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Potential for sustainable irrigation expansion in a 3 °C warmer climate

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Climate change is expected to affect crop production worldwide, particularly in rain-fed agricultural regions. It is still unknown how irrigation water needs will change in a warmer planet and where freshwater will be locally available to expand irrigation without depleting freshwater resources. Here, we identify the rain-fed cropping systems that hold the greatest potential for investment in irrigation expansion because water will likely be available to suffice irrigation water demand. Using projections of renewable water availability and irrigation water demand under warming scenarios, we identify target regions where irrigation expansion may sustain crop production under climate change. Our results also show that global rain-fed croplands hold significant potential for sustainable irrigation expansion and that different irrigation strategies have different irrigation expansion potentials. Under a 3 °C warming, we find that a soft-path irrigation expansion with small monthly water storage and deficit irrigation has the potential to expand irrigated land by 70 million hectares and feed 300 million more people globally. We also find that a hard-path irrigation expansion with large annual water storage can sustainably expand irrigation up to 350 million hectares, while producing food for 1.4 billion more people globally. By identifying where irrigation can be expanded under a warmer climate, this work may serve as a starting point for investigating socioeconomic factors of irrigation expansion and may guide future research and resources toward those agricultural communities and water management institutions that will most need to adapt to climate change.

climate change | water sustainability | sustainable irrigation expansion | water scarcity | agriculture

Rain-fed agriculture sustains ~60% of global food production (1). Rain-fed cropping systems are highly dependent on climatic conditions and vulnerable to changes in precipitation and temperature patterns, which are intensifying as a result of global warming (2). Climate change is expected to alter rainfall patterns (3) and exacerbate water- and heat-stress events over rain-fed croplands (4–8). Irrigation expansion over water-stressed rain-fed croplands is an effective agricultural adaptation measure in response to climate change (9, 10). Irrigated cropping systems, which use both rainwater ("green water") and surface water and/or groundwater (or "blue water"), contribute to a more reliable and resilient crop production while boosting agricultural productivity. In fact, the use of irrigation enables reliable water supply and can also alleviate crop's heat stress, highlighting how important irrigation is to food-producing regions that will be affected by climate change (11).

Irrigation provides higher yields than rain-fed agriculture (1). However, irrigation expansion increases the pressure on global freshwater resources, often leading to their unsustainable use (12–14). Moving forward, humanity is facing the challenge of increasing productivity to meet the burgeoning demand for agricultural commodities (15) while reducing the environmental impacts of agricultural systems (16). Irrigation water management has a pivotal role in the sustainable intensification of agriculture (17)—an effort to increase crop yields over underperforming croplands without expanding agricultural land use (18). While this is a promising approach to meet the increasing food needs of humanity, it is still unclear to what extent climate change will influence the potential for sustainable expansion of irrigation into rain-fed areas.

The construction of large infrastructure has dominated irrigation expansion in the 20th century (19). However, this "hard-path" water governance approach with large, centralized, capital-intensive irrigation projects and water storage infrastructure (i.e., large reservoirs) has shown its vulnerability to fast-changing sociohydrological conditions and is often criticized for its socioenvironmental impacts, such as habitat destruction, human displacement, and altered sediment and hydrologic regimes (20). On the other hand, "soft-path" water harvesting for irrigation through capturing water resources in small and check dams has been suggested as an alternative approach to bring irrigation to rain-fed croplands (21–23). This soft-path water management approach relies on small, modular, and decentralized water management infrastructure and has the potential to improve rainwater use and climate resilience (24) while minimizing the environmental impacts of large irrigation infrastructure (25).

Significance

Climate change is expected to reshape the distribution of irrigated lands. Using climatic projections from three global climate models, we investigate global patterns of irrigation water demand and availability in 1.5 °C and 3 °C warmer climates. We find that in up to 35% of currently rain-fed croplands, irrigation could be expanded as an adaptation strategy to climate change without negative environmental externalities on freshwater resources. Irrigation expansion could reduce vulnerability to water stress and improve crop productivity to feed up to 300 million additional people using small-scale water storage and up to 1.4 billion additional people using large-scale water storage. This work contributes to identifying target regions where investments in sustainable intensification of agriculture through irrigation expansion are needed.

Author contributions: L.R., A.A.B.-P., P.D., and I.F. conceived the study; L.R., M.S., A.A.B.-P., P.D., and I.F. designed research; L.R. collected data, analyzed data, and wrote the paper with inputs from P.D. and I.F.; D.D.C. and M.C.R. assessed crop water requirements using WATNEEDS Model; and M.S. processed CMIP5 data.

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The authors declare no competing interest.

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Predictions of global irrigated areas are widely used to guide water and food security strategies. Considering current climate conditions, a 2011 FAO (Food and Agriculture Organization of the United Nations) study estimated that global irrigated areas could expand by 32 million hectares by 2050 (26). More recently, by considering future uncertainties in population growth rates, it has been suggested that current models underestimate irrigation expansion, suggesting that future irrigation could expand by at least 70 million hectares by 2050 (27). These studies, however, did not consider potential freshwater limitations to irrigation expansion to currently rain-fed croplands under a changing climate. For example, freshwater limitations in some regions that are currently irrigated could require the reversion of 20 to 60 million hectares from irrigated to rain-fed management by the end of the century due to climate change (28). They also fall short of elucidating where and to what extent irrigation can be expanded into rain-fed croplands without depleting freshwater resources and impairing aquatic ecosystems. A limited hydrological understanding of the effects of irrigation expansion potential under a changing climate adds uncertainties to future climate adaptation strategies in agriculture.

Herein, we present a global hydrological analysis of the potential impacts of climate change on irrigation water demand and availability. We used the output from three earth system models from the Coupled-Model-Intercomparison-Project (CMIP5) archive (*Materials and Methods*) to quantify sustainable irrigation expansion potential (SI) under baseline and 3 °C warmer climate conditions with respect to preindustrial era. Irrigation practices are classified as sustainable when their water consumption does not exceed local renewable water availability (WA; surface water and groundwater) and does not impair environmental flows and deplete freshwater stocks (14). We first identify croplands affected by green water scarcity (GWS)—croplands where the natural soil moisture regime is insufficient to sustain unstressed crop production and additional water needs to be supplemented by irrigation to boost yields (10). Second, using estimates of irrigation water requirements (IWRs) based on a crop water model (29), we identify the currently rain-fed croplands that will need to be irrigated in a 3 °C warmer climate. Third, we map presently rain-fed agricultural regions where the local surface water and groundwater resources would allow for a sustainable expansion of irrigation using monthly water storages (*Materials and Methods*). Fourth, because farmers might practice water management strategies to conserve water and adapt to climate change (22, 30, 31), we also consider a soft-path scenario coupled with deficit irrigation where only 80% of the IWR is applied to crops. Lastly, we account for the fact that under climate change, water availability and demand will have larger intra-annual variability (32), leading to the construction of reservoirs to store excess runoff and releasing it during the growing season to meet irrigation water demand (33). Thus, as an additional climate adaptation strategy, we consider a hard-path scenario where IWRs can be met by storing runoff with large annual water storage. Therefore, we identify rain-fed cropping systems where IWRs can be sustainably met either with soft-path monthly irrigation storage alone, or through deficit irrigation with soft-path monthly irrigation storage, or with hard-path annual water storage infrastructure. Finally, we estimate the amount of arable land and water that is suitable for irrigation expansion and the number of people who could be potentially fed from the increased crop productivity due to irrigation expansion.

Soft-path approaches to irrigated agriculture were investigated through an analysis of the potential for sustainable irrigation expansion at monthly timescales. Soft-path irrigation expansion is feasible when WA is locally available in a specific month to sustainably meet IWRs. Hard-path approaches to irrigated agriculture were investigated by looking at the potential for sustainable irrigation expansion at annual timescales, assuming that the effect of seasonal fluctuations in water availability could be compensated by relying on annual (i.e., interseasonal) water storages. In other words, even though there is not enough water available to sustainably meet the IWRs during some months, such requirements could be met at the annual timescale by transferring water from the wet to the dry seasons. Such transfers likely require the construction of medium- to large-scale reservoirs and associated infrastructure, although other approaches based on groundwater storage or managed aquifer recharge could also be explored.

Results

GWS in a 3 °C Warmer Climate. We assessed GWS in rain-fed cropping systems under baseline (circa year 2000) and 3 °C warmer climate conditions (Fig. 1). Under baseline climate conditions, we find that only 14% (130 million hectares) of global croplands do not face monthly GWS, and therefore, here crops can grow well under primarily rain-fed conditions. The rest of the rain-fed croplands do not achieve maximum yield because of water stressed crop growth under GWS conditions. In a 3 °C warmer climate, only 60 million hectares of cropland would not be exposed to GWS. Alarmingly, the remaining 70 million hectares of these rain-fed croplands that would face additional GWS currently provide food that feeds ~700 million people globally. The United States will have an additional 14 million hectares of rain-fed croplands exposed to GWS. China, Russia, and Canada will each have an additional 5 million hectares of rain-fed croplands exposed to GWS (Fig. 1). We also find that rain-fed cropping systems in low-income countries will face additional GWS, often in regions where local populations depend the most on rain-fed agriculture (34, 35). Brazil and Indonesia are expected to have an additional 10 and 5 million hectares of rain-fed croplands exposed to GWS, respectively. Rain-fed cropping systems in the Philippines, Angola, Bolivia, Angola, Mozambique, Democratic Republic of Congo (D.R.) Congo, India, and Cambodia will also face additional GWS (Fig. 1). These croplands affected by GWS would need supplemental irrigation water to adapt to climate change and avoid crop growth under water-stressed conditions. We assessed that in a 3 °C warmer climate, global IWR over rain-fed croplands will increase by 40% compared with baseline climate conditions due to changes in precipitation patterns and evaporation (*SI Appendix*, Fig. S1).

Irrigation Expansion Potential in a 3 °C Warmer Climate. The widespread exposure to GWS is of particular concern for global and local food security. The expansion of irrigation into rain-fed croplands facing GWS could avoid crops' exposure to water stress, increase crop yields and therefore adapt agriculture to climate change. We assessed SI over rain-fed cropping systems under baseline and 3 °C warmer climate conditions. Considering a soft-path approach that requires small monthly water storage, the additional area of cropland suitable for sustainable irrigation expansion is 140 million hectares under baseline climate conditions (Fig. 2) and only 53 million hectares in a 3 °C warmer climate (Fig. 3). We estimate that the expansion of irrigation over rain-fed croplands under a warmer climate would feed ~200 additional million people, much fewer than the additional ~600 million people under baseline climate conditions (Fig. 3).

We also find that different water management strategies yield different irrigation expansion potentials. By allowing for monthly water storage with 20% deficit irrigation (i.e., meeting 80% of the IWR), the extent and potential for sustainable irrigation expansion on rain-fed croplands would increase by an additional 16 million hectares (Fig. 3). This sustainable expansion of irrigation would feed ~100 million more people globally (Fig. 3). By storing runoff with hard-path annual water storage, it would be

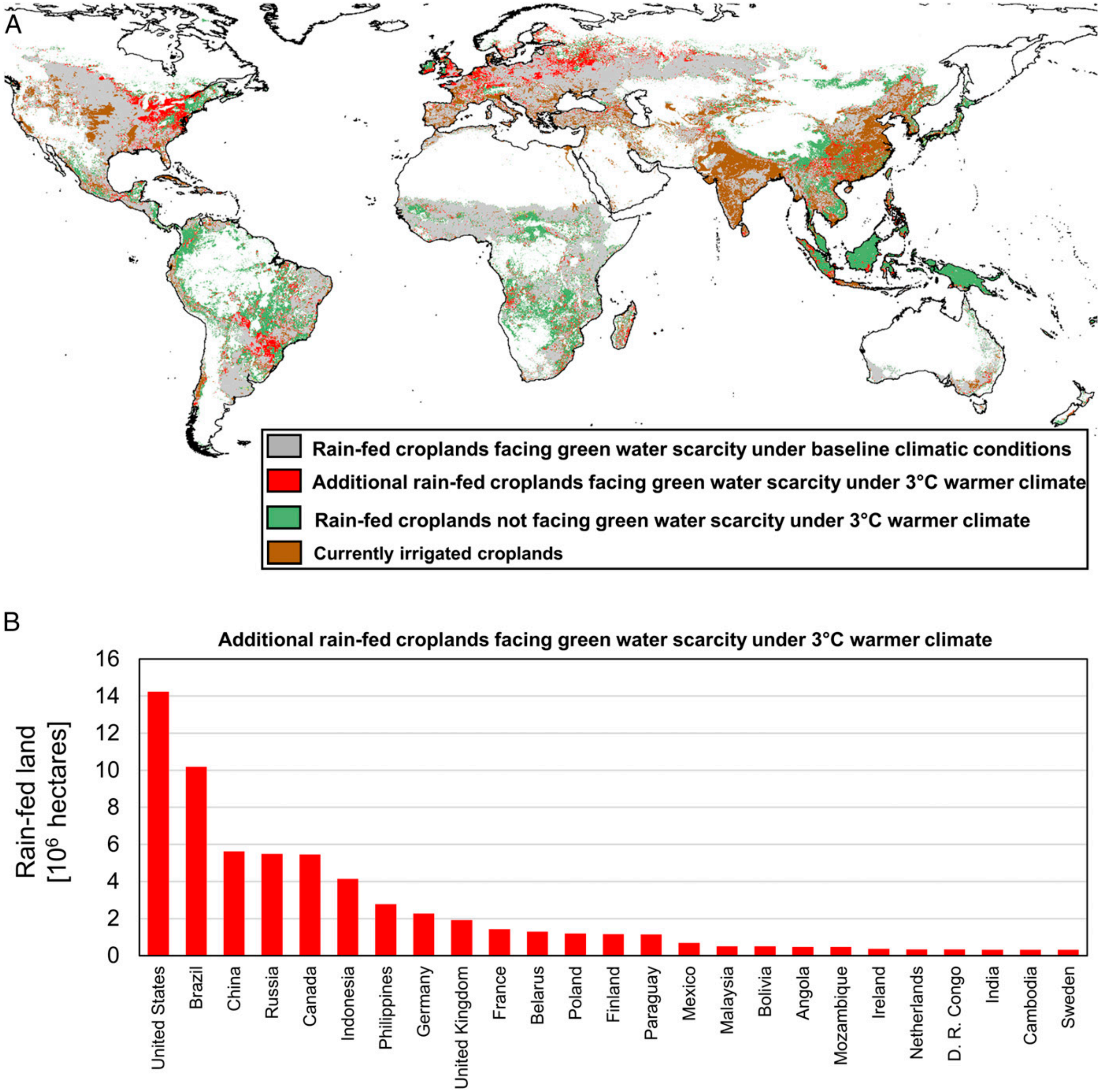

Fig. 1. Additional rain-fed croplands facing GWS in a 3 °C warmer climate. (*A*) Change in the geography of rain-fed cropping systems facing GWS in a 3 °C warmer climate. (*B*) Country-specific additional hectares of rain-fed croplands that will be exposed to GWS in a 3 °C warmer climate. We selected 20 countries with the highest hectares of lands that will be additionally exposed to GWS. "Currently irrigated croplands" represent the most up-to-date global dataset with the extent of global irrigated cropping systems (39).

possible to sustainably expand irrigation up to 350 million hectares while producing food for 1.4 billion additional people (Fig. 3).

Regions with potential for sustainable irrigation expansion tend to concentrate in eastern Europe, central Asia, Latin America, and sub-Saharan Africa (Fig. 4). In eastern Europe and central Asia, soft-path irrigation expansion combined with deficit irrigation practices would produce enough food to feed 60 million more people while expanding irrigation over 13 million hectares. In Latin America, soft-path irrigation expansion combined with deficit irrigation practices would produce enough food to feed an additional 50 million people, expanding irrigation over 17 million hectares. In sub-Saharan Africa, soft-path irrigation expansion combined with deficit irrigation would produce enough food to feed 35 million people while expanding irrigation over 8 million hectares (~80% increase with respect to current irrigation extent). Opportunities for irrigation expansion differ markedly by country (*SI Appendix* has detailed country-specific data). Nigeria, Russia, Ukraine, Kazakhstan, Canada, Turkey, India, Poland, Romania, and Niger will be affected the most by a reduction in areas suitable for sustainable irrigation expansion under climate change. Conversely, Brazil, United

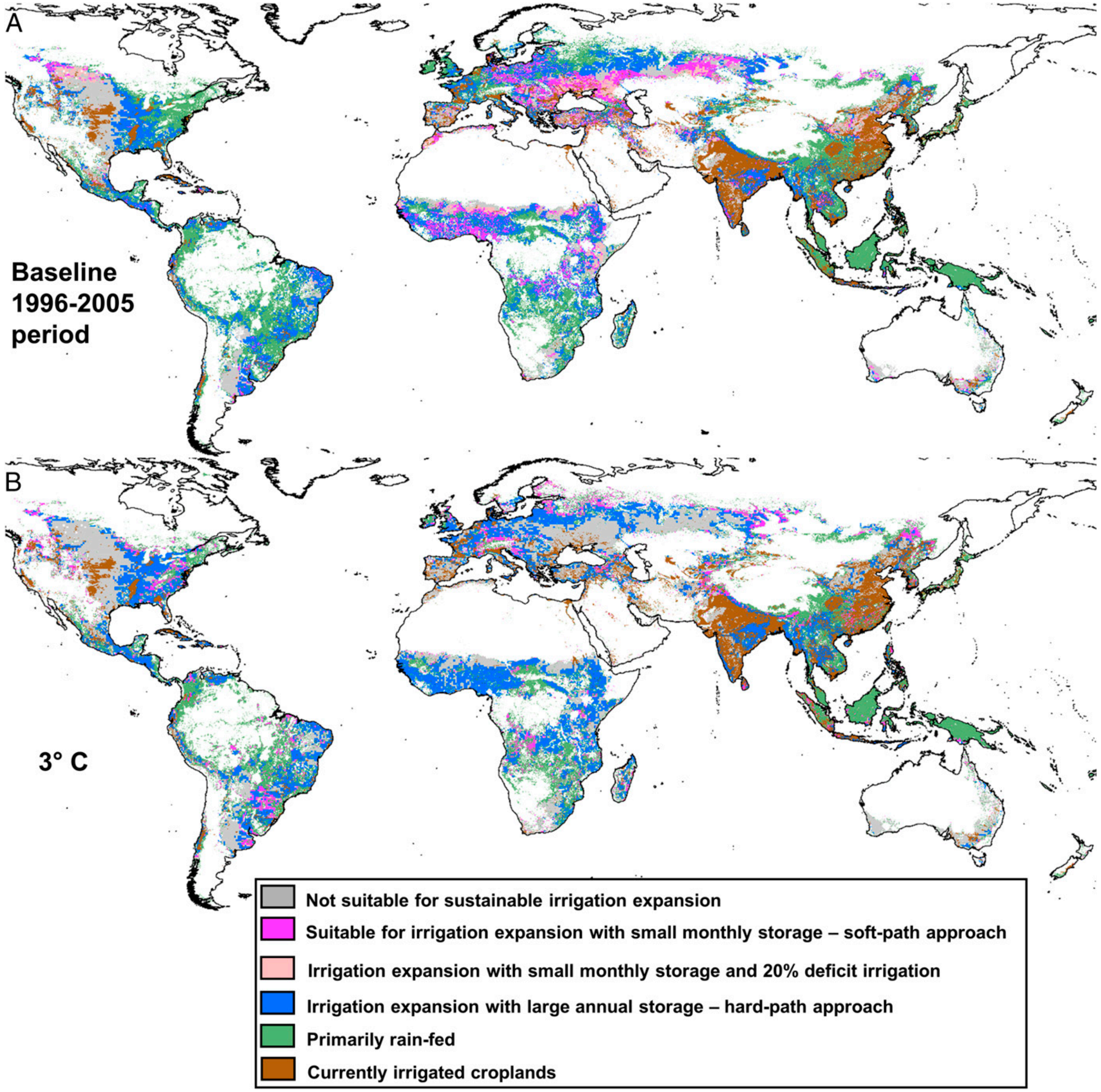

Fig. 2. The geography of SI under climate change. The maps show global distributions of areas suitable for irrigation expansion under baseline (*A*) and 3 °C warmer climate (*B*) conditions. The figure shows the geography of the additional SI obtained with 1) soft-path approaches (i.e., small monthly storage) with full or 2) 20% deficit irrigation and 3) hard-path approaches (i.e., large annual water storage). Deficit irrigation is an agricultural practice under which crops are grown under mild water-stressed conditions with minimal effects on yields (10). Primarily rain fed indicates croplands not facing GWS under baseline and 3 °C warmer climate conditions. The figure shows results from the median among the ensemble of scenarios used in this study. The soft-path scenario with deficit irrigation is additional to the soft-path scenario, and the hard-path scenario is additional to soft-path scenarios.

States, Indonesia, and the Philippines will have substantial gains in areas suitable for sustainable irrigation expansion (Fig. 2).

We also find that climate change will increase seasonal water scarcity and will require an increase in large annual water storage to maintain current SIs. Under baseline climate conditions, the global water consumption deficit to meet crop water requirements in the irrigation expansion scenario is 196 km^3 (Fig. 3). In a 3 °C warmer climate, the water consumption deficit required to maintain a similar irrigation expansion potential would increase to 406 km^3. Sub-Saharan Africa, eastern Europe, and central Asia are regions where large annual water storage will be particularly required to maintain a similar irrigation expansion potential compared with baseline conditions (Fig. 4). In fact, we estimate that without annual water storage for irrigation, these regions will lose 120 million hectares of croplands suitable for sustainable irrigation expansion under baseline climate conditions (Fig. 4). We also find that different crop types and locations create diverging patterns of irrigated lands, water consumption,

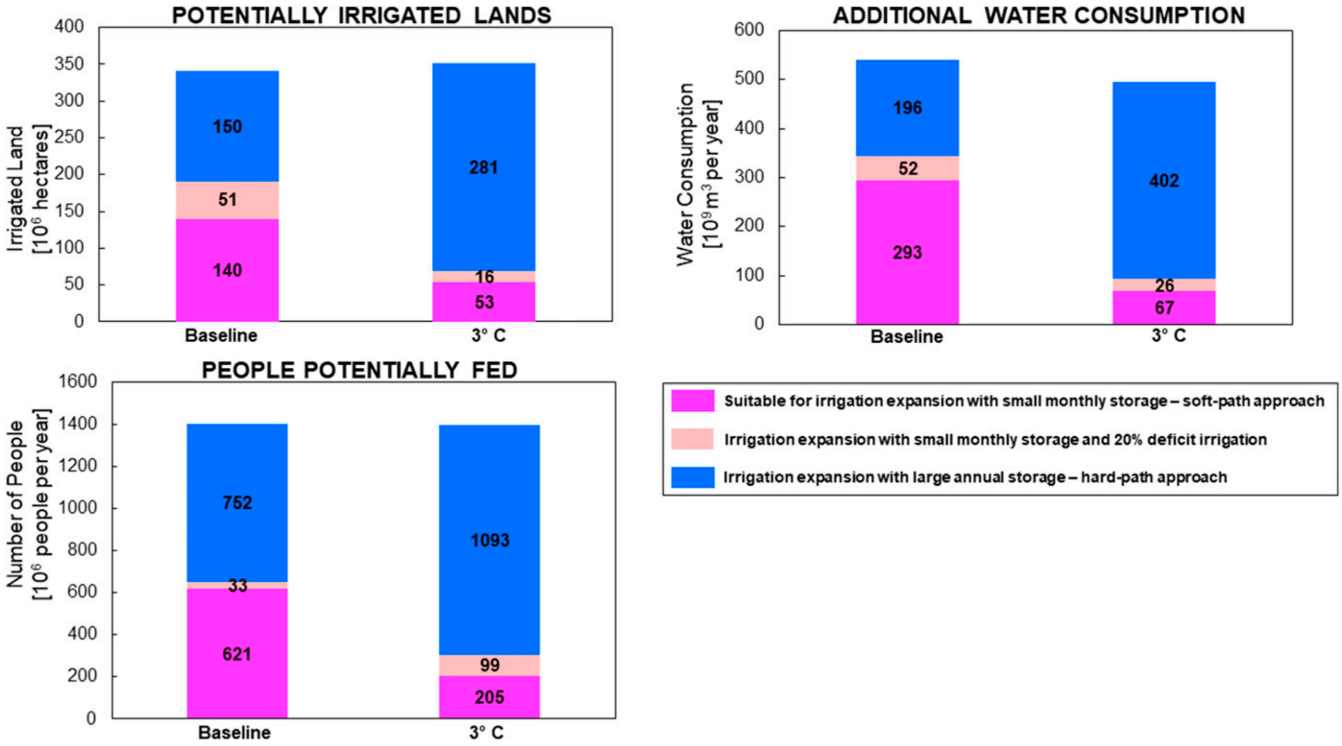

Fig. 3. The global potential for sustainable irrigation expansion under different climate conditions: additional land (*Upper Left*), water (*Upper Right*), and people who could be sustainably fed by applying different water management practices (*Lower Left*).

and people fed among scenarios and regions (Fig. 4). For instance, our results show that in North America, irrigated areas and the number of people fed increase compared with baseline conditions, while water consumption decreases in a 3 °C warmer climate because of changes in precipitation patterns.

Discussion

Rain-fed agriculture still has large untapped potential to ensure sustainable use of blue water resources to enhance food production and meet the growing needs of the global population (36). Marginalized rural communities in developing countries tend to rely on rain-fed agriculture and are therefore expected to be impacted the most by the changing climate (35, 37). This study highlights the SI of rain-fed cropping systems under climate change. We identify the rain-fed cropping systems that hold the greatest potential for investment in irrigation expansion because water will likely be available to meet irrigation water demand. An additional 70 million hectares of rain-fed cropping systems, mostly in developing countries, will be exposed to GWS in a 3 °C warmer world (Fig. 1). If at-risk rain-fed croplands are not able to introduce adaptation strategies (including irrigation), crop yields will decrease. Our results show that there is substantial potential for sustainably expanding irrigation in eastern Europe, central Asia, sub-Saharan Africa, and Latin America (Fig. 2). Even though large tracts of contemporary agricultural land are not suitable for irrigation in a warmer climate, in up to 35% of currently rain-fed croplands, water resources will be locally available for an expansion of irrigation without negative environmental externalities on freshwater resources. Our results also show that different irrigation strategies have different irrigation expansion potentials. Under climate change, a soft-path irrigation expansion with monthly water storage and deficit irrigation has the potential to expand irrigated land by ~70 million hectares and feed ~300 million more people globally (Fig. 4), thereby compensating the expected reversion of 60 million hectares of currently irrigated lands to rain-fed management due to freshwater limitations (28). We also find that a hard-path irrigation expansion with annual water storage can sustainably expand irrigation up to 350 million hectares while producing food for 1.4 billion more people globally, although with other socioenvironmental impacts not accounted for in this study.

The study is also based on the assumption of a suitable environmental flow scenario—the minimum streamflow required to sustain freshwater ecosystems. Therefore, we tested the sensitivity of our results to different environmental flow requirements. With the current assumption that 60% of runoff is allocated to environmental flows, irrigation can be sustainably expanded to up to 350 million hectares in annual storage (hard-path) scenario. By adopting a more conservative approach, where 80% of available water is left to environmental flows, the areas suitable for sustainable irrigation expansion would decrease to 220 million hectares (Dataset S1). Considering soft-path monthly storage, the areas suitable for irrigation expansion would decrease from 53 million to 27 million hectares. We also tested the sensitivity of our results to 1.5 °C warmer climate conditions (*SI Appendix*, Fig. S3). When we consider a 60% environmental flows threshold with soft-path monthly storage, 58 million hectares are suitable for irrigation expansion under a 1.5 °C warmer climate. With an 80% environmental flows threshold under this warming scenario, the global area suitable for irrigation expansion with soft-path approaches is 29 million hectares (Dataset S1).

The term "sustainable irrigation" is used here to indicate a situation in which water consumption does not exceed water availability and protects environmental flows and freshwater stocks. This study emphasizes the potential for sustainable irrigation expansion in a system that maintains the current crop distribution and yields (38, 39) without consideration of crop response to increased temperature and atmospheric CO_2 concentrations or farmers' adaptation to climate warming through

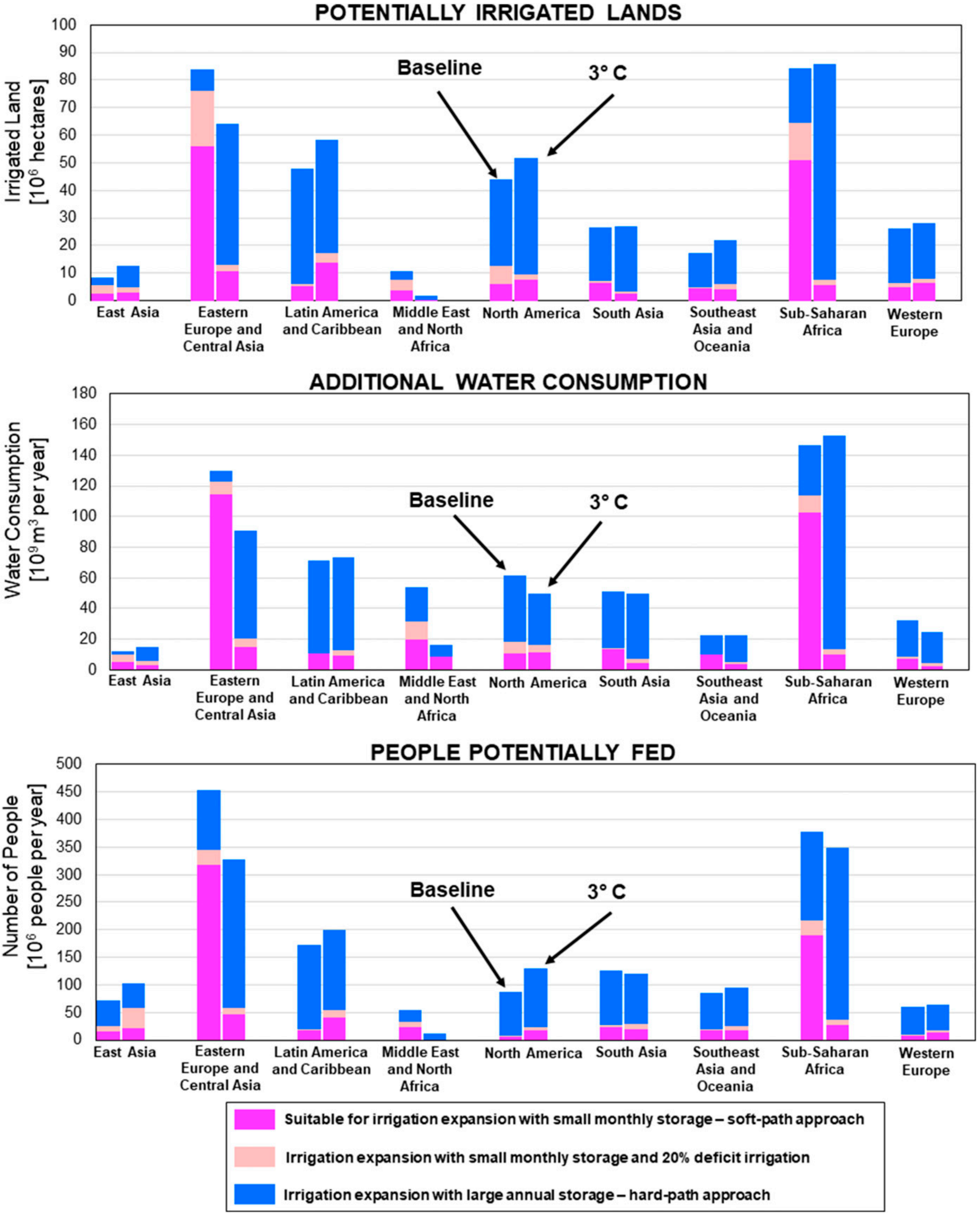

Fig. 4. Regional distribution of potential irrigated areas (*Top*), water consumption (*Middle*), and people fed with sustainable irrigation expansion (*Bottom*).

changes in crop varieties and location (40–44), nutrient amendments through fertilizers (17), or of the feedback of irrigation expansion on the regional climate (45). The hydrologic models used do not account for all existing water infrastructure or the feasibility of their expansion. Inclusion of these factors, as well as changing domestic and industrial water demand (46), and other soft-path water management practices, such as mulching, pitting, terracing, no-till farming, and agroforestry (22, 47), would likely reduce the amount of water available or needed for irrigation. In this sense, the estimates provided by this study serve as an upper limit to irrigation water needs. Beyond the scope of this work are considerations of technologic innovations in agriculture and in water storage and delivery systems, legal and political restrictions on water use, other socioeconomic factors and barriers that may limit or prevent the expansion of irrigation, and the implications on equity and justice through an analysis of who benefits on large-scale irrigation schemes. This study could serve as a starting point for the inclusion of these other factors.

We find that a hard-path irrigation expansion with annual water storage could be adopted to store enough water to maintain irrigation expansion potential under climate change compared with baseline climate conditions. However, increasing annual water storage could also fuel vicious cycles, leading to overproportionate growth in demand and reliance on reservoir storage, thereby favoring unsustainable water use and increasing vulnerability to climatic extremes (48). Moreover, while hard-path approaches may appear to be sustainable adaptations to climate change from a water use perspective, they typically require the construction of dams and other infrastructures that are far from being environmentally sustainable measures to cope with water scarcity. Importantly, the proposed reservoirs would need to have storage capacities greater than the water withdrawals, which in turn, would exceed the irrigation water consumption deficits, by amounts that would depend on irrigation technology and water losses throughout the system.

The potential for irrigation expansion is an important factor to evaluate for future climate adaptation strategies in agriculture (49). Increases in water-stress and changes in precipitation patterns over rain-fed croplands are already well documented (50). By investigating where rain-fed cropping systems are suitable for and benefit the most from sustainable irrigation expansion, this work contributes to identifying future target regions where investments in sustainable intensification of agriculture through irrigation expansion are needed.

Materials and Methods

We used climate output from three earth system models from the CMIP5 archive to quantify SI under baseline, 1.5 °C warmer, and 3 °C warmer climate conditions with respect to the preindustrial era. The baseline scenario refers to the 1996 to 2005 period—the reference period for global agricultural datasets (39). The 1.5 °C warming scenario refers to the Paris climate target, while the 3 °C warming scenario is a way of bypassing model differences in transient response timing and "normalizing" the response of different models to the same warming (51, 52). First, the climate projections obtained with the earth system models are fed into the WATNEEDS crop water model to assess IWRs and total crop water requirements (CWRs). Second, IWR and CWR were used to assess GWS and SI over global croplands. Third, we estimated the additional land that could be irrigated and the people who could be potentially fed with the increased agricultural productivity from SI. This study has been performed at 30 by 30-arc min resolution (~50-km resolution), the resolution of climate outputs from earth system models.

Climatic Data. We used climatic data (precipitation, runoff, and evaporation) under baseline and future climate forcing (under 1.5 °C and 3 °C warmer climate conditions). Long-term climatic data for the baseline scenario (1996 to 2005 period) were taken from datasets calibrated using historical observations. Local (surface and subsurface) runoff estimates were obtained from the Composite RunoffV1.0 database (53). Precipitation came from the Climate Hazards Group Infra-Red Precipitation with Station version 2.0 dataset (54). Potential reference evapotranspiration came from the University of East Anglia's Climate Research Unit Time Series version 4.01 dataset (CRU TS v. 4.01) (55).

For long-term future climate forcing, we used CMIP5 RCP8.5 and downloaded monthly precipitation, evaporation, and runoff (surface and subsurface) from the outputs of three global climate models (GFDL-ESM2M, HadGEM2-ES, MIROC-ESM-CHEM) and three global hydrological models (LPJmL, H8, WATERGAP2) as provided by the Inter-Sectoral Impact Model Intercomparison Project (https://www.isimip.org/) (56) (*SI Appendix*, Tables S1 and S2). Following de Graaf et al. (46), we selected the wettest (GFDL-ESM2M), average (HadGEM2-ES), and driest (MIROC-ESM-CHEM) global climate model outcomes in terms of projected future global precipitation change. In total, we selected 18 climate outputs: 9 with 1.5 °C and 9 with 3 °C warmer climate conditions (*SI Appendix*, Tables S1 and S2). For each climatic output, we calculated the difference between projected and historical precipitation, runoff, and evaporation throughout the world and added this difference to the baseline observed precipitation, runoff, and evaporation data. Adding the perturbation (model projection climate minus model historical climate) to an observed reference climate is a standard practice in the analysis of climate model results. This is because model historical climates differ among models. There is insufficient observations/information, and hence, differing assumptions, about the time history of some terms of climate forcing, especially aerosols and land use. Also, each CMIP5 model has a different treatment of aerosols and clouds, and this in turn influences the regional distributions of precipitation. By "anchoring" the climate change to a known observed reference climate from which the present-day irrigation scenarios are derived, we have greater confidence in our findings (i.e., assessing the change in irrigation expansion potential in 1.5 °C and 3 °C warmer climates). The main results of this study are presented using the median of the ensemble of the nine simulations considered for each climate warming scenario, and therefore, we did not investigate the range of variability between the driest and wettest models.

Assessment of IWR and CWR. CWR is the amount of water needed by a crop to satisfy its water demand and avoid water-stressed crop growth. CWR can be satisfied through precipitation and supplemented with IWR if precipitation is insufficient to meet CWR. CWR and IWR were assessed using the WATNEEDS crop water model (ref. 29 has a detailed description). WATNEEDS is a global process-based crop water model that is set up to calculate CWR and IWR for 130 primary crops (nearly 100% of global crop production). The model calculates a crop-specific CWR using a daily soil water balance during each crop's growing season using as inputs crop-specific distribution data, crop-specific parameters, precipitation, evaporation, and soil information. We run WATNEEDS using baseline, 1.5 °C warmer, and 3 °C warmer precipitation and evaporation data while keeping the spatial extent of global croplands fixed to the MIRCA2000 dataset (39)—the most updated dataset containing spatially explicit information of global croplands extent. WATNEEDS has been extensively used to assess CWR and IWR (9, 10, 14, 57, 58).

Assessment of GWS and Sustainable Irrigation Expansion Potential. GWS was computed as the ratio between IWRs (or green water deficits) and CWRs (10):

$$GWS = \frac{IWR}{CWR}.$$

Crops face GWS when rain-fed conditions cannot meet CWR. We classify as green water-scarce croplands those regions with a GWS greater than 0.1, assuming that a smaller level of GWS would not justify investments in irrigation infrastructure because it would be associated with low levels of crop water stress and associated crop yield reduction (9, 10).

The potential for SI was evaluated by identifying croplands facing GWS that are currently not equipped for irrigation and where the ratio between total water consumption (IWR + other uses [OUs]) and WA is smaller than 1 (9, 10):

$$SI = \frac{IWR + OU}{WA} < 1.$$

WA was assessed as the difference between blue water flows in each grid cell (including both local runoff generation and runoff from upstream) and environmental flow requirements. WA accounts for surface and subsurface runoff water flows. Blue water flows were assessed from local runoff estimates and calculated using the upstream–downstream routing "flow accumulation" function in ArcGIS. Environmental flows requirements were assessed considering that 60% of available runoff has to be left into the environment for environmental flows protection (10, 14, 59). OU is water consumption from OUs (industrial and domestic water consumption). OU for the 1996 to 2005 period was taken from Hoekstra and Mekonnen (60) and following de Graaf et al. (46), kept constant in the warmer climate scenarios.

Assessment of People Potentially Fed. For each crop, baseline and maximized calorie productions were assessed as the product of crop yield (tons per hectare), crop calorie content (kilocalories per tons), and crop harvested area (hectares). Baseline and maximized crop yields were taken from Monfreda et al. (38) and Mueller et al. (17), respectively. Maximized crop yields are assumed to be attained in irrigated croplands where CWR is fully met with irrigation. Calorie content for each crop was taken from D'Odorico et al. (61). Crop harvested areas were taken from Portmann et al. (39). We considered a linear relation between crop yields and biophysical water deficit (10, 28), assuming that irrigated production decreases by 20% under a 20% irrigation deficit scenario. We calculated the number of people who can be potentially fed by the global croplands considering a global average diet of 3,343 vegetal kcal per capita per day, which includes both crops for direct human consumption and feed to sustain feed-fed livestock production, as well as food waste (9, 10).

Data Availability. All data needed to evaluate the conclusions in the paper are present in the paper and in *SI Appendix*. The maps containing GWS and irrigation expansion potential (used to generate Figs. 1 and 2) are available in Zenodo (https://zenodo.org/record/3995044#.X43aOtBKiUk).

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Supplementary Materials for

Potential for sustainable irrigation expansion in a 3C warmer climate

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This PDF file includes:

- Supplementary Tables 1 and 2
- Supplementary Figures 1 to 4

Other supplementary materials for this manuscript include the following:

- Supplementary dataset (uploaded as an .xlsx file).

Table S1. Time period when the three selected global climate models used in the study (GFDL-ESM2M, HadGEM2-ES, MIROC-5) are projected to reach 1.5ºC and 3ºC warmer climate conditions respect to pre-industrial era. The global mean temperature in year 2019 was estimated to be 1.1°C above the average temperature of the late 19th century, from 1850-1900, a period often used as a pre-industrial baseline for global temperature targets (World Meteorological Organization, 2019).

	1.5ºC	**3ºC**
MIROC 5	2022-2031	2063-2072
GFDL-ESM2M	2033-2042	2077-2086
HadGEM2-ES	2011-2020	2047-2056

Table S2. Combination of simulation with global climate models and hydrological models used to obtain precipitation, runoff and evaporation outputs from the Inter-Sectoral Impact Model Intercomparison Project ISIMIP (https://www.isimip.org/). In total, we selected 18-climate outputs, nine with 1.5ºC warmer climate and nine with 3ºC warmer climate conditions.

Climate model	**Hydrological model**
GFDL-ESM2M	H8
GFDL-ESM2M	WATERGAP2
GFDL-ESM2M	LPJmL
MIROC5	H8
MIROC6	WATERGAP2
MIROC7	LPJmL
HadGEM2-ES	H8
HadGEM2-ES	WATERGAP2
HadGEM2-ES	LPJmL

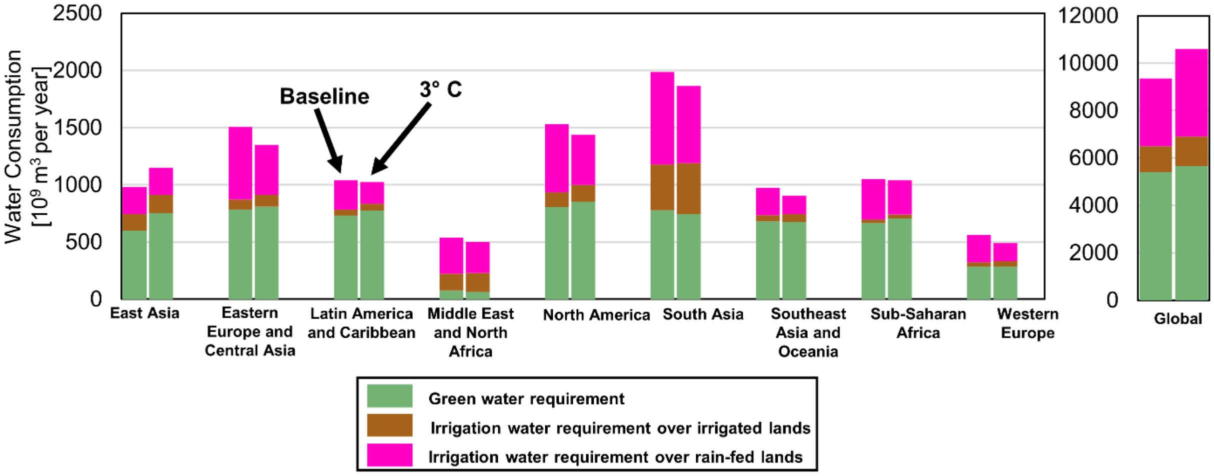

Figure S1. Global green and irrigation (blue) water requirements over cultivated lands. Volumes are assessed considering baseline (1996-2005 period) and 3ºC warmer climate conditions.

Figure S2. Regions used to create figure 4.

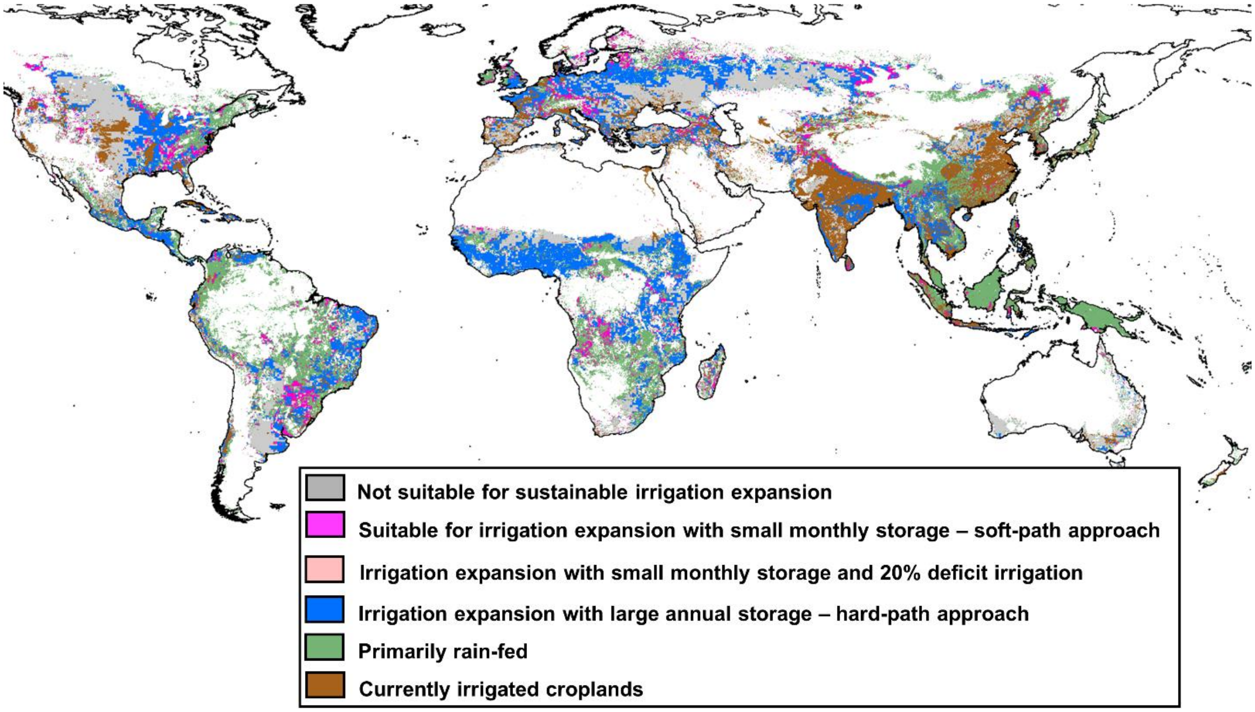

Figure S3. The geography of sustainable irrigation expansion potential under a 1.5ºC warmer climate. The map shows global distribution of areas suitable for irrigation expansion under baseline and 1.5ºC warmer climate conditions. The figure shows the geography of the additional sustainable irrigation expansion potential obtained with: i) soft-path approaches (i.e., small monthly storage) with full or ii) 20% deficit irrigation and iii) hard-path approaches (i.e., large annual water storage).

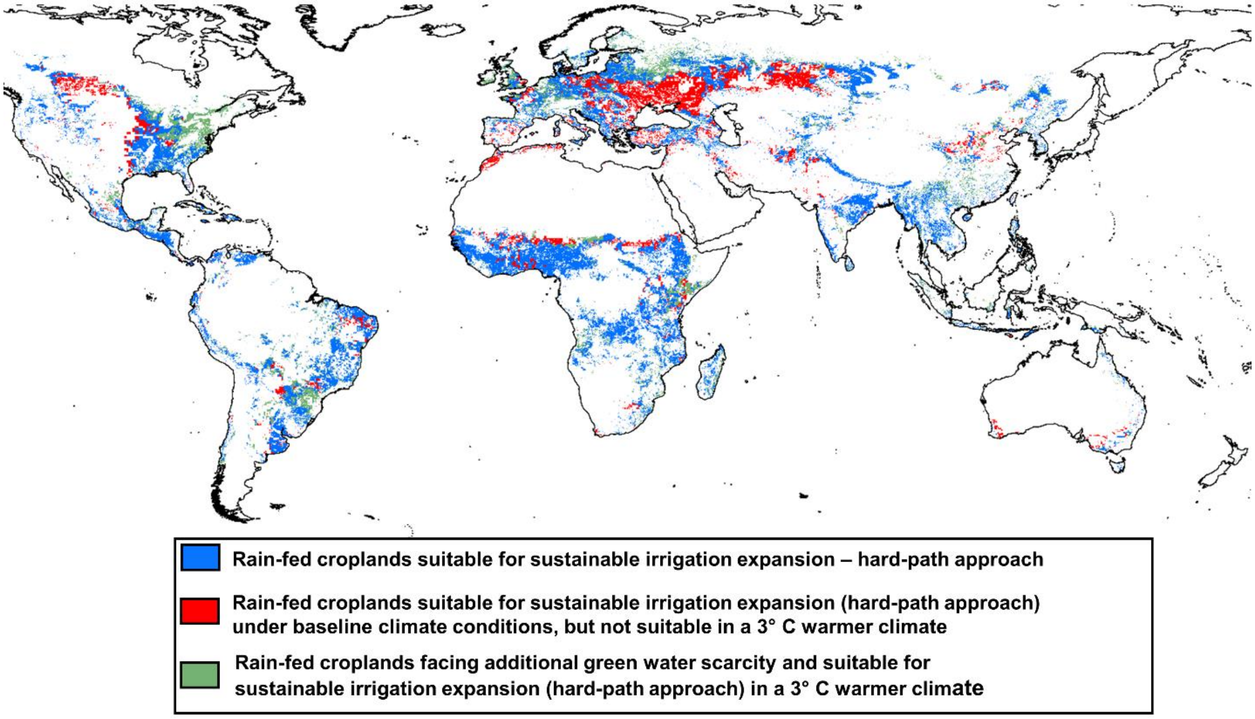

Figure S4. Additional rain-fed croplands suitable and not suitable for irrigation expansion in a 3° C warmer climate compared to baseline climate conditions.

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