irrigation equipment. In our estimation, only 682 Mha would be irrigated when considering economic constraints; 476 Mha of these could be irrigated sustainably.

1 Introduction

Irrigation plays an important role for global food production (Foley et al., 2011; Ringler & Zhu, 2015), and the expansion of irrigation is an important intensification measure to satisfy the increasing global demand for agricultural outputs (Keating et al., 2014). The further growing world population (United Nations et al., 2019) will go hand in hand with rising absolute food demand (Bodirsky et al., 2020). At the same time, food demand in developing and emerging economies is expected to grow and shift to an increasingly land- and water-intensive diet (Tilman & Clark, 2014; Ringler & Zhu, 2015; Bodirsky et al., 2020). Additionally, with the increasing role of bioenergy crop production for climate change mitigation, competition for land and water resources between the food and bioenergy sector is rising (Klein et al., 2014; Bonsch et al., 2016; Stenzel, Gerten, & Hanasaki, 2021). Irrigation can contribute to closing the yield and demand gap by producing higher agricultural outputs per hectare (Foley et al., 2011; Mueller et al., 2012; Rosa et al., 2018).

A defining question of our time is how human demands can be satisfied within environmental and economic limits (Rockström et al., 2009; Rosa et al., 2018; Soergel et al., 2021). In many parts of the world, irrigation relies on unsustainable withdrawals (Wada & Bierkens, 2014) and taps environmental flows necessary to maintain aquatic and riverine ecosystem functioning (Jägermeyr et al., 2017). Human water abstractions divert river flows and affect downstream availability (Wada, van Beek, et al., 2013; Veldkamp et al., 2018). Economic productivity and profitability are central decision criteria for the allocation of water to different uses within a river basin. To account for economically viable irrigation water use, the potential yield value gain through irrigation, capturing the marginal return to irrigation, can be used to project potential water abstractions along the river under consideration of economic aspects. A global quantification of economic irrigation potentials considering land- and water-sustainability criteria in terms of potential irrigation water use (withdrawals and consumption) as well as potentially irrigated areas is useful to address various sustainability challenges of the land system (e.g., how to feed a growing population without transgressing planetary boundaries (Gerten et al., 2020); trade-offs between climate targets and other sustainability dimensions with regards to biomass production (Stenzel, Greve, et al., 2021); how to close the yield gap without violating environmental flow requirements (Rosa et al., 2018).

Global land-system models (LSMs) address such questions and use water availability data from hydrological models as input, constraining irrigated crop production and non-agricultural water abstractions (e.g., Calzadilla et al. (2010); Biewald et al. (2014); Liu et al. (2017)). However, they usually lack a hydrologically-founded spatial representation of the interaction of water availability, potential cropland area, water abstractions, and the accompanying upstream-downstream effects. For data availability and computational reasons, especially global-scale optimization models assessing optimal land-use patterns under environmental constraints run at an aggregated scale of spatial clusters, nations or world regions (e.g., Pastor et al. (2019); Dietrich et al. (2019); Woltjer and Kuiper (2014)). When different data sets are aggregated independently, their interaction is lost. For example, despite sufficient water and cropland availability in the aggregated cluster, the suitable land might not be close enough to the water source for irrigation. To avoid a misrepresentation of irrigation potentials in LSMs, spatially explicit irrigation dynamics - including upstream-downstream relationships - should be taken into account in the aggregation of water-related input data, and can be useful also for the disaggregation of land-use outputs provided by these models back to a finer resolution.

Our global open-source spatially explicit (0.5 °resolution) hydro-economic data processing routine allocates irrigation water abstractions based on a productivity ranking. Moreover, it considers competition by upstream water consumption and downstream water withdrawals to determine local water availability, considering also other (human and environmental) water uses. It takes both biophysical conditions as well as economic criteria into account to derive gridded potential irrigation water (PIW) as well as potentially irrigated areas (PIA). These can be used to derive marginal PIA curves at aggregated levels, such as river basins or national territories. To account for aspects of land and water sustainability, we include scenarios that limit irrigation water withdrawals to maintain minimum environmental flow requirements and prevent irrigation in areas of ecological importance to safeguard aquatic and riverine ecosystems.

To the best of our knowledge, no global-scale study exists that determines (sustainable) irrigation potentials while considering biophysical and economic suitability criteria and their spatially explicit interaction. Previous approaches quantifying irrigation potentials and sustainable irrigation water use focused solely on current cropland and irrigation expansion into currently rainfed areas. D'Odorico et al. (2020) assess the value of irrigation water in a global biophysical framework at a 0.08 °resolution based on the additional agricultural output achieved through irrigation. However, they do not derive irrigation potentials or economic irrigation potential curves from this valuation and do not take cropland expansion into account. Rosa, Chiarelli, Rulli, et al. (2020) introduce the concept of economic water scarcity to quantify the additional potential global agricultural production that is achievable focusing on biophysical water availability. They do not assess whether it would actually be profitable to irrigate these areas and only include existing cropland areas. Rosa, Chiarelli, Sangiorgio, et al. (2020) derive biophysical irrigation potentials in currently rainfed cropland at a 0.5 °resolution. However, they neither provide information on potentials under cropland expansion nor take economic considerations for the allocation of potential irrigation water abstractions including their downstream effects into account. Since LSMs provide future projections of land-use change and global crop production, it is important that irrigation water availability and irrigation potentials are provided for both current and potential cropland. Previous approaches estimating irrigation water demand curves have been focusing on selected countries, basins or even sub-basins and derived irrigation water demand based on mathematical programming models (e.g., Moore and Hedges (1963); Scheierling et al. (2004); Manos et al. (2009)), econometric models (e.g., Davidson and Hellegers (2011); Hendricks and Peterson (2012)) or adjusted contingent valuation approaches (e.g., Storm et al. (2011)). Due to a lack of data, these approaches are not suitable for global scale analyses.

To illustrate the outcome of our hydro-economic data processing routine, we address the research questions: How much area can be irrigated given spatially explicit environmental and human uses on current cropland and on potential cropland, considering upstream-downstream relationships and environmental and human uses along the river? What is the economic benefit of irrigation on currently irrigated areas; on potentially irrigated current cropland areas; and on potential cropland under cropland expansion? How would these potentials be reduced if water and land use were sustainable?

2 Methodology

Our method aims at providing economic potentials for irrigated area, water withdrawals and consumption on current and potential cropland. To account for the upstream-downstream effects of water abstractions for reserved (environmental and human) water uses along the river, we developed a river routing routine for water flows and water abstractions. It comprises two main calculation steps (see figure 1): (1) the Reserved Water Use Accounting (see section 2.1) and (2) the River Basin Surplus Discharge Allocation Algorithm (see 2.2). Our approach relies on an unequivocal relationship between water use in one cell and reduced water availability in downstream cells. These relationships can only be established when impacts on the temporal distribution of water as well as effects of storage and transport duration are ignored. Therefore, the river routing is based on a spatial water balance approach with 30-year average water flows.

All hydrological inputs (yearly runoff, monthly discharge, evaporation from water bodies) as well as yields and crop water requirements are provided by the Lund–Potsdam–Jena

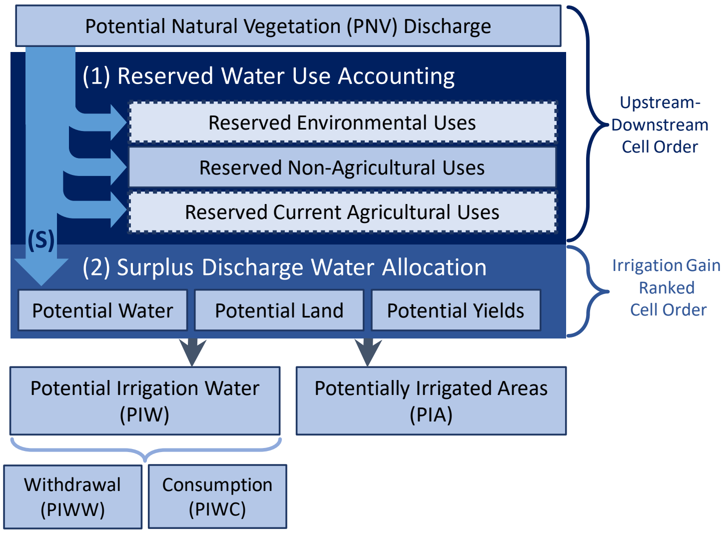

Figure 1. River routing iteration structure to determine Potential Irrigation Water, PIW (in $km^3\,yr^{-1}$), and Potentially Irrigated Areas, PIA (in $Mha\,yr^{-1}$). Calculation steps include the Potential Natural Vegetation Discharge initialization river routing, the Reserved Water Use Accounting consisting of three (partially optional) upstream-downstream river routings; and the allocation of the river basin's surplus discharge (S) based on an irrigation yield value gain cell-ranking determining the calculation order of cells. The river basin's surplus discharge (S) is the discharge of the estuary cell that is not (yet) consumed along the river in the last Reserved Water Use Accounting river routing and is available as potential water for additional irrigation within the river basin. Scenario-dependent optional iterations are indicated with a dashed box.

dynamic global vegetation model with managed Land (LPJmL). It comprises a spatially explicit representation of crop growth dynamics as well as the hydrological cycle and operates at a daily resolution (Schaphoff et al., 2018; von Bloh et al., 2018). LPJmL simulates the terrestrial water cycle considering the daily soil water balance and evapotranspiration; a river routing routine at 3-hourly temporal scale; and a human water use representation (including non-agricultural water demand, irrigation water demand as well as seasonal water availability effects of dams and reservoirs) as described in Gerten et al. (2004), Rost et al. (2008), Biemans et al. (2011) and Schaphoff et al. (2018). Because non-agricultural and irrigation water use are explicitly modeled in our river routing routine, human consumptive water use is not considered in the LPJmL simulations used for this analysis. For a detailed LPJmL model description including specific modeling assumptions and the model versions used in this model, see Supplementary Information (SI) section 1.

To initialize river discharge (see figure 1), we derive the 'potential natural vegetation (PNV) discharge' (q^{PNV}, see equation 1).

$$\begin{aligned} q_c^{PNV} &= in_c + r_c - e_c \\ in_c &= \sum_{up} q_{up}^{PNV} \end{aligned} \tag{1}$$

where in_c is the inflow into cell c from its direct upstream neighbor cells up; r_c is runoff on cell c; and e_c lake evaporation in cell c. PNV discharge refers to discharge under potential natural vegetation ignoring the influence of anthropogenic effects on discharge. To this end, we use runoff and lake evaporation provided by a simulation of runoff with LPJmL4 (Schaphoff et al., 2018) for a hypothetical 100 % potential natural vegetation only setup with current climate forcing data from the Global Soil Wetness Project Phase 3 (GSWP-3) data set (Kim, 2017) homogenized to W5E5 (Cucchi et al., 2020; Lange et al., 2021; Lange, 2019). Runoff is the surplus water that cannot be stored in the soil column, after accounting for losses from evapotranspiration. To determine lateral flows of discharge from the most upstream grid cell to the next up to the estuary, we use the flow direction and stream order of halfdegree grid cells of the global STN-30p drainage network (Vörösmarty et al., 2011); (see also Vörösmarty et al. (2000), Vörösmarty et al. (2011), and Lehner et al. (2011) for a data set description). It is the same drainage network that is used in the LPJmL simulations used here and is therefore consistent with our hydrological inputs (von Bloh et al., 2018). The underlying land mask used in our study is the 0.5 °high-resolution gridded land mask provided by the Climate Research Unit (CRU (Harris et al., 2014, 2020)).

2.1 Reserved Water Use Accounting

Following the determination of PNV discharge, water volumes are reserved for certain uses (see figure 1), giving priority to environmental flows (for sustainability scenarios only) over human uses; and giving priority to non-agricultural human uses over agricultural water uses. In the process of reserving specific water volumes, cellular discharge is adjusted in every iteration of the respective river routing. The reservation of water volumes is limited by local water availability. Water uses that exceed this amount are not reserved. In terms of human water uses, we differentiate water withdrawals and water consumption (see section 2.3 for a detailed description of the withdrawal and consumption constraints). We define water consumption as the total irrigation water volume incorporated into the plant or evaporated to the atmosphere during the growing period (including evaporative transport losses). Withdrawal refers to the water volume diverted from water bodies. Withdrawals that are not consumed are returned to the river in the same grid cell (return flow) (Jägermeyr et al., 2015).

Environmental flow requirements (EFR) - i.e. the minimum flow to maintain the aquatic and riverine ecosystem in a 'fair condition' (Smakhtin et al., 2004) - are reserved to prevent unsustainable human water abstractions in the sustainability scenarios (see section 2.5). EFR are calculated using the variable monthly flow method (VMF) method (Pastor et al., 2014). Because the calculation of EFR requires information on timing and variability of discharge, we use monthly PNV discharge calculated by the temporally highly resolved river routing routine of LPJmL4 (Schaphoff et al., 2018). The monthly EFR are then aggregated to yearly values, which is the temporal scale of our river routing routine. For the full EFR methodology applied in this study, see SI section 4.

Non-agricultural water uses are prioritized over agricultural uses (see figure 1), because domestic and industrial water uses usually have a higher marginal return compared to agricultural water use (United Nations, 2021). Similar assumptions are also made in several global economic optimization models (Bonsch et al., 2016; Pastor et al., 2019; Robinson et al., 2015; Baldos et al., 2020). Non-agricultural annual water withdrawals and consumption for domestic and industrial uses are provided by the Inter-Sectoral Impact Model Intercomparison Project (version ISIMIP3b (2020)) input data for the historical period for the years 1901 to 2014. These data are a multi-model average provided by the Water Futures and Solutions project (Wada et al., 2016). Because of a lack of spatially explicit data, we do not include water consumption by livestock. With around 1-2 % of total water use, it is negligible (United Nations, 2021).

Cellular irrigation water withdrawals and consumption are calculated based on blue water consumption requirements of crops as provided by LPJmL5 (von Bloh et al., 2018; Lutz et al., 2019) and the current grid cell specific crop mix as well as irrigated areas. Irrigated areas are derived from national crop harvesting data from FAOSTAT (FAO, 2021) and grid cell specific irrigated and rainfed cropland area shares from LUH2 (Hurtt et al., 2019, 2020) (see SI section 3 for more details). Water withdrawals further depend on the irrigation efficiency of the irrigation system in use. We take country-specific irrigation system shares for surface, sprinkler and drip irrigation as provided by Jägermeyr et al. (2015) assuming the same irrigation system mix for all modeled crops. For simplicity, we assume global average irrigation efficiencies for each of the three irrigation systems. Conveyance efficiency (i.e. the percentage of irrigation water diverted from water bodies that reaches the field (Jägermeyr et al., 2015) is assumed to be 70 % for open canals (surface), and 95 % for pipes (sprinkler and drip) following Schaphoff et al. (2018) and Jägermeyr et al. (2015). Field efficiencies (i.e. the percentage of irrigation water applied to the field that is consumed (Jägermeyr et al., 2015) of 52 % (surface), 78 % (sprinkler) and 88 % (drip) are taken from Jägermeyr et al. (2015). For further details see SI section 3.

After having accounted for the reserved water uses, the river basin 'surplus discharge' (see (S) in figure 1) can be determined. It is the discharge of the estuary cell that is not (yet) consumed along the river after the Reserved Water Use Accounting and can potentially be used for additional irrigation in the respective grid cells with available discharge or their downstream cells.

2.2 River Basin Surplus Discharge Allocation Algorithm

The surplus discharge determined in the Reserved Water Use Accounting is distributed within the basin to cells with sufficient water availability based on a ranked cell ordering. For this purpose, the potential yield value gain through irrigation is calculated considering the current crop mix of the year 2010 as derived from FAO country statistics and current globally averaged agricultural crop prices reported by FAO (FAO, 2021) (see equation 2). Similar to D'Odorico et al. (2020), the valuation of water as an economic input is based on the yield difference between irrigated and rainfed crops within the same grid cell valued at FAO prices representing the monetary return from irrigated as opposed to rainfed crop production.

$$\Delta z_c = \sum_k s_{c,k} \cdot (y^{ir}_{c,k} - y^{rf}_{c,k}) \cdot p_k \tag{2}$$

where Δz_c is the potential yield value gain through irrigation (in USD ha^{-1}) in cell c; $s_{c,k}$ is the share of crop k in cell c; $y^{ir}_{c,k}$ ($y^{rf}_{c,k}$) are irrigated (rainfed) yields of crop k in cell c (in tons of dry matter (tDM) per hectare); and p_k is the global average price of crop k (in USD tDM^{-1}).

Spatially explicit irrigated and rainfed crop yields are provided by LPJmL5 (von Bloh et al., 2018; Lutz et al., 2019). To be consistent with FAOSTAT production, we calibrate LPJmL yields to meet FAO country yields (FAO, 2021) by using a multiplicative factor. The calibration accounts for country-specific management effects on yields, such as fertilizer and pesticide use, different crop varieties and mechanization as well as cropping intensity. For a detailed description of the LPJmL versions used as well as for the yield calibration, see SI section 1.

Based on Δz_c all cells within each river basin are ranked. Irrigation water is then allocated across the river basin cells starting with the highest ranked cell up to the lowest ranked cell that still exceeds a minimum irrigation yield value gain (h). The total water requirements necessary to irrigate all of the available cell area that is available for cropland under a given crop mix assumption (full irrigation requirements) are distributed to the respective cells with sufficient local discharge. The reason for setting a minimum threshold (h) is that irrigation is costly (Schoengold & Zilberman, 2007) and - in the absence of subsidies - irrigation would only take place in locations where positive profits from irrigation could be achieved (i.e., additional yield value gain from irrigation > additional costs associated with irrigation) (Esteve et al., 2015). As no information on irrigation costs is available, we use a set of different thresholds to derive PIA curves based on the marginal return to irrigated area (i.e. the willingness-to-pay for an additional hectare of irrigation). With an irrigation yield value gain threshold of $h = 0$, the technically possible maximum irrigation potential can be determined under consideration of optimized local irrigation water availability (technical irrigation potential). Higher thresholds allow an assessment of economically viable irrigation potentials and locally specific willingness-to-pay for irrigation.

The River Basin Surplus Discharge Allocation Algorithm also accounts for water accessibility. For current human abstractions (accounted for in the Actual Human Water Use Accounting), it is assumed that efforts of making hardly-accessible water accessible (e.g. by building dams and reservoirs) are already in place, such that all locally available discharge can be used. For new irrigation locations, determined in the River Basin Surplus Discharge Allocation Algorithm, we constrain water accessibility to account for the unequal temporal distribution of river discharge due to seasonal and inter-annual variations. For a detailed description of the accessibility constraints see SI section 4.

2.3 River Routing Constraints

Throughout both the (1) Reserved Water Use Accountingas well as the (2) River Basin Surplus Discharge Allocation, two constraints of local cellular and downstream discharge must be fulfilled (see figure 2): the 'withdrawal constraint' (A) and the 'consumption constraint' (B).

(A) **Withdrawal constraint**: Local withdrawals (ww_c) in each grid cell are constrained by local availability, avl_c (equation 3). Locally available renewable water is calculated from local runoff (r_c), local lake and river evaporation (e_c) and upstream inflows into cell c (in_c). Additionally, in calculation steps with previously considered other uses (environment; non-agriculture; current agriculture), the respectively reserved withdrawals (res_c) in each cell c are subtracted from the available water in that cell.

$$ww_c \leq \underbrace{in_c + r_c - e_c - res_c}_{avl_c} \tag{3}$$

(B) **Consumption constraint**: Local consumption (wc_c) is additionally constrained by providing sufficient water to reserved downstream withdrawals (equation 4). More concretely, water that is reserved to be withdrawn in a downstream cell (ds) of cell c, that cannot be fulfilled by local runoff in that particular downstream cell, needs to come from inflows into this cell. Therefore, it must not have been consumed in the respective upstream cell(s).

$$wc_c \leq \min_{ds} \left\{ \underbrace{(in_{ds} + r_{ds} - e_{ds}) - res_{ds}}_{avl_{ds}} \right\} \tag{4}$$

with ds representing the set of downstream cells to cell c.

2.4 Potentially Irrigated Areas and Economic Viability

Based on the allocated and reserved discharge per cell, crop water requirements of the grid cell specific crop mix, as well as the (potentially) available cropland area per cell, we calculate how much area could potentially be irrigated per cell (PIA in figure 1). In terms of available cropland area, we differentiate current cropland and potential cropland. The current cropland extent and spatial resolution is based on LUH2 (see section 2.1 and SI section 3). We refer to 'potential cropland' as the area that is suitable for cropland according to Zabel et al. (2014)'s global agricultural suitability data set that determines suitability for agriculture based on local topography, soil and climatic conditions. Acknowledging that not all marginal land is suitable for agricultural production, the bottom 33$^{\text{th}}$ percentile of marginal land (suitability index 0-33) is considered as not suitable for agricultural production.

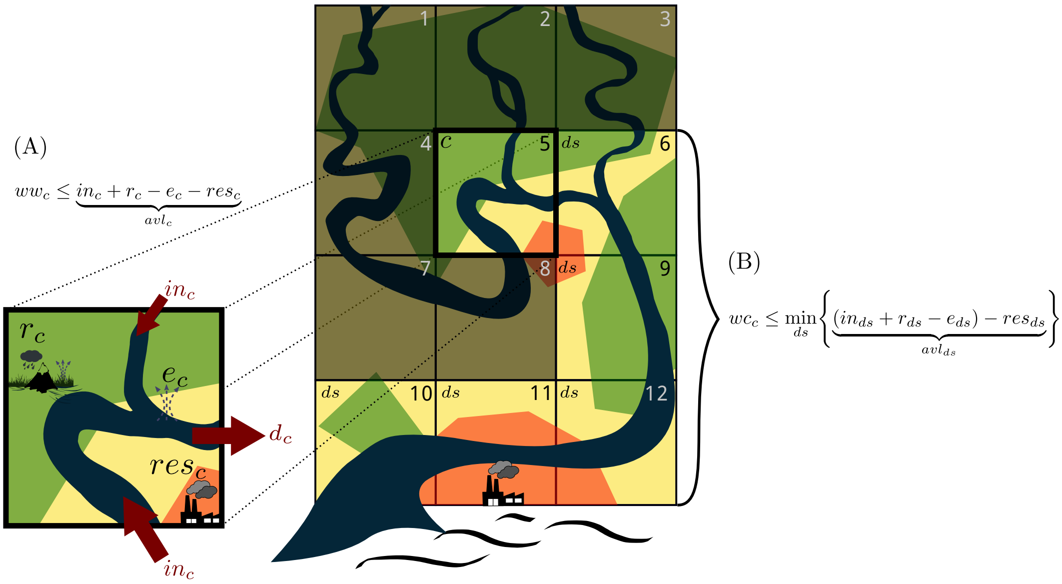

Figure 2. Illustration of river routing constraints at the example of cell $c = 5$. According to the local withdrawal constraint (A), water withdrawals in cell c (ww_c) must not violate local availability (avl_c). According to the downstream consumption constraint (B), water consumption in cell c (wc_c) must not violate downstream availability (avl_{ds}) where $ds = \{6, 9, 12, 11, 10\}$ are the respective downstream cells of $c = 5$. Availability is determined by inflows (in), runoff (r), lake and river evaporation (e) and reserved flow (res). The latter capture environmental flows; non-agricultural withdrawals; and current agricultural withdrawals.

Spatially explicit irrigation potentials in terms of potentially irrigated areas (PIA), potential irrigation water withdrawals (PIWW) and potential irrigation water consumption (PIWC) are presented for the year 2010. We assume current human water abstractions and current climatic conditions for the biophysical input data.

2.5 Scenario Description

In this study, we analyze PIWW, PIWC and PIA for a set of scenarios presented in the scenario matrix (table 1). We differentiate actual irrigation area (ACT-), available current cropland areas (both rainfed and irrigated) and areas that are suitable for agricultural production (POT-). We differentiate two sustainability dimensions (WATSUS and LANDSUS). The water dimension (WATSUS) is a quantitative restriction of water withdrawals such that minimum flows are maintained to ensure a ‘fair’ aquatic and riverine ecosystem status that relies on low- and high-flow requirements (Smakhtin et al., 2004). Protection of EFR in our study assumes that the required minimum flow can be released from reservoirs under water management. In line with the narrative of the Half-Earth land sparing scenario, the land-related protection scenarios in this study (LANDSUS) assume that no irrigation can take place in areas of ecological importance to safeguard freshwater ecosystems following a strict preservation approach that aims at reducing human pressure at half of the Earth’s land surface (Wilson, 2017; Kopnina, 2016; Kok et al., 2020; Immovilli & Kok, 2020). The Half-Earth area map is provided by Kok et al. (2020). For a detailed description of the data, see SI section S2. As compared to WATSUS, which focuses on water quantity, LANDSUS emphasises the conservation of (intact) ecosystems by preventing irrigation area expansion and water abstractions in areas of ecological importance. In the sustainability scenario

(SUS) both environmental flows are preserved and irrigation is limited to areas that do not fall into these special ecological zones.

Sustainability constraint \ Available area for irrigation	Irrigation allowed on currently irrigated areas	Irrigation allowed on all of current cropland	Irrigation allowed on all suitable land for agricultural production
No water limitation	ACT	CUR	POT
Constrained by local water availability	ACT-UNSUS	CUR-UNSUS	POT-UNSUS
Constrained by local water availability & respecting environmental flow requirements	ACT-WATSUS	CUR-WATSUS	POT-WATSUS
Constrained by local water availability & excluding protected land from irrigation expansion	ACT-LANDSUS	CUR-LANDSUS	POT-LANDSUS
Constrained by local water availability & respecting environmental flow requirements & excluding protected areas from irrigation expansion	ACT-SUS	CUR-SUS	POT-SUS

Table 1. Scenario overview. ACT, CUR and POT represent area constraints without consideration of local water availability or sustainability constraints. The extensions -UNSUS, -WATSUS, -LANDSUS and -SUS stand for different sustainability criteria respecting local water availability constraints.

All scenarios are calculated for different yield value gain thresholds and for one scenario where the reservation of current agricultural water uses is activated as well as one where it is deactivated such that irrigation potentials are purely determined by the economic cell ranking. Detailed results at the country level are provided in the SI. The reservation of current agricultural water uses is relevant because currently irrigated areas already have irrigation infrastructure (such as reservoirs and canals) in place that divert natural river flows (Biemans et al., 2011; Wada, van Beek, et al., 2013; Veldkamp et al., 2018) and therefore affect water availability and irrigation potentials for other grid cells. It is helpful for analyses where current irrigation patterns should be maintained, for example for the initialization period of global land-use models to meet observed irrigated areas in the initialization year. In this study, they are calculated to show the potential expansion of currently irrigated areas on current cropland and on potential cropland (see 4). To derive irrigation potentials, the marginal willigness-to-pay for irrigation and IAD curves for the case of an economically efficient allocation, all other results in this study are provided without this constraint.

3 Results

3.1 Current Irrigation and Irrigation Potentials on Currently Irrigated Areas

Globally, a consumptive water volume of 959 $\mathrm{km^3\,yr^{-1}}$ is required to irrigate the given cropmix on currently irrigated areas (265 Mha). Of these irrigation water requirements, 788 $\mathrm{km^3\,yr^{-1}}$ could be fulfilled given the local water availability in this study (see figure 3). This corresponds to an irrigated area of 228 Mha (see figure 4a for their spatial distribution). If EFR were to be maintained, the consumptive volume (irrigated area) would reduce to 728 $\mathrm{km^3\,yr^{-1}}$ (213 Mha).

The share of current irrigation water demand under full irrigation requirements that can be fulfilled by locally available renewable water resources captured in our data set is depicted in figure 3. Areas where not all current irrigation can be fulfilled by the local water resources of this study include mainly the Nile river basin in Egypt, North-West India and Pakistan, North-East China and parts of Central Asia and the Western USA.

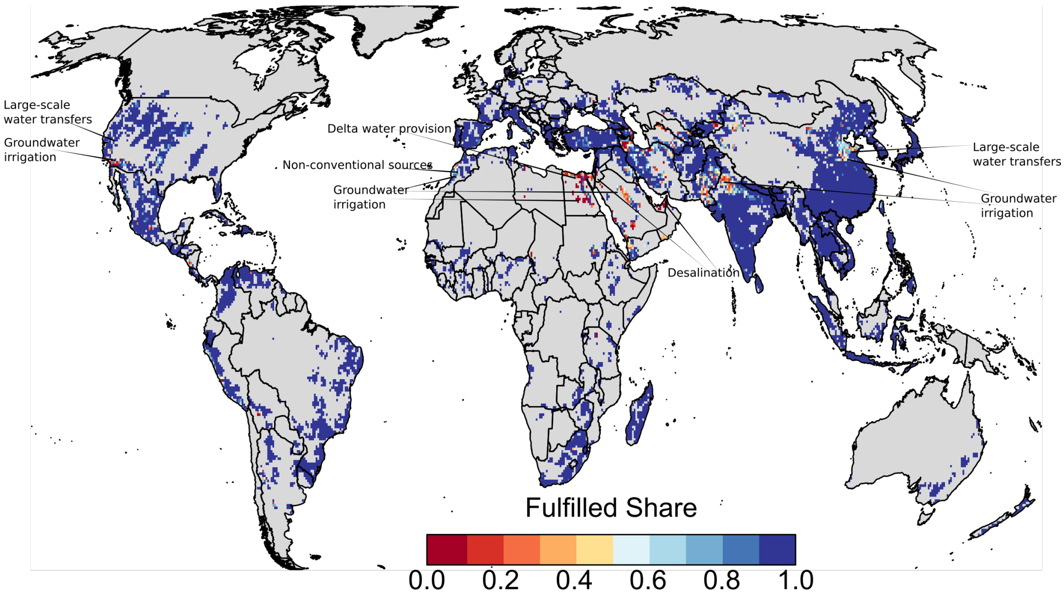

Figure 3. Share of current irrigation water demand under full irrigation requirements (ACT) that can be fulfilled by locally available renewable water resources captured in our data set (ACT-UNSUS). Grey areas are currently not irrigated. Cells with very small cropland areas (cropland area share below 1 %) are excluded from the visualization. Annotations are potential explanations for unfulfilled current irrigation water.

Under consideration of an optimal distribution of irrigated areas following the yield value gain ranking and applying the threshold approach, PIA on currently irrigated areas (see ACT scenarios in table 2A) would reduce to 140 Mha (ACT-UNSUS). If areas of ecological importance were excluded from irrigation, PIA would reduce to 138 Mha (ACT-LANDSUS). Protecting EFR would reduce PIA on currently irrigated areas to 132 Mha (ACT-WATSUS). The sustainable PIA on currently irrigated areas (land and water protection, ACT-SUS) is 130 Mha.

3.2 Technical Irrigation Potentials on Current and Potential Cropland

Table 2A shows the technical irrigation potentials in terms of PIA, PIWC and PIWW for all scenarios modeled for this study. In terms of potentially irrigated areas on current cropland, 781 Mha could be irrigated given local water resources (CUR-UNSUS). If irrigation could only expand into cropland outside of areas of ecological importance and EFR were maintained (CUR-SUS), 711 Mha could be irrigated. This area corresponds to about 46 % of current cropland (1531 Mha, CUR) and 446 Mha more than currently irrigated areas (265 Mha, ACT). The local distribution of potentially irrigated areas on current cropland considering today's actually irrigated areas can be seen in figure 4b. Under cropland expansion into non-protected areas that are suitable for cropland activities (3888 Mha), 64 % (2492 Mha, POT-UNSUS) could be irrigated given local water availability. Around 41 % (1578 Mha) could be irrigated sustainably (POT-SUS). The local distribution of PIA on potential cropland considering today's actually irrigated areas can be seen in figure 4c.

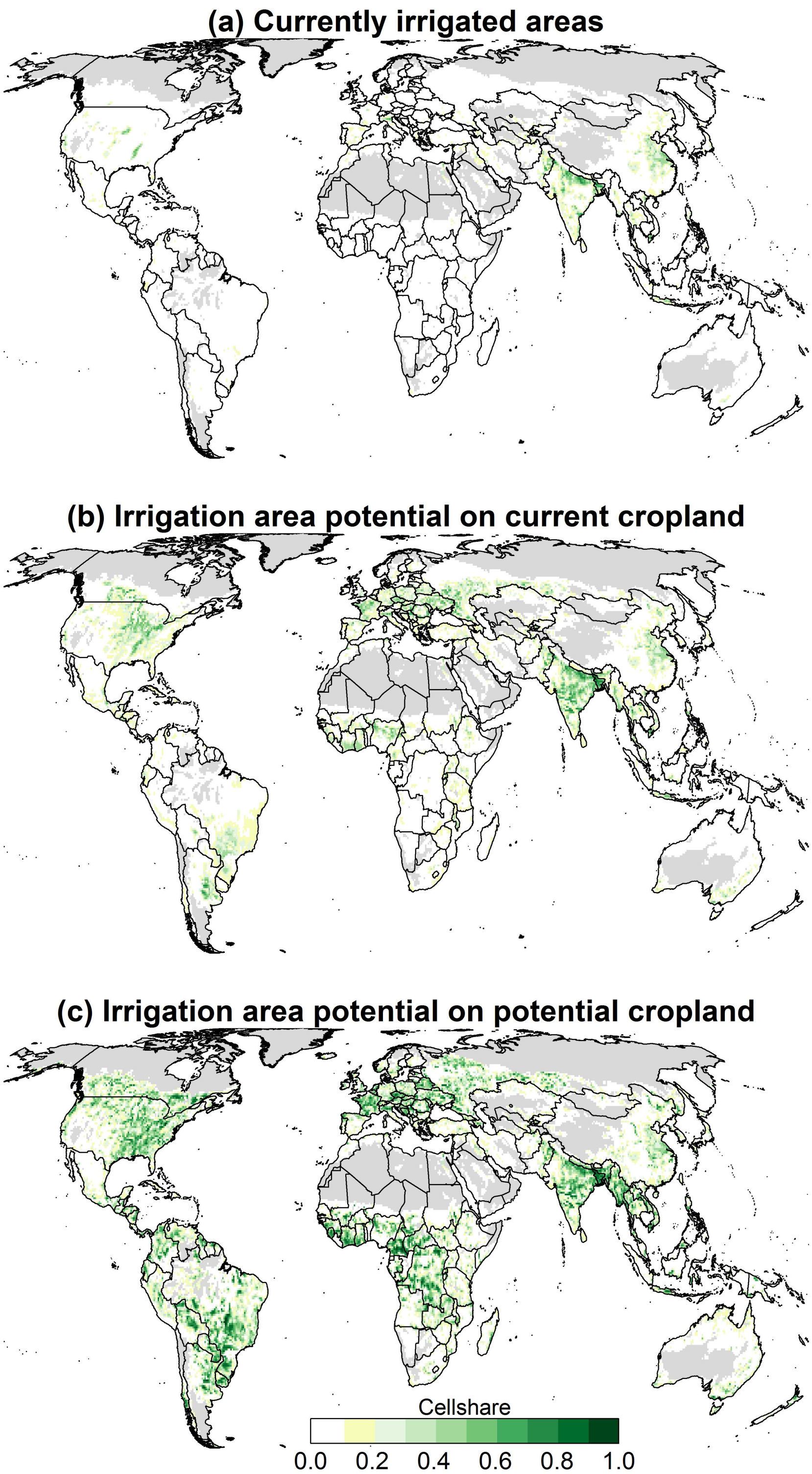

Figure 4. Potentially irrigated areas (as share of grid cell area) for different scenarios: (a) Currently irrigated areas (ACT); (b) potentially irrigated areas on current cropland considering already irrigated areas (CUR-UNSUS); (c) potentially irrigated areas on potential cropland considering already irrigated areas (POT-UNSUS). Current agricultural water uses are reserved for this graph to visualize additional potentials beyond currently observed irrigation. Cells with very small potential cropland area (potential cropland area share below 1 %) are excluded from the visualization.

Scenario	(A) Technical Potential PIA (in Mha)	PIWC (in km^3)	PIWW (in km^3)	(B) Economic Potential PIA (in Mha)	PIWC (in km^3)	PIWW (in km^3)
ACT	265	957	1780	146	643	1187
ACT-UNSUS	140	503	925	84	351	925
ACT-WATSUS	132	472	868	79	329	600
ACT-LANDSUS	138	495	910	84	347	634
ACT-SUS	130	465	854	78	325	593
CUR	1531	4304	7723	545	2096	3774
CUR-UNSUS	781	2089	3700	279	995	1777
CUR-WATSUS	728	1933	3426	259	919	1642
CUR-LANDSUS	763	2035	3603	273	972	1735
CUR-SUS	711	1884	3336	254	897	1602
POT	6315	17046	30600	2013	7857	14034
POT-UNSUS	2492	5591	9941	682	2213	3952
POT-WATSUS	2336	5169	9194	632	2030	3627
POT-LANDSUS	1682	3979	7072	516	1716	3069
POT-SUS	1578	3679	6544	476	1570	2808

Table 2. Irrigation potentials in terms of potentially irrigated areas (PIA), potential irrigation water consumption (PIWC) and potential irrigation water withdrawals (PIWW) for different scenarios. Technical irrigation potential (A) refers to the irrigation potential at a yield value gain threshold (h) of 0 USDha^{-1}. Economic irrigation potential (B) refers to the irrigation potential at h of 500 USDha^{-1}.

PIW on current cropland area considering all technically available local discharge allocated to its most productive use while taking current non-agricultural and agricultural water uses into account (technical irrigation potential, see table 2A) amounts to 2089 km^3 yr^{-1} (consumptive, i.e. PIWC) [3700 km^3 yr^{-1}, withdrawal, i.e. PIWW] (CUR-UNSUS); 1884 km^3 yr^{-1} (3336 km^3 yr^{-1}) of which could be consumed (withdrawn) while maintaining EFR and without irrigation in areas of ecological importance (CUR-SUS). On potential croplands, i.e. land that is suitable for agricultural production, 5591 km^3 yr^{-1} of water could be consumed when unregulated, i.e. without land and water protection (POT-UNSUS). If EFR were respected, PIWC would be reduced to 5169 km^3 yr^{-1} (POT-WATSUS). If ecologically important zones were protected from irrigation, 3979 km^3 yr^{-1} would be available for consumptive agricultural water use without explicitly accounting for EFR (POT-LANDSUS). If both land and water sustainability criteria were respected, 3679 km^3 yr^{-1} of water could be consumed for sustainable irrigation globally (POT-SUS).

3.3 Economic Irrigation Potentials

Globally, the simulated yield value gain through irrigation differs depending on the location (see also figure S1 in appendix section 2). Surprisingly, on currently irrigated areas, the average yield value gain is only 455 USD ha^{-1}. By contrast, on current cropland, the average yield value gain is 910 USD ha^{-1}; on potential cropland that is not under protection in our LANDSUS scenario 931 USD ha^{-1}; and on all potential land suitable for agricultural production, the average yield value gain is 939 USD ha^{-1}. For a detailed discussion on this aspect, see section 4.3.

To visualize which areas would be irrigated given different irrigation yield value gain thresholds, figure 5a and 5b show the spatial distribution of PIAs under yield value gains greater than 1000 USD ha^{-1} (red areas; global area of 386 Mha (POT-UNSUS) and 271 Mha

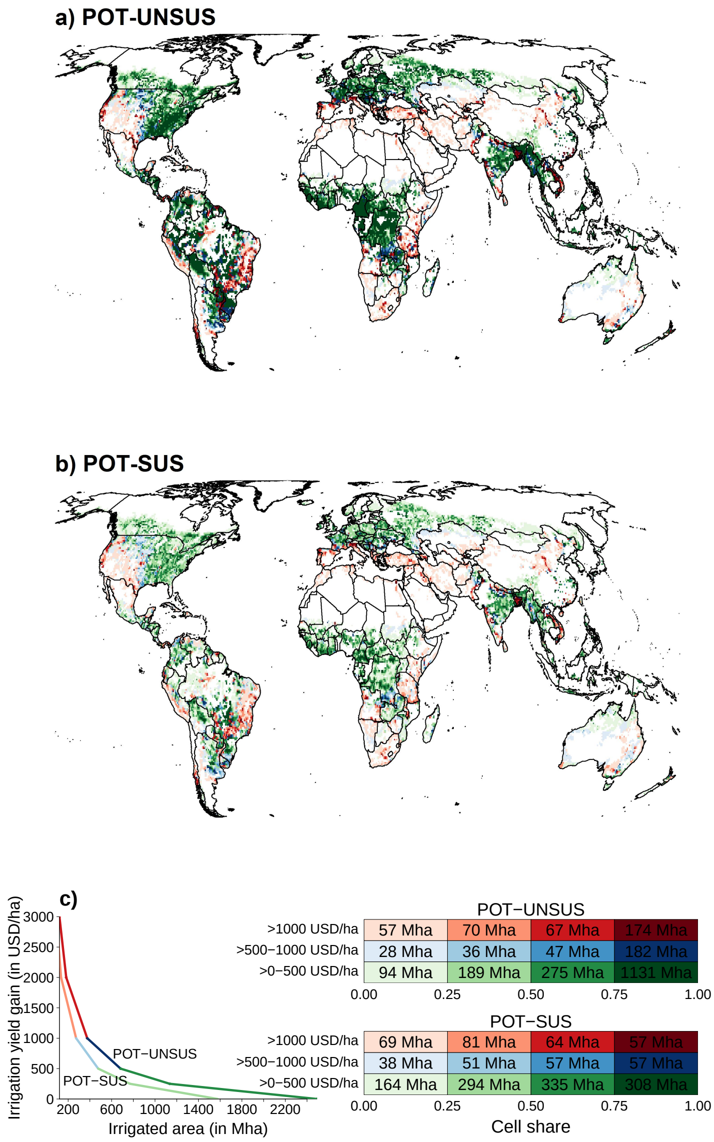

Figure 5. Potentially irrigated areas (PIA) (displayed as share of the grid cell area) for three different irrigation yield value gain thresholds ($h = 0, 500, 1000$) on potential cropland for two scenarios (POT-UNSUS; POT-SUS). Cells with very small potential cropland area (potential cropland area share below 1 %) are excluded from the map visualization. Red areas: PIA with yield value gains > 1000 USD ha^{-1}. Blue areas: PIA with yield value gains between >500 and 1000 USD ha^{-1}. Green areas: PIA with yield value gains between >0 and 500 USD ha^{-1}. Legends show the global sum of potential cropland that falls into each category.

(POT-SUS)), smaller or equal 1000 USD ha^{-1} and greater than 500 USD ha^{-1} (blue areas; global area of 293 Mha (POT-UNSUS) and 203 Mha (POT-SUS)) and potential yield value gains greater than 0, but smaller or equal 500 USD ha^{-1} (green areas; global area of 1689 Mha (POT-UNSUS) and 1101 Mha (POT-SUS)). The global irrigated area for different irrigation yield value gains is summarized in the PIA curves shown in figure 5c.

While technically, 711 Mha of current cropland could be irrigated sustainably, only 254 Mha would be irrigated when considering a minimum yield value gain threshold of 500 USD ha^{-1}. On potential cropland excluding areas of ecological importance, the total biophysical PIA allocated to areas above a minimum yield value gain threshold of 0 taking the productivity ranking into account (technical potential) would be 1578 Mha (POT-SUS in table 2A). Assuming that irrigation would only be viable economically at a minimum yield value gain of at least 500 USD ha^{-1}, the global PIA would be reduced to a third of this area to 476 Mha (POT-SUS in table 2B).

3.4 Aggregated Irrigation Potentials

The following country-level results provide an example of data aggregation that can be useful for LSMs with country-level resolution. The supplementary material to this study includes detailed country results for 235 countries and six irrigation yield value gain thresholds, both in terms of PIA (in Mha) as well as PIWC and PIWW (in km^3 yr^{-1}) for currently irrigated areas, current cropland areas as well as for potential cropland areas. Both irrigation potentials with reserved currently irrigated areas as well as purely yield-value-gain-determined irrigation potentials are provided.

The potential yield value gain (in USD ha^{-1}) for the PIAs of selected countries is shown in Figure 6. These curves represent country-specific PIA for sustainable and unsustainable irrigation. The yield value gain through irrigation can be interpreted as the maximum willingness-to-pay to irrigate a certain hectare of land in a specific location. Realistically, not all technical potential with positive yield value gains (yield value gain > 0) would be irrigated due to costs for irrigation. The curves represent the marginal value to irrigation. For example in Mexico, where 14 Mha of current cropland (26.2 Mha) show a yield value gain of at least 500 USD ha^{-1}, 7.1 Mha (CUR-UNSUS) could be irrigated and 6 Mha (CUR-SUS) could be irrigated sustainably. Currently, LUH2 reports 5 Mha of irrigated area in Mexico. Of the available non-protected areas in Mexico (87.5 Mha), 53.1 Mha have yield value gains above 500 USD ha^{-1}, but only 9.6 Mha could be sustainably irrigated given local water constraints. Under cropland expansion into potential croplands, 13 Mha could be irrigated, but only 9.2 Mha when respecting EFR and restricting irrigation to areas as prescribed in our sustainable scenario.

Depending on the model application and data availability, another useful level of aggregation is the basin scale. Figure 7 shows PIA curves for selected river basins across the globe. There are river basins with highly unelastic irrigation area demand (steep PIA curves, e.g. Huang He). Other basins are more heterogeneous (e.g., Parana, Ganges, Indus) that have both areas with high yield value gains and low yield value gains in the same basin. The variation in the functional relationships shows how diverse and location specific irrigation water challenges are.

4 Discussion

4.1 A Novel Aggregation Method for Land-System Models

Considering the spatial location as well as upstream-downstream relations of water resources is crucial for the estimation of irrigation potentials. This is challenging for a number of applications, such as LSMs, that work on an aggregated scale. Our hydro-economic data processing routine provides a valuable hydrological input aggregation and output disaggregation tool to global LSMs. These models usually operate on simulation units of spatial clusters of grid cells and aggregate water availability to this spatial scale. At this aggregation, cost-free water transfers over large distances and across basin boundaries are implicitly assumed. Furthermore, to provide aggregated water availability data to spatial clusters that do not necessarily respect river basin boundaries in the first place, the basin's runoff has to be allocated to the grid cells within the basin. When this water is distributed

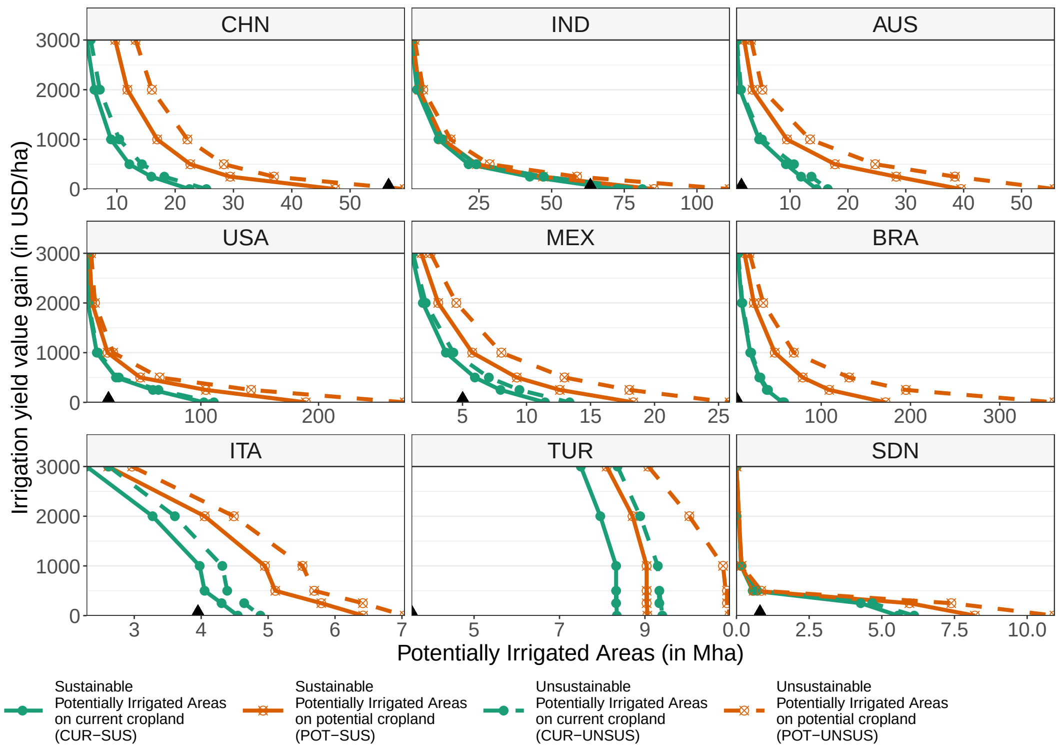

Figure 6. Marginal yield value gain from unsustainable and sustainable irrigation for potentially irrigated areas of selected countries (abbreviated in titles by iso3 country codes). The black triangular symbol indicates currently irrigated area (ACT).

across the basin grid cells based on discharge (e.g., Pastor et al. (2019); Bonsch (2015)), this creates a bias towards downstream irrigation as most of the discharge accumulates downstream when not used - even if certain upstream cells would be more productive whilst having sufficient discharge available and therefore would be more likely to be irrigated in the LSM for which the input is generated. By accounting for non-agricultural human water uses and potential irrigation water use based on a productivity ranking, our algorithm takes more information into account in the water allocation and avoids a misrepresentation of water availability at the aggregated scale.

4.2 Sustainability of Irrigation Potentials

In this study, we provide a global spatially explicit quantification of global PIW and PIA for the year 2010 on current and potential cropland. According to our analysis, 5591 $km^3\,yr^{-1}$ of water would be available on suitable cropland for irrigation water consumption without considering sustainability criteria (POT-UNSUS). 3679 $km^3\,yr^{-1}$ could be consumed when considering both water and land sustainability criteria for irrigation water use (POT-SUS). Adding water consumption that is reserved for non-agricultural consumption in a sustainability setting in our algorithm (191 $km^3\,yr^{-1}$), global sustainable water consumption amounts to 3870 $km^3\,yr^{-1}$. This value falls into the uncertainty range of the planetary boundary (PB) of water suggested by Gerten et al. (2013) of 1100-4500 $km^3\,yr^{-1}$. Previous top-down estimates for the water PB (Rockström et al., 2009) have been criticised for not being sufficiently grounded in bottom-up data (Gerten et al., 2013). Our analysis of PIWC considers spatially explicit EFR rather than global averages. Beyond this water quantity dimension, our sustainability definition includes a land protection component

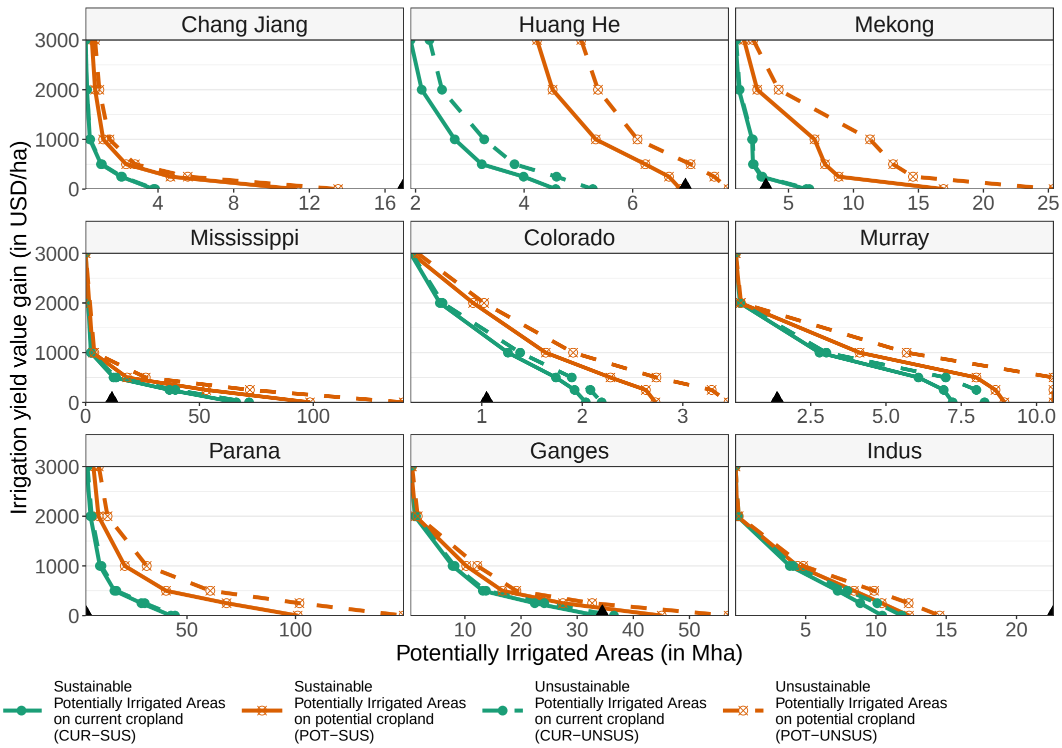

Figure 7. Marginal yield value gain from unsustainable and sustainable irrigation for potentially irrigated areas of selected river basins. The black triangular symbol indicates currently irrigated area (ACT).

(preventing irrigation activities in areas of ecological importance to sustain freshwater and riverine ecosystems). While PIWC amounts to 5169 $km^3\,yr^{-1}$ when only environmental flows are protected (POT-WATSUS), the protection of areas of ecological importance reduces global PIWC to 3979 $km^3\,yr^{-1}$ (POT-LANDSUS). The combination of both sustainability dimensions further reduces PIWC by 300 $km^3\,yr^{-1}$ to 3679 $km^3\,yr^{-1}$ (POT-SUS). This shows that there are likely synergies between the land, water and biodiversity PBs (Rockström et al., 2009). A limitation of this sustainabiliy setting is that the impact of river fragmentation through dams and reservoirs on aquatic biodiversity is ignored (Nilsson et al., 2005; Lehner et al., 2011). Moreover, the impact of irrigation on water quality (van Vliet et al., 2017) as well as soil quality (Khan et al., 2006) is not considered.

4.3 Economic Aspects of Irrigation

To estimate 'planetary water opportunities', assessing societal water demands and areas where the water would actually be used (i.e., excluding subarctic and inner tropical regions) is important (Gerten et al., 2013). Our assessment of irrigation potentials excludes areas that are not suitable for cropping activities and considers potential human water demands. Furthermore, we add economic criteria to the estimation of PIWC. While a total volume of 5591 $km^3\,yr^{-1}$ (POT-UNSUS) could be consumed in irrigated agriculture, not all of this would actually be consumed when considering economic decision criteria. With a minimum yield value gain of 500 USD ha^{-1}, PIWC would only be 2213 $km^3\,yr^{-1}$ (POT-UNSUS) according to our estimate. The threshold approach is based on the assumption that not all technical irrigation potentials would be put into productive use when considering cost-benefit criteria. There are farm-level costs (installation and maintenance of irrigation equipment on the field; additional input costs (Harou et al., 2009; D'Odorico et al., 2020) as well as large infrastructure investment costs associated with the construction and maintenance of dams, reservoirs and canals (Inocencio et al., 2007; Schoengold & Zilberman, 2007) that pose an economic barrier. However, so far no reliable spatially explicit irrigation cost data with global coverage exist. In the absence of such cost data, our PIA curves describe the geographical ranking of grid cells implicitly assuming homogeneous costs for a given aggregation unit.

The spatial distribution of irrigation driven by economic criteria largely depends on the difference between irrigated and rainfed yields as modeled by LPJmL. We observe that the simulated yield value gain on currently irrigated areas is smaller than the simulated yield value gain on other cropland or potential cropland. One reason are institutional and political considerations that impede irrigation (Rosa, Chiarelli, Rulli, et al., 2020; Boelens et al., 2016) and are not accounted for in this study. Furthermore, large-scale water infrastructure projects are not solely constructed for reasons of stable irrigation water provision, but also to provide energy through hydro-power, for reasons of flood control, or navigation (Biemans et al., 2011). Furthermore, irrigation can facilitate additional cropping seasons (multiple cropping) in subtropical and tropical regions (Waha et al., 2020). This is not captured in our model. Because of potential shifts in the growing period in irrigated LPJmL model runs compared to rainfed LPJmL model runs, some areas (especially in China and Southeast Asia) show no yield value gain through irrigation. While the yields in the wet season are not water-limited, irrigation allows farming these croplands also in the dry seasons. Irrigation-dependent multiple cropping, which plays an important role in East and South Asia (Waha et al., 2020), is therefore likely the main reason for the observed irrigation in these areas. It is an aspect that is ignored in most global irrigation assessments and LSMs.

4.4 Modeling Assumptions

For land-use simulations of future scenarios, projections of future yields under climate change impacts, future projections of non-agricultural water abstractions and an adjusted crop mix have to be used as model inputs. Depending on the concrete model application and given data availability, our modeling parameters can easily be adapted in the open-source code (i.e., farm-gate prices rather than averaged global agricultural prices; relevant crop-mix; irrigation-system of interest). The open-source code (Beier et al., 2021) allows to switch between these settings. For example, while the assumption of one global price per crop is reasonable for our analysis that investigates a cross-country comparison of economic irrigation potentials without distorting policies such as tariffs, national or even farm-gate prices could be used to value irrigation yield gains when focusing on local economic analyses or for scenarios of regional rivalry (e.g., SSP3 of the shared socio-economic pathways defined in (O'Neill et al., 2015). Similarly, the results can be aggregated to different resolutions (basin scale, country-level, or any other appropriate simulation unit), such that the relevant PIA curves and willingness-to-pay enter the model.

4.5 Modeling Uncertainty

Projections of global hydrological models (GHMs) come with large uncertainties including modeling and downscaling uncertainties from global climate models (GCMs) affecting the temperature and precipitation estimates that are propagated in GHMs. Furthermore, modeling and parameter uncertainty is introduced in GHMs (Gudmundsson et al., 2012; Hagemann et al., 2013; Wada, Wisser, et al., 2013; Schewe et al., 2014). These uncertainties result in largely differing estimates of yearly runoff under natural conditions across different GHMs. Because the focus of this study is the introduction of a new river routing routine to aggregate water availability information for the application in LSMs, we only used one observed atmospheric climate data set (GSWP-3) and one combined hydrology-vegetation model (LPJmL) to derive river discharge. Nevertheless, for robust estimates of

PIW and PIA, the model is flexible to be applied on an ensemble of GCM-GHM combinations (Gudmundsson et al., 2012; Haddeland et al., 2011).

4.6 Limitations

In terms of currently irrigated areas, the 265 Mha correspond to an PIWC of 957 km^3 yr^{-1} of irrigation water consumption in our study. This value falls into the range of previous ensemble studies by Hoff et al. (2010) and Haddeland et al. (2014) that find current global irrigation water consumption to range between 927 - 1530 km^3 yr^{-1} and 940 - 1284 km^3 yr^{-1}, respectively. The spatial distribution of areas where current irrigation water cannot be served by local renewable water resources (red areas in figure 3) is similar to the areas that suffer under extreme blue water over-use in Rost et al. (2008) (see figure 3e in Rost et al. (2008) and to the areas that face water scarcity and unsustainable water use in parts of the growing period Rosa, Chiarelli, Rulli, et al. (2020)). Mismatches of irrigation patterns using local renewable water availability and current observed irrigation can be explained by our modeling assumptions with regards to water transport, groundwater resources and non-conventional water sources for irrigation.

In our river routing, water transfers can only take place within the respective 0.5°grid cell. This implies a maximum water transport distance of around 78 km at the equator and decreasing transport distance towards the poles. Therefore, no costly large-scale water transport is allowed. In reality, long-distance water pipelines or canals exist, however; for example, the South-North Water Transfer Project that supplies drinking and sanitary water to cities in North-East China (Rogers et al., 2020) or California's State Water Project that serves farmers and households in the dry regions of California (Grigg, 2021). Similarly, regions where river deltas provide water for irrigation are misrepresented because the global river drainage network data set (STN-30p) does not consider deltas (i.e., one grid cell cannot discharge into several downstream grid cells) (Vörösmarty et al., 2000, 2011; Lehner et al., 2011). This explains the water deficits as observed in the Nile delta (figure 3). Water transfers between grid cells are a topic of future research. However, especially for not yet established water transfer projects, such an implementation would require information on costs related to such large-scale infrastructure projects rather than allowing free water transport across large distances.

Renewable groundwater is implicitly included in our model via the base flow component of runoff simulated in LPJmL (Rost et al., 2008). Because of a lack of spatially explicit information on groundwater aquifers and their drainage as well as the temporal aggregation of our river routing routine that prevents us from explicitly modeling temporal storage and subsurface runoff speed, it might be misrepresented in its spatial distribution, however. This is visible in our results in that regions that rely heavily on groundwater irrigation (e.g. northern India, Pakistan, North-East China, western USA (Siebert et al., 2010; Wada et al., 2012; Rodell et al., 2018; Rogers et al., 2020)) cannot fulfill current irrigation water requirements given the local water availability as represented by our river routing (see figure 3). Non-renewable groundwater is not captured in our analysis due to a lack of data on fossil groundwater reservoirs. Since the focus of our study is a projection of sustainable irrigation potentials considering renewable water resources rather than an estimation of current actual irrigation patterns, the exclusion of non-renewable water resources is justified. The mismatches with irrigation observed in reality can be seen in figure 3, for example in the California (USA) and Saudi Arabia that heavily rely on fossil groundwater for irrigation (Scanlon et al., 2012; Chandrasekharam, 2018). Similarly, other non-conventional sources are not covered. These include the use of desalination plants or wastewater reuse that play a role in some states of the Arab Peninsula, such as Kuwait, Qatar, Saudi Arabia and the United Arab Emirates as well as Israel (Siebert et al., 2010; Lattemann et al., 2010). In figure 3, this can be seen in Morocco that uses non-conventional sources such as wastewater reuse and desalination besides groundwater irrigation (Hssaisoune et al., 2020).

5 Conclusion

Our spatially-explicit irrigation water processing routine captures local hydrological information and water abstractions for human uses along rivers to derive potentially irrigated areas and potential irrigation water use (withdrawal and consumption) taking upstream-downstream effects into account. We find that, on the one hand, current irrigation partly relies on large-scale water transfers and unsustainable irrigation practices (e.g., violation of environmental flow requirements); while, on the other hand, there are large untapped sustainable irrigation potentials both on current cropland (711 Mha) and on potential cropland (1578 Mha). Not all of these technical irrigation potentials are viable due to irrigation costs. Globally, the irrigation potential of 781 Mha on current cropland (CUR-UNSUS) would reduce to 279 Mha if only areas with yield value gains of at least 500 USD ha^{-1} would be irrigated. The sustainable potential on current cropland under this yield value gain threshold amounts to 254 Mha. There are considerable potential irrigation yield value gains and expansion potentials, for example in Southern Africa and Brazil. There is an economic incentive to irrigate areas that should be protected from irrigation due to their ecological importance and excessive withdrawals where minimum environmental flows should be maintained. Therefore, land- and water-protection policies are important to prevent water overuse; especially in highly productive areas, where irrigation water abstractions are not limited by economic constraints.

Our assessment also reveals a number of research gaps in current global irrigation literature. Irrigation may often be motivated by enabling multiple cropping, yet multiple cropping is still poorly considered in global modeling studies. Next to yield gains, also the costs for dams, reservoirs, canals, irrigation equipment and maintenance are decisive for economic irrigation potentials, but no global spatially explicit irrigation cost data set exists yet.

Together with future climatic and socio-economic scenarios and simulated data on required inputs such as non-agricultural water uses, the irrigation potentials calculated by the presented processing routine can be used to inform global land-system simulation models on local water availability in the present and the future. Further, they can provide spatially more explicit information on potential irrigation patterns and irrigation area expansion. The method can be used as a tool to aggregate hydrological input data to the required LSM simulation unit; and to disaggregate LSM outputs (such as irrigation withdrawals) to a high spatial resolution. This facilitates addressing water- and irrigation-specific research questions explicitly across different scales in a global context.

Acknowledgments

The open-source code ((Beier et al., 2021)) is developed on github (https://github.com/pik-piam/mrwater/) and available at https://doi.org/10.5281/zenodo.5801680. The script used to visualize results for the purpose of this publication is published in the github repository https://github.com/FelicitasBeier/IrrigationPotentials. The respective data used was created with the code published at https://doi.org/10.5281/zenodo.5801680 and is available at https://doi.org/10.5281/zenodo.5811905.

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The authors declare no conflict of interest.

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Supporting Information for "Economically Efficient and Environmentally Sustainable Irrigation Potentials: a Spatially Explicit Global Assessment"

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Contents of this file

1. Detailed Methods: LPJmL Model Description
2. Detailed Methods: Yield Value Gain Potential
3. Detailed Methods: Reserved Current Agricultural Uses

Additional Supporting Information (Files uploaded separately)

1. PIA_bycountry_a.xlsx
2. PIA_bycountry_b.xlsx
3. PIWC_bycountry_a.xlsx
4. PIWC_bycountry_b.xlsx

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*Also funded by Deutsche Bundesstiftung Umwelt (DBU)

5. PIWW_bycountry_a.xlsx

6. PIWW_bycountry_b.xlsx

Introduction

This Supporting Information provides additional details to the methods applied in the article.

Additionally, country-level results of irrigation potentials (potentially irrigated areas (PIA); potential irrigation water consumption (PIWC); potential irrigation water withdrawals (PIWW)) for 235 countries are provided for two model setups as separate files: (a) under consideration of currently irrigated areas that affect the river flow; (b) not considering currently irrigated areas for irrigation potentials that are purely determined by economic considerations.

1. Detailed Methods: LPJmL Model Description

The Lund-Potsdam-Jena managed Land (LPJmL) model is a spatio-temporally explicit process-based model that simulates the growth and geographical distribution of 11 plant functional types (natural vegetation) and 12 crop functional types (field crops) and additionally pasture as well as (woody and herbaceous) bioenergy crops. It accounts for feedbacks between vegetation, the global terrestrial water, carbon, and nitrogen cycles, and energy fluxes (von Bloh et al., 2018; Schaphoff, von Bloh, et al., 2018; Lutz et al., 2019). The model simulates the terrestrial water balance considering precipitation, snow melt, seepage, interception, plant transpiration and soil evaporation resulting in daily simulations of runoff and discharge and considers its close interactions with plant vegetation in terms of plant growth and productivity that is linked to soil and atmospheric moisture (Schaphoff, Forkel, et al., 2018). It delivers consistent estimates for spatially explicit irrigated and rainfed potential crop yields, plant water uptake and surface runoff that are the basis for our model. Evaporation of irrigation water during the growing season is calculated based on the fraction of irrigation water in soil moisture and canopy interception (Rost et al., 2008).

The crop types considered in LPJmL are mapped to the crop types considered in our analysis using the following mapping (see table S1). Since LPJmL considers fewer crops than our analysis, LPJmL's groundnut is also the proxycrop for both oilpalm and cotton; maize is also the proxycrop for fodder (forage) and the 'other' crop category including fruits, vegetables and nuts; temperate roots represent both sugar beet and potatoes.

Irrigated and rainfed crop yields as well as consumptive blue water requirements are provided by LPJmL5 with unlimited nitrogen supply (von Bloh et al., 2018). As opposed to previous LPJmL versions (Sitch et al., 2003; Bondeau et al., 2007; Schaphoff, von Bloh, et al., 2018; Schaphoff, Forkel, et al., 2018), LPJmL5 includes an implementation of the global terrestrial nitrogen cycle and consistently accounts for water, grassland and crop management. Since the LPJmL4 and LPJmL5 model version have diverged during the Nitrogen cycle implementation phase, certain natural vegetation dynamics (Forkel et al., 2014) have not yet been included in the newest LPJmL5 version (von Bloh et al., 2018). For this reason, natural vegetation inputs, such as lake evaporation, runoff and monthly discharge are provided by its predecessor LPJmL4 (Schaphoff, von Bloh, et al., 2018; Schaphoff, Forkel, et al., 2018).

2. Detailed Methods: Yield Value Gain Potential

The difference of irrigated and rainfed crop yields as estimated by LPJmL provides the yield gain through irrigation in tons of dry matter. Negative yield gains (irrigated yield < rainfed yield) are technically possible because irrigation may lead to a shift in the growing period in LPJmL resulting in lower irrigated yields. In such cases, the irrigation yield gain is set to 0.

To account for country-specific management effects on yields (e.g. fertilizer and pesticide use; different crop varieties; mechanization; cropping intensity representing multiple cropping or fallow land), LPJmL potential yields are calibrated to meet country-level production as reported by FAO (FAO, 2021) using a multiplicative factor for both rainfed and irrigated yields. Note that both rainfed and irrigated yields are calibrated to FAO country-levels. A potential multiple cropping effect is therefore applied to both irrigated and rainfed yields and cannot capture the effect that irrigation may lead to an additional cropping season and increase yields by one or two additional harvests per year.

Figure S1 shows the potential yield value gain through irrigation in USD per hectare for the historical crop mix in 2010. It represents the areas that would achieve yield gains through irrigation considering irrigated and rainfed potential yields valued at global FAO average prices (in USD per tDM).

3. Reserved Current Agricultural Uses

To derive the grid cell area (in Mha) that was irrigated in the year 2010, we use the irrigated area share provided by the Land-Use Harmonization 2 (LUH2) data set presented in Hurtt et al. (2020) (Hurtt et al., 2019, 2020). LUH2 is based on the HYDE 3.2 data set (Klein Goldewijk et al., 2017) that estimates historically irrigated areas based on Siebert et al. (2015), Portmann, Siebert, and Döll (2010) and FAOSTAT data (FAO, 2021). To obtain grid cell specific crop area for the 19 crop types used in our analysis, we combine the spatially explicit LUH2 cropland map with national crop-type specific data from FAOSTAT that provides country-level harvested areas of crop items.

The LUH2 cropland map is subdivided into only five crop functional types (C3 annuals; C4 annuals; C3 perennials; C4 perennials; C3 nitrogen fixers). These five functional types are further disaggregated into crop groups using relative shares of area harvested on country level from FAOSTAT. Because rice plays a special role in terms of irrigation as well as greenhouse gas accounting, the spatial distribution of rice areas is especially important. We therefore determine the distribution of physical rice areas by assigning the country's rice production first to flooded areas provided at cellular level by LUH2. Upland (aerobic) rice is accounted by distributing country-level FAO rice areas beyond country-aggregated LUH2 flooded area (i.e. where FAO reports higher country-level rice areas than there are LUH2 flooded areas in the respective country) equally across the remaining country's cropland area. Note that flooded areas are not accounted as irrigated areas. For one, because flooded rice production is often only partially irrigated with blue water and often just retains the rainwater in paddies (Klein Goldewijk et al., 2017; Hurtt et al., 2020) and also because flooding fulfills a special management purpose in terms of pest control (Ampong-Nyarko & De Datta, 1991).

Given the area irrigated and the crop pattern in 2010 derived from LUH2 and FAOSTAT, the volume of current cellular irrigation water use ($U_{c,w}$) is calculated (see equation 1).

$$U_{c,w} = \sum_{k} V_{c,k,w} \cdot A_{c,k} \tag{1}$$

where $V_{c,k,w}$ refer to the crop water requirements per crop type (k) and grid cell (c) for the two water use types ($w =$ consumption and withdrawal), $A_{c,k}$ is the irrigated area per grid cell and crop.

4. Environmental Flow Requirements

The share of yearly discharge to be reserved for EFR per grid cell is calculated over a long-term reference period (1985-2015) based on monthly discharge provided by LPJmL4 (Schaphoff, von Bloh, et al., 2018). For a functioning freshwater ecosystem, a certain base flow (low flow requirements, LFR) is necessary to avoid aquatic species loss. Additionally, flooding plays an important role for riverine vegetation and wetlands. It can be accounted for by high flow requirements (HFR) (Smakhtin et al., 2004). We follow the Variable Monthly Flow (VMF) method introduced by Pastor, Ludwig, Biemans, Hoff, and Kabat (2014). It determines EFR using the flow variation throughout a year with different requirements for low-, intermediate- and high-flow months parametrized to a 'fair' ecosystem preservation status. In low-flow months (i.e. months in which mean monthly flow is smaller or equal to 40 % of the mean annual flow), 60 % of mean monthly flows are reserved for the environment; in intermediate-flow months (i.e. months in which mean monthly flow is greater than 40 %, but smaller than 80 % of the mean annual flow) 45 %; and in high-flow months (i.e. months in which mean monthly flow is greater than 80 % of the mean annual flow) 30 % of mean monthly flows is reserved (Pastor et al., 2014). We adopted this method by splitting EFR into LFR and HFR-equivalents. Discharge reserved in low-flow months is attributed to LFR, discharge reserved in high-flow months is attributed to HFR, and half of intermediate-flow requirements are attributed to LFRs and the other half to HFRs to appropriately consider the interaction of EFR and inaccessible discharge.

Not all water on Earth can easily be brought into productive use (Postel et al., 1996; de Fraiture et al., 2001). Especially highly variable flows are difficult to access for humans and could only be used for irrigation with appropriate storage infrastructure (reservoirs), which are costly to install. To account for such inaccessible (or hardly accessible) discharge, we use the coefficient of variation (CV) of monthly discharge over a reference period of 30 years (here: 1980-2010) assuming a functional relationship that leads to a decrease in accessibility with increasing long-term seasonal variability of discharge (see equation 2).

$$a_c = 2^{\frac{\sigma_c}{\mu_c}} \tag{2}$$

where a_c is the share of discharge in cell c that can be accessed, σ is the standard deviation of long-term monthly discharge in cell c and μ is the mean discharge of cell c over the same long-term period. The CV is the ratio of the two ($\frac{\sigma_c}{\mu_c}$). With the monthly discharge time series provided by LPJmL4, the CV ranges between 0 and 19.11 resulting in a functional form as displayed in figure S2b). The bulk of the data lies between 0 and 3.61 with the 25$^{\text{th}}$ percentile at 1.08 and the 75$^{\text{th}}$ percentile at 2.09 (see figure S2a). Only a few grid cells show discharge variability that results in complete inaccessibility.

We assume that seasonally highly variable flows are difficult to access by humans, but may serve an ecosystem function similar to HFRs. The baseflow or LFR, on the other hand, cannot be served by such variable flows and must be left untouched by human intervention when the environmental flow protection is considered. For this reason, we split discharge reserved for EFR into HFRs and LFRs. When discharge is constrained based on the accessibility constraint, HFRs count towards the inaccessible discharge, while LFRs are excluded from human access in addition to inaccessible discharge.

Natural Land Protection

The following map shows areas of ecological importance following the Half-Earth protection approach based on the data provided by Kok et al. (2020). It includes currently protected areas based on the World Database of Protected Areas (WDPA), biodiversity hotspots (Mittermeier et al., 2005) and intact forest landscapes (Potapov et al., 2017). On top of these areas, at least 50 % of the land surface of each 'ecoregion' as described in Dinerstein et al. (2019) is protected.

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Crop types considered in LPJmL	**Crop types considered in this study**
Temperate cereals	Temperate cereals
Tropical cereals	Tropical cereals
Maize	Maize; Others (fruits, vegetable, nuts); Forage
Rice	Rice
Oil crops (soybean)	Soybean
Oil crops (rapeseed)	Other oil crops (including rapeseed)
Oil crops (groundnut)	Groundnuts; Oilpalms; Cotton
Oil crops (sunflower)	Sunflower
Pulses	Pulses
Temperate roots	Potatoes; Sugar beet
Tropical roots	Tropical roots (including cassava)
Sugar cane	Sugar cane
Biomass grass	Short rotation grasses
Biomass trees	Short rotation trees

Table S1. Mapping of LPJmL crop types to crop types considered in our analysis.

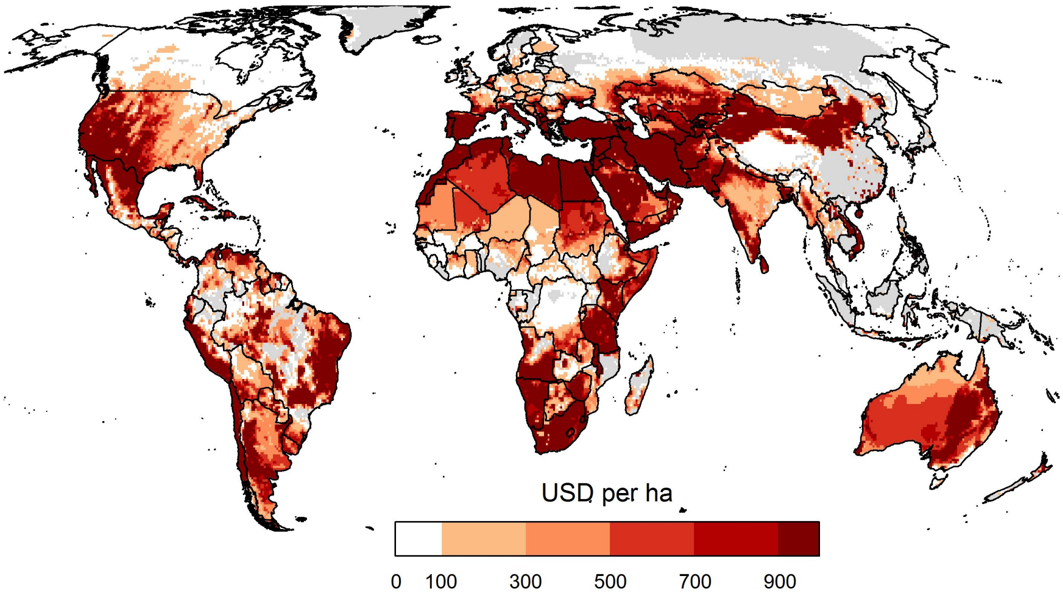

Figure S1. Potential yield value gain through irrigation in USD ha^{-1}. Areas in grey have a yield value gain of 0.

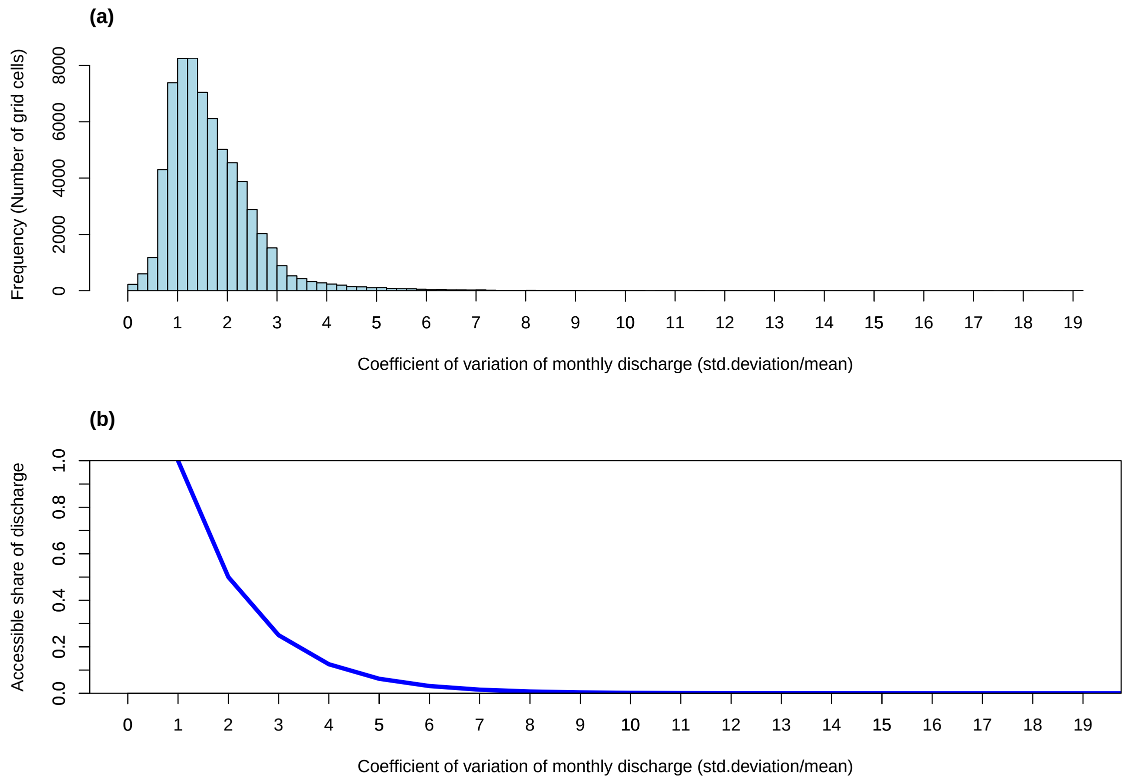

Figure S2. Frequency Coefficient of Variation of monthly discharge (a) and functional relationship between discharge accessibility share and coefficient of variation of discharge for time series of monthly discharge over the period from 1980 to 2010.

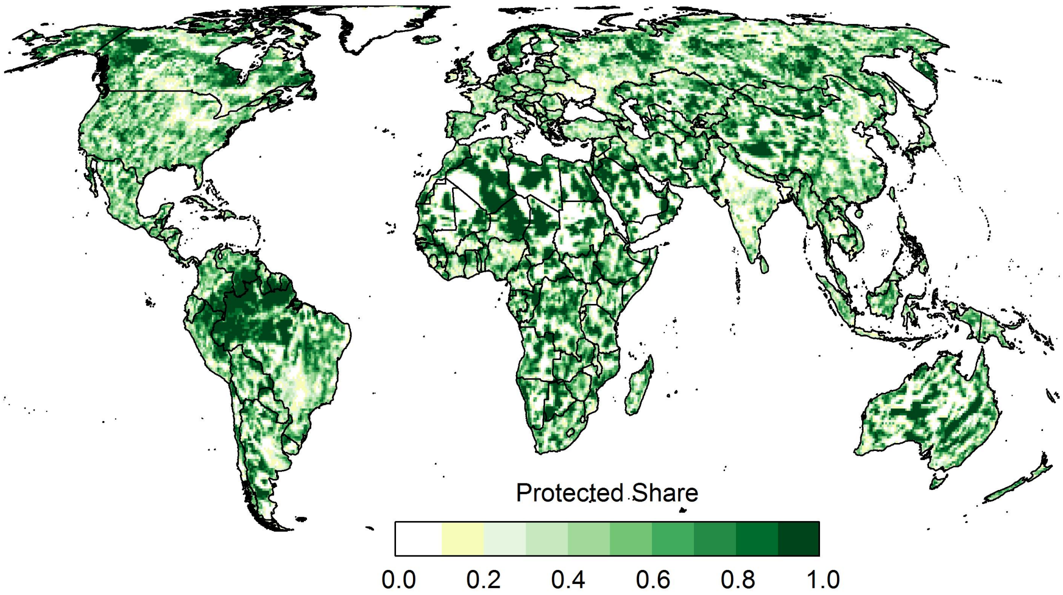

Figure S3. Share of grid cell that would be protected according to the Half-Earth protection approach.