PNAS Nexus

PNAS Nexus, 2023, **2**, 1–11
https://doi.org/10.1093/pnasnexus/pgad117
Advance access publication 4 April 2023
Research Report

Solutions to agricultural green water scarcity under climate change

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Edited By: Joann Whalen

Abstract

Rain-fed agricultural systems, which solely depend on green water (i.e. soil moisture from rainfall), sustain ~60% of global food production and are particularly vulnerable to vagaries in temperature and precipitation patterns, which are intensifying due to climate change. Here, using projections of crop water demand and green water availability under warming scenarios, we assess global agricultural green water scarcity—defined when the rainfall regime is unable to meet crop water requirements. With present-day climate conditions, food production for 890 million people is lost because of green water scarcity. Under 1.5°C and 3°C warming—the global warming projected from the current climate targets and business as usual policies—green water scarcity will affect global crop production for 1.23 and 1.45 billion people, respectively. If adaptation strategies were to be adopted to retain more green water in the soil and reduce evaporation, we find that food production loss from green water scarcity would decrease to 780 million people. Our results show that appropriate green water management strategies have the potential to adapt agriculture to green water scarcity and promote global food security.

Keywords: agriculture, food security, water scarcity, green water, climate adaptation

Significance Statement

Global warming is expected to negatively affect rain-fed crops, which largely depend on green water (i.e. the soil moisture from rainfall). Quantifying future impacts of climate change on agricultural systems is paramount to design adaptation solutions. Considering plausible future warming scenarios, we quantify the exposure to green water scarcity of rain-fed croplands—defined when precipitation and soil moisture are not able to meet crop water demand. We find that an additional 150 million hectares of croplands will be affected by prolonged and more intense green water scarcity. We then quantify the climate adaptation potential of solutions that retain more green water in the soil and reduce evaporation. We find that green water management solutions can reduce the extent of rain-fed croplands facing green water scarcity by ~50 million hectares, averting crop loss that can feed 670 million people. Green water management solutions have potential to sustain cropland productivity, despite the high probability of green water scarcity in the future.

Introduction

An increasing scarcity of freshwater resources is now evident in many geographies (1). Water scarcity is a global socioeconomic threat affecting four billion people (2). Projected population growth, climate change, and an increase in food and energy demands are expected to further exacerbate water scarcity in the 21st century (3–5). Water scarcity refers to a geographical and temporal imbalance between freshwater availability and demand (1). In addition to biophysical factors, economic and institutional settings are important elements that determine water scarcity (6, 7).

The concept of water scarcity encompasses both physical and economic factors (3, 8). Physical water scarcity occurs when physical access to water is limited (9). It affects both blue water (i.e. water from water bodies or aquifers) and green water (i.e. soil moisture from rainfall) (10, 11). Economic water scarcity occurs when water resources are physically available but the lack of institutional and economic capacity limits access to that water (6, 7).

Agriculture is the world largest user of freshwater and commits global food security to rely on reliable and resilient freshwater availability (12). These commitments necessitate increasing attention to global agricultural water scarcity in the context of humankind's ability to meet future food demand. Agricultural green water scarcity (GWS) occurs when the amount of rainfall is unable to meet crop water requirements (CWR), which can lead to water-stressed crop growth (6, 13, 14). In such cases, supplemental blue water is provided by irrigation to ensure adequate crop growth and prevent water stress (15). Agricultural blue water

Competing Interest: The authors declare no competing interest.
Received: January 19, 2023. **Revised:** March 22, 2022. **Accepted:** March 27, 2023

scarcity occurs when blue water resources cannot meet irrigation water requirements (16). In many regions, agricultural blue water scarcity leads to unsustainable irrigation practices, which deplete blue water stocks and/or impair water ecosystems (17, 18). Furthermore, agricultural economic water scarcity is defined as the lack of irrigation due to limited institutional and economic capacity instead of hydrologic constraints (6).

Agricultural blue water scarcity has been the focus of the water scarcity debate, and it is increasingly perceived as a global socio-environmental threat to food and energy security (19–22). Alarmingly, half of irrigated croplands are facing blue water scarcity or are under unsustainable irrigation practices (23, 24). Recent attention has also been given to agricultural economic water scarcity (6, 7), showing that up to one fourth of global rain-fed croplands are suitable for sustainable irrigation expansion but the lack of institutional and economic capacity is hindering irrigation deployment (6).

Global warming has increasingly reduced crop production and affected food security (25–29). Despite projected irrigation expansion to offset negative impacts of anthropogenic warming on crop yields, rain-fed agriculture will continue to be a major component of global food systems (30). However, rain-fed agriculture is highly vulnerable to climatic conditions due to its strong dependence on rainfall patterns. Climate change is expected to reshape the extent of agricultural water scarcity worldwide (16, 31–34). Indeed, by the end of the century, agricultural blue water scarcity could require the transition of 60 million hectares of croplands from irrigated to rain-fed (31). Global warming will increase intra-annual variability in water resources, requiring the construction of water storage to preserve the potential for sustainable irrigation expansion over croplands facing agricultural economic water scarcity (16). Compared with irrigated croplands, rain-fed croplands are expected to be more affected by climate change (35), but with little attention given to quantify agricultural GWS under global warming. This limited understanding of the impacts of climate change on green water availability and demand adds uncertainties to future water and food security and adaptation solutions in agriculture.

Here, we quantify global agricultural GWS under future climate change. GWS is defined as the ratio between monthly irrigation blue water requirements (BWR) (or green water deficits) and CWR (6). In this study, we define the reference scenario of GWS as occurring when the rainfall regime is unable to meet at least 20% of CWR (6). We also consider upper and lower bound estimates, which represent GWS when at least 10 and 30% of CWR are not meet by the rainfall regime, respectively. First, we use climate output from earth system models (36) and feed it into a crop water model (37) to quantify CWR and BWR of crops. Second, we identify the extent, timing, and duration of croplands affected by GWS under baseline, 1.5°C warmer, and 3°C warmer climate conditions with respect to the preindustrial era. The baseline scenario refers to the 1996–2005 period—the reference period for global agricultural data sets (38). The degree to which the Earth's climate will warm above preindustrial levels and by when is highly dependent on climate policies and programs enacted. The 1.5°C warming scenario refers to the Paris climate target, and the 3°C warming scenario represents the plausible level of global warming to be reached by the end of the century under current policies (39, 40). Third, we quantify the potential of adaptation solutions that could be implemented to reduce the exposure to GWS by reducing evapotranspiration and/or increase rainfall infiltration in soils. Finally, we estimate global food production that will be affected by GWS and the corresponding number of people impacted. While irrigated croplands are also affected by GWS, our analysis focuses solely on rain-fed croplands—the croplands most vulnerable to climate vagaries (35, 41). This study aims to quantify the water scarcity risks that rain-fed croplands will face under global warming and the potential role of green water management solutions in mitigating GWS.

Results

The extent of agricultural GWS

By quantifying green water deficit and crop water requirement under different climatic conditions, we assess GWS over rain-fed cropping systems under baseline (1996–2005 climatic conditions), 1.5°C warmer, and 3°C warmer climates (Fig. 1). The exposure to GWS strongly varies depending on geographic location and climate scenario (Fig. 1). Under baseline climate, we find that almost 394 million hectares (Mha), which accounts for 53% of global rain-fed croplands, experiences GWS. These croplands cannot achieve maximum productivity because crops are grown under water-stressed conditions. Russia, the United States, and India currently have 48, 44, and 26 Mha rain-fed croplands experiencing a shortage of green water, respectively (Fig. 1). European countries are also intensively experiencing a shortage of green water. For example, Ukraine, a major grain exporter in Europe, exhibits 13 Mha of rain-fed croplands facing GWS (Fig. 1). The sub-Saharan African and Latin American regions, where local populations rely heavily on rain-fed agriculture, also experience widespread GWS. For instance, Nigeria, Brazil, and Argentina have 18, 9, and 6 Mha of rain-fed croplands facing GWS, respectively (Fig. 1).

Change in temperature and precipitation patterns will exacerbate future GWS (Fig. 1). Under 1.5°C warming, an additional 102 Mha of rain-fed croplands will face GWS, exposing 67% global rain-fed croplands to GWS (Fig. 1). With an additional 15 Mha experiencing a shortage of green water, Russia shows the highest increase in GWS, followed by Argentina (an additional 13 Mha), the United States (10 Mha), Ukraine (9 Mha), and India (6 Mha) (Fig. 1). Under 3°C warming, 54 million more hectares of rain-fed croplands will face GWS compared to 1.5°C warming, which results in 75% global rain-fed systems under GWS (Fig. 1). The United States will be the most affected country, with an additional 18 Mha facing GWS, followed by Russia with an additional 6 Mha (Fig. 1). Because croplands in India and China are mainly irrigated and have few rain-fed cropping systems, these countries will show little increase in GWS under warming (38, 42, 43) (Fig. 1). The future exacerbation of GWS is a risk to global and local food security.

Prolonged GWS under warming

The extent but also the duration of GWS is important to quantify the impacts of GWS to global food production. We quantify the number of months per year to which rain-fed croplands are experiencing a shortage of green water under baseline, 1.5°C warmer, and 3°C warmer climates (Fig. 2). Under baseline climate, we find that 600 Mha (81% of global rain-fed croplands) faces GWS at least one month (Fig. 2C). In India, Nigeria, and Australia, over 95% rain-fed croplands face GWS at least one month per year and over 60% rain-fed cropping systems experience GWS more than six months per year (Fig. 2A). Under 1.5°C, an additional 65 Mha will face prolonged periods of GWS. Brazil, Russia, and Ukraine will experience a significant increase in the number of months facing GWS (Fig. 2B and C). While there will be an overall exacerbation of GWS in the United States, some regions in the

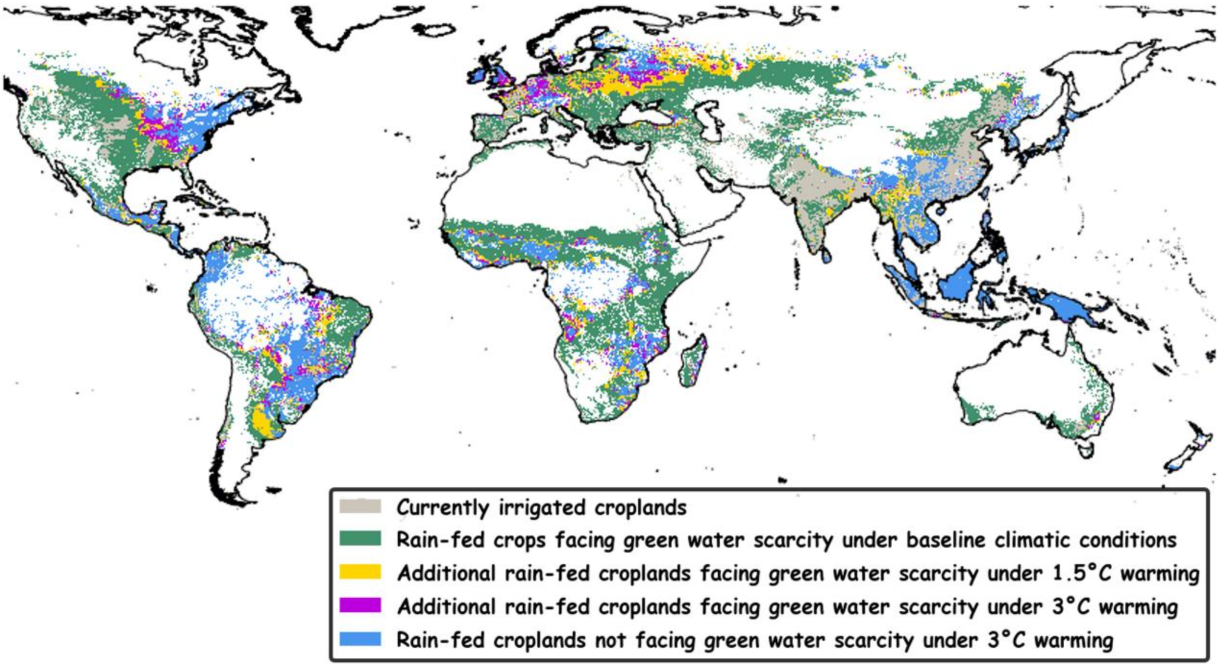

Fig. 1. The geography of global agricultural GWS. The map shows the distribution of rain-fed croplands facing agricultural GWS under baseline (1996–2005 period), 1.5°C warmer, and 3°C warmer climatic conditions. "Currently irrigated croplands" represent the most up-to-date extent of global irrigated lands in 2015 (42).

Midwest show reductions in the number of months facing GWS, due to increased precipitation and a decrease in vapor pressure deficit (44) (Fig. 2B). Additional rainfall is also projected in some regions of Russia, China, and Brazil (44), which leads to a shorter exposure to GWS. Under 3°C, we find that 25 million more hectares will face prolonged periods of GWS compared to that under 1.5°C, with significant increases in the United States, Russia, and Brazil (Fig. 2D).

Timing of GWS

The exposure to GWS varies with geographic location but also with the timing of the year (Fig. 3). To assess the sensitivity of our results to different thresholds of GWS, we present the timing of rain-fed croplands facing GWS under baseline, 1.5°C warmer, and 3°C warmer climates using three different thresholds (Fig. 3). Our reference scenario defines GWS as the rainfall regime being unable to meet at least 80% of CWR or crops facing a 20% water deficit. We also use thresholds as 10 and 30% water deficit, which are shown as interval bars to represent the upper and lower bound estimates of GWS under different climate conditions. The United States, Russia, Canada, Ukraine, and Germany show widespread GWS during June to September—the period of peak growing season for their summer crops (Fig. 3). In contrast, India experiences large GWS in winter but small in summer due to the Indian summer monsoon rainfall between June and September. Under warming climates, all countries show an increase in the areas facing GWS. The most significant changes are observed in the United States, Russia, Canada, Ukraine, and Germany during June to September with additional 106 (53), 58 (44), 27 (16), 36 (32), and 22 Mha (7) facing GWS under 3°C (1.5°C) warming, respectively (Fig. 3).

People fed by rain-fed croplands facing GWS

GWS poses a threat to global food security as it reduces agricultural productivity. Previous work has established a linear relationship between relative crop yield losses and water deficit (12, 45). Indeed, plant growth (i.e. photosynthesis) and transpiration are directly influenced by stomatal regulation and scale linearly with stomatal conductance (45). By adopting a commonly used linear relationship between crop yields and biophysical water deficit or GWS (see Materials and methods), we quantify the number of people affected by calorie loss due to crop yield reduction during periods of GWS on rain-fed croplands.

We find that rain-fed crop production facing GWS can provide food that feed 890 million people per year under baseline climate (lower bound 850 million people and upper bound 910 million people) (Fig. 4). Under 1.5°C and 3°C warming, an additional 340 and 560 million people equivalent of rain-fed production, respectively, will be impacted by GWS (Fig. 4). Consequently, the total number of people affected by GWS will reach 1.23 billion (lower bound 1.20 billion and upper bound 1.25 billion) and 1.45 billion people (lower bound 1.42 billion and upper bound 1.46 billion) under 1.5°C and 3°C warming, respectively (Fig. 4). Notably, the United States is currently the country most affected by GWS, with 157 million people impacted. As the world's largest food exporter, it is important to notice that the 157 million people affected by GWS in the United States are not just people fed within the country but also people around the world that depend on imports from the United States. In addition to the United States, Russia, China, Australia, and India are among the countries where food production that feeds 66, 56, 49, and 40 million people annually, respectively, is facing GWS. Under 3°C warming, the exposure of GWS in these five countries will affect an additional 133, 31, 7, 12, and 20 million people annually, respectively. Without effective water management strategies to reduce GWS, crop yields are expected to decline and and more people will suffer from food insecurity.

Solutions to reduce GWS

Under 3°C warming, 9% (or 63 Mha) of global rain-fed croplands will face GWS for only 1 or 2 months per year (Fig. 2). Expanding

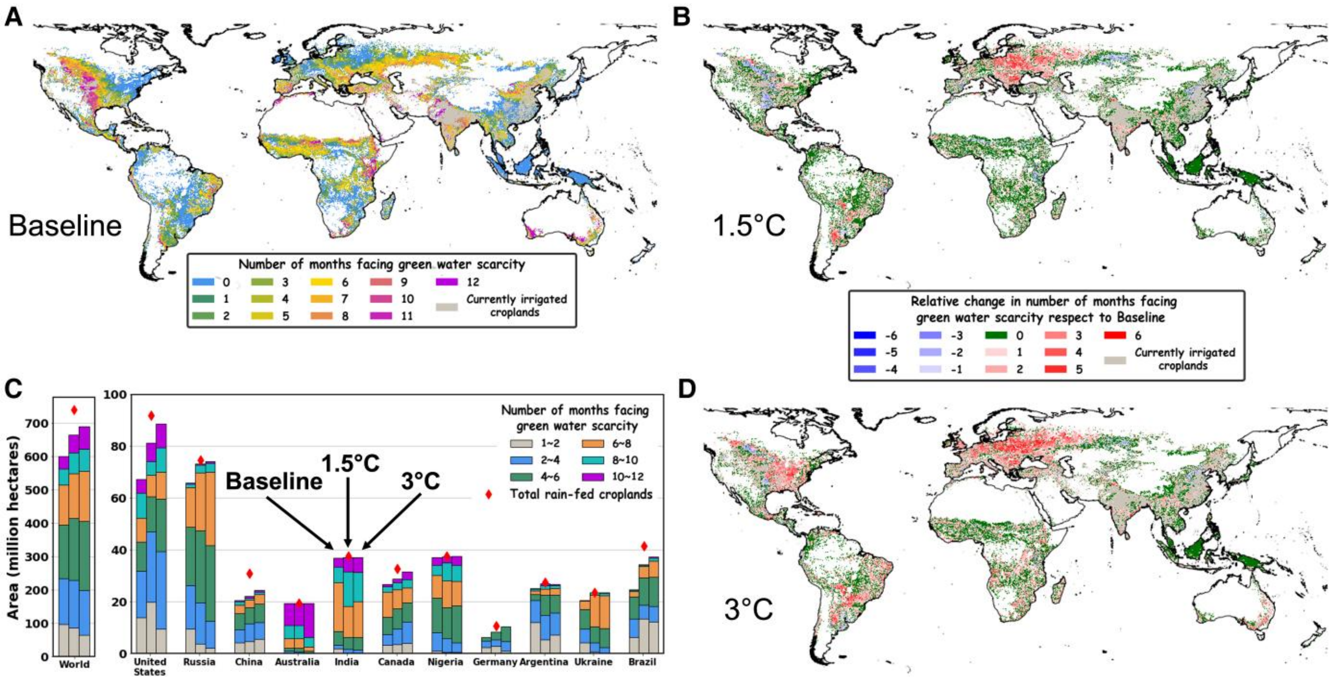

Fig. 2. Number of months per year facing agricultural GWS. (A) Number of months per year facing GWS under baseline climate. (B) and (D) show relative change in number of months facing GWS under 1.5°C and 3°C warmer climates with respect to baseline. (C) Croplands under GWS in countries with the highest exposure to GWS and number of months under baseline, 1.5°C warmer, and 3°C warmer climates.

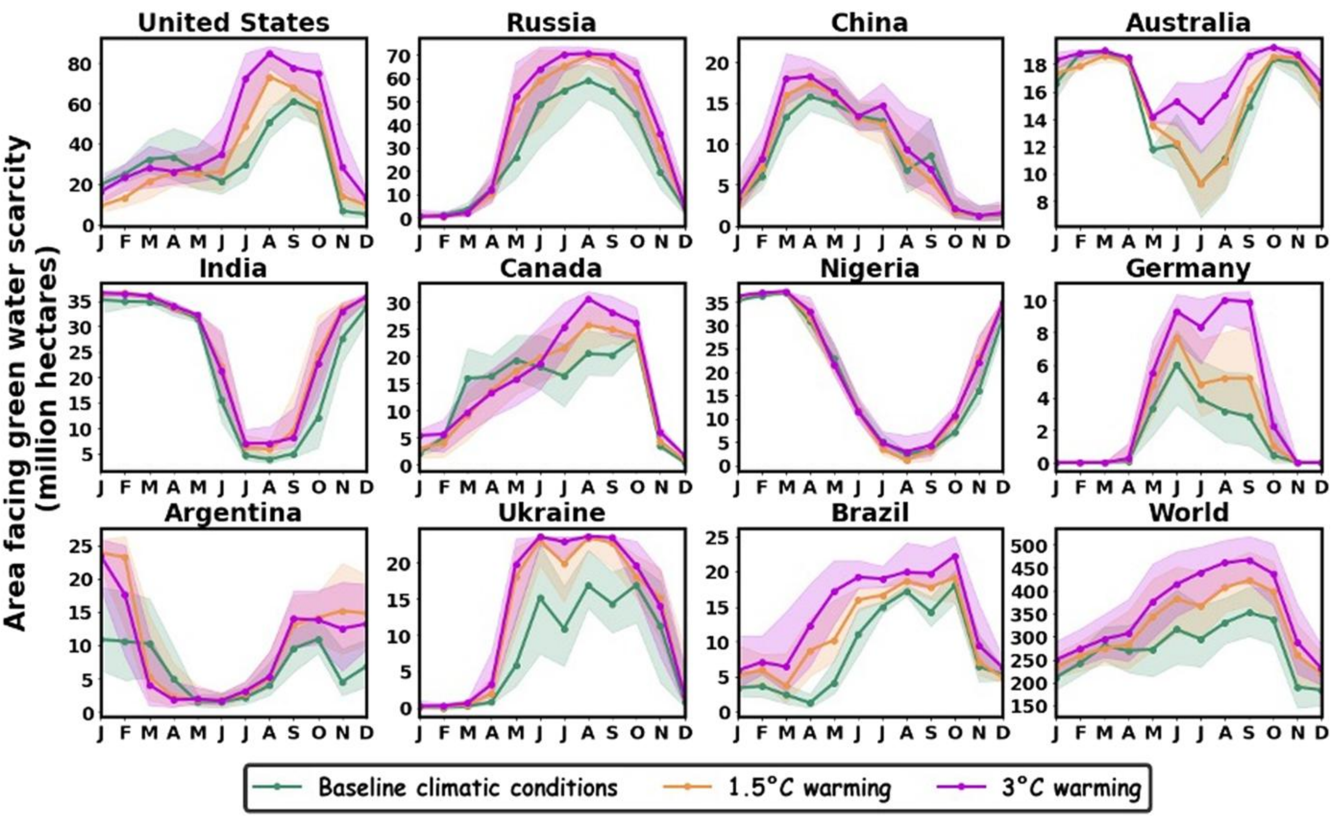

Fig. 3. Area of rain-fed croplands experiencing green water shortage during the year. The figure shows the countries with the highest cropland area experiencing a shortage of green water under baseline, 1.5°C warmer, and 3°C warmer climates. The solid line shows the croplands facing GWS considering the reference GWS ratio threshold of 0.2 or 20% water deficit. The shaded area shows the upper and lower bound of areas facing GWS considering a GWS ratio of 0.1 and 0.3 or 10 and 30% green water deficit, respectively.

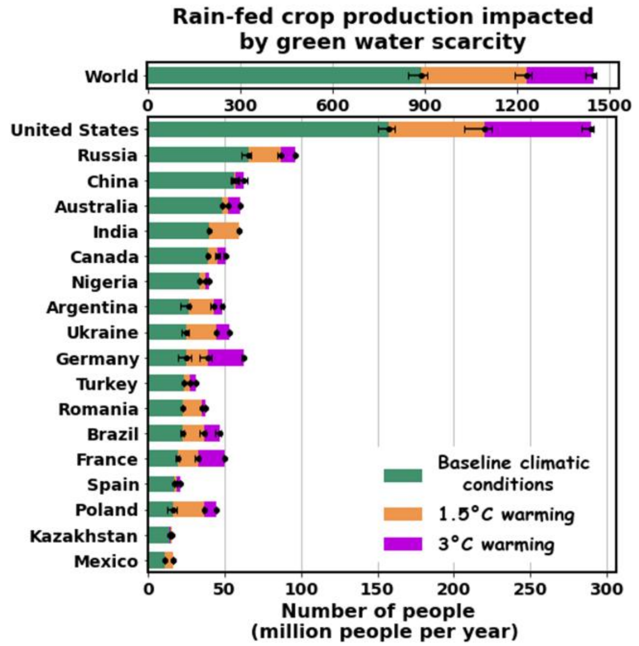

Fig. 4. Rain-fed crop production impacted by agricultural GWS under baseline, 1.5°C warmer, and 3°C warmer climates. Interval bars show the number of people fed from croplands facing GWS considering an upper and lower bound estimate of exposure to GWS by considering a water deficit of 10 and 30%, while the central estimate in the bar diagrams shows the reference results considering a water deficit of 20%.

irrigation might not be a feasible solution over these croplands considering socioeconomic trade-offs between increased agricultural productivity and capital and operational costs of new irrigation systems (46). However, adopting nature-based agricultural practices with appropriate low-cost land and water management can help retain more green water in the soil by reducing soil evaporation (30, 47). Some promising solutions include no-till farming and mulching, which can conserve soil moisture by reducing evaporation from lower soil temperature due to shading (47–49). Cover crops and no-till practices can also prevent runoff and soil erosion by holding soils in place and encouraging infiltration of rainfall instead of runoff (47). Another potential solution is agrivoltaics, which involves combining agriculture with solar panels and has been shown to reduce crop exposure to sunlight and therefore reduce evapotranspiration by ∼15% (50). Switching from water-intensive crops to less water-intensive crops can reduce crop water demand (51), while weed removal can reduce nonproductive green water use (47). Pitting, contouring, and terracing farming techniques that increase soil moisture by increasing infiltration and reducing runoff have also been found to be effective (52).

To evaluate the potential of green water management solutions in mitigating GWS, we consider different levels of evaporation reduction and infiltration increase, ranging from 0 to 100% (Fig. 5). Our analysis shows that increasing green water management solutions can decrease the area affected by GWS and increase the number of people being fed (Fig. 5A and B). However, these benefits are not proportional to the level of intervention. We find that the marginal benefits of these solutions decrease after a 20% reduction in evaporation or increase in infiltration (Fig. 5C). This suggests that a 20% evapotranspiration reduction and infiltration increase accounts for approximately half of the potential of green water management solutions to alleviate GWS (Fig. 5C).

We then assess the potential of green water management solutions to reduce exposure to GWS by considering a 20% reduction in crop water use or a 20% increase in soil moisture. The implementation of these solutions resulted in a significant decrease of rain-fed croplands facing GWS. Specifically, we observe an 85, 71, and 54 Mha decrease under baseline, 1.5°C warming, and 3°C warming, respectively (Fig. 6A). Accordingly, by reducing GWS over these croplands, an estimated 560, 630, and 670 million people can be fed under baseline, 1.5°C warming, and 3°C warming, respectively (Fig. 6B). Our results also show a nonlinear relation between areas and yield (or people fed) under different climates (Fig. 6). The increases of additional population fed accompanied with less reduced global area facing GWS under warming can be explained by the different crop productivity in different regions. In fact, the same amount of GWS reduction over more productive croplands leads to greater food production enhancment and feeding more people. These results imply that under future warming, green water management solutions have much more potential in highly productive croplands. We find that the United States and Russia are the top two countries showing largest reduction of area facing GWS and increase of the number of additional people fed under baseline, 1.5°C warming, and 3°C warming scenarios (Fig. 6).

Discussion

Quantifying future impacts of climate change to agricultural systems is paramount to design adaptation solutions. This study evaluates the negative impacts of future warming on rain-fed croplands by assessing global agricultural GWS. Our findings show that the exposure to GWS varies geographically and seasonally (Figs. 1 and 3). We find that today, there are 394 Mha or 53% of global rain-fed croplands affected by GWS (Fig. 1). An additional 102 and 156 Mha of rain-fed cropping systems will be experiencing a shortage of green water in 1.5°C and 3°C warmer climates, respectively (Fig. 1). Under global warming, there will be prolonged periods of GWS, with an increase in the duration and intensity of GWS (Fig. 2).

This study quantifies the exacerbation of GWS under climate change in a system that maintains current crop distribution and yields. Farmers are likely to adapt to global warming by introducing high-temperature or drought-tolerant crops or fallowing croplands under warmer climates (53, 54). For instance, cultivating crops that are more drought tolerant or C4 crops (e.g. corn, sorghum, and millet) can help alleviate water scarcity problems. Compared to C3 crops (e.g. soybean, wheat, and rice), C4 crops conserve more water and are better adapted to arid environments (55). These potential changes may add uncertainties to predict agricultural GWS in the future. Some rain-fed croplands can tap into shallow groundwater and therefore be less impacted by GWS (56). Future work is needed to account for the representation of shallow groundwater table in agrohydrological models. The relationship between crop yield loss and GWS may change across different crop types and growing stages. Extensive field work from the Food and Agriculture Organization of the United Nations (FAO) reports that reduction in crop yields is linearly correlated with water deficit over the growing season, with slightly different coefficients across different crops, ranging from 0.8 to 1.25 (12, 45). Given the uncertainty in these estimates, we use a 1:1 relationship between crop yield losses and biophysical water deficit or GWS as widely adopted in previous studies (6, 12, 16, 45, 57), e.g. GWS of 0.2 leads to 20% yield losses. We also tested the sensitivity of our results to different GWS thresholds (10, 20,

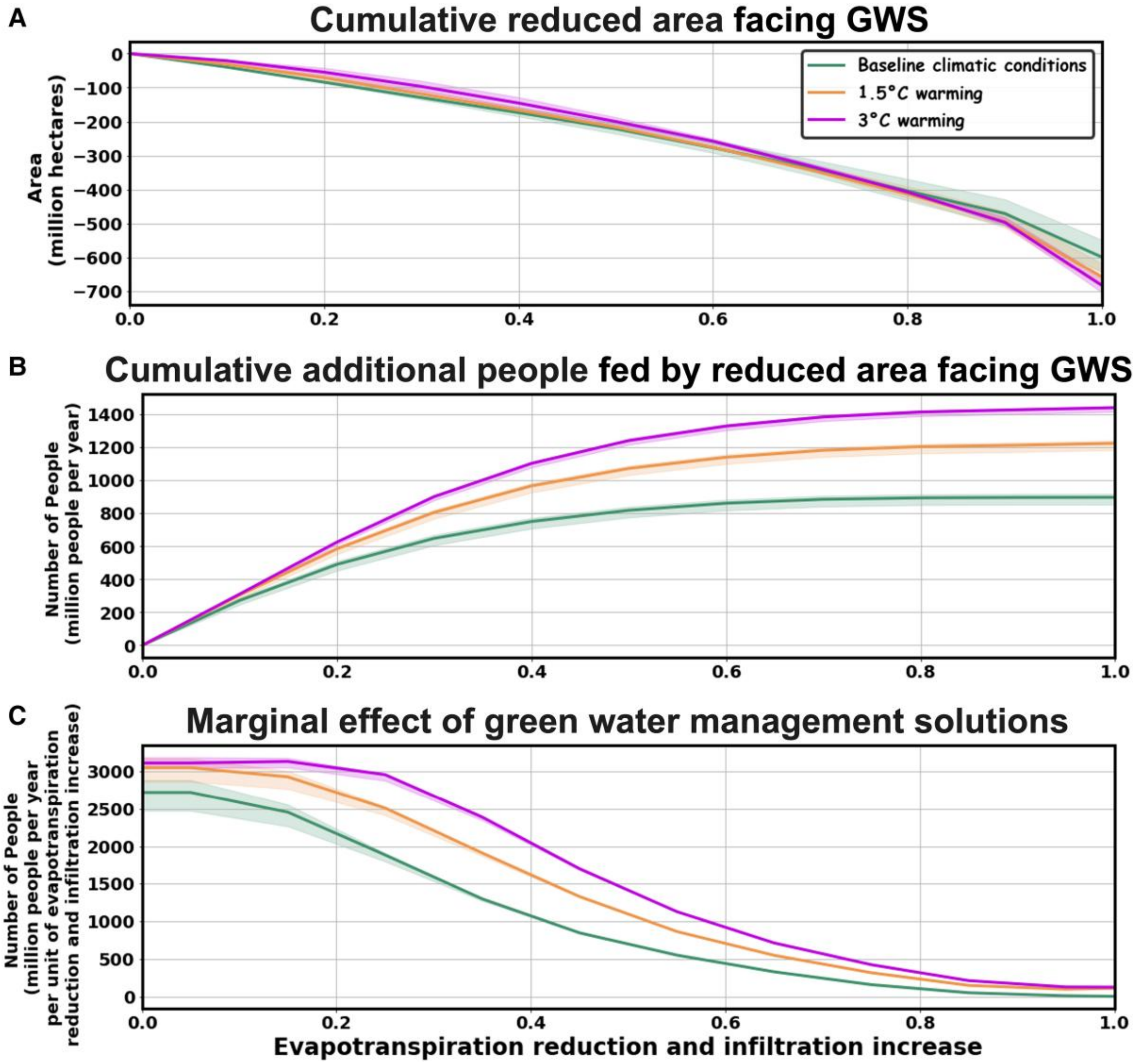

Fig. 5. Global potential of green water management solutions to reduce exposure to agricultural GWS under different evapotranspiration reduction and infiltration increase levels. (A) Reduced global rain-fed cropland areas affected by GWS, (B) additional people fed by adopting green water management solutions, and (C) marginal effects on the number of people who benefited from reduced GWS. The area under the curve in panel C represents the total number of people who benefited by green water management solutions. The solid line shows the land and number of people fed from croplands facing GWS considering the reference threshold of 0.2 or 20% water deficit. The shaded area shows the upper and lower bound of land and number of people considering a GWS ratio of 0.1 and 0.3 or 10 and 30% green water deficit, respectively.

and 30% water deficits) to account for uncertainties in yield response to GWS.

Water scarcity and food security implications

Currently, global croplands produce food that can feed 8.2 billion people, of which 4.8 billion people can be potentially fed from rain-fed croplands and 3.4 billion people from irrigated croplands (30) (Fig. S1). We find that under baseline climate, GWS affects cropland productivity for 890 million people (Fig. S1). In addition, current unsustainable irrigation practices, or irrigation cropping systems facing blue water scarcity, produce food that feed 1.3 billion people (30) (Fig. S1). Climate change will further exacerbate exposure to green and blue water scarcity. It has been estimated that climate change will require the transition of irrigated croplands from irrigated to rain-fed systems leading to a loss of calorie production that can feed an equivalent of 490 million people (31) (Fig. S1). We find that food that fed 1.45 billion people will be affected by exposure to GWS under 3°C warming (Figs. 4 and S1). The projected food production loss from GWS and blue water scarcity under global warming threatens global and local food security.

While we project an exacerbation of GWS, green water management solutions, which retain more rainfall in the soils or reduce water loss via evapotranspiration, are expected to buffer against GWS. Over croplands experiencing relatively short periods of GWS, especially over the 63 Mha of croplands that will face GWS for 1 or 2 months per year under 3°C warming (Fig. 2), expanding irrigation might not be a feasible solution considering trade-offs among increased agricultural productivity and capital and operational costs of irrigation systems (12). We find that the marginal effects of green water management solutions decrease, especially with greater than 20% evapotranspiration reduction and infiltration increase (Fig. 5). However, a 20% evapotranspiration reduction and infiltration increase accounts for approximately half of the total potential of green water management

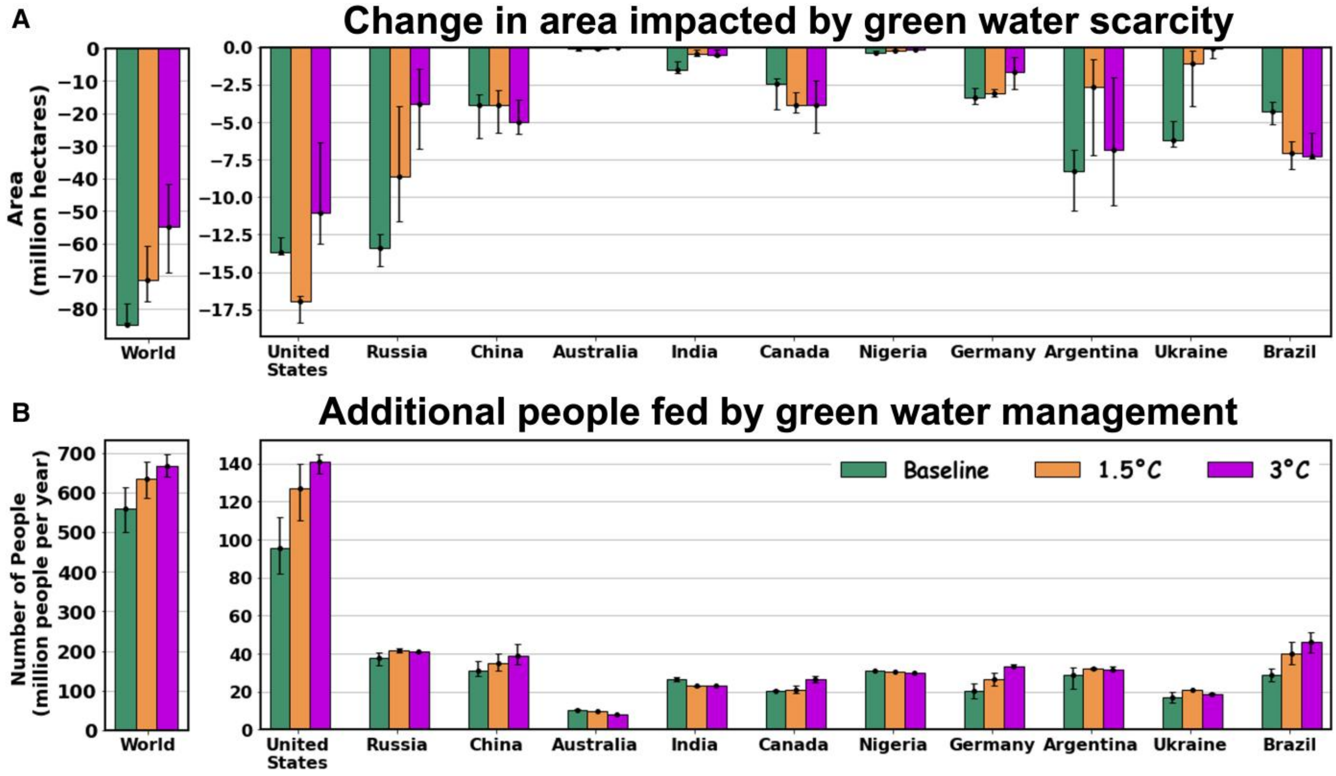

Fig. 6. Potential of green water management solutions to reduce exposure to agricultural GWS. (A) Reduced rain-fed croplands facing GWS and (B) additional people fed from decreased GWS. Interval bars show land and number of people fed from croplands facing GWS considering an upper and lower bound estimate of exposure to GWS by considering a water deficit of 10 and 30%, while the central estimate in the bar diagrams shows the reference results considering a water deficit of 20%.

solutions to alleviate GWS (Fig. 5C). Implementing green water management solutions with 20% evapotranspiration reduction could lead to an additional 670 million people fed by reducing exposure to GWS under 3°C warming (Fig. 6). Nonetheless, it is important to acknowledge that ensuring healthy soil conditions, such as avoiding soil degradation that reduces water-holding capacity, is essential for long-term water retention. Sustainable agriculture practices like crop rotation, reduced tillage, and organic fertilization can maintain soil structure and fertility for efficient water retention (58). Moreover, the effectiveness of green water management solutions may vary depending on factors such as soil type, climate, and agricultural practices in each specific country. Future studies focusing on local scales can provide more insight into these factors and help to tailor solutions for more effective mitigation of GWS.

For the 626 Mha of croplands receiving less rainfall than required for maximum crop yield for longer than two months per year (Fig. 2), green water management solutions might not be enough to avert water-stressed crop production. In such cases, irrigated cropping systems, which use both rainwater (green water) and surface water and/or groundwater (blue water), can contribute to a more reliable and resilient crop production while boosting agricultural productivity (30, 59, 60). Irrigation not only ensures a relibale water supply but also alleviates crop heat stress due to evapotranspiration cooling (61). Sustainable irrigation expansion over rain-fed croplands experiencing a shortage of green water can be an effective agricultural adaptation solution to climate change (16, 18). Under a 3°C warming, up to 350 Mha of global rain-fed croplands is suitable for sustainable irrigation expansion (16). This irrigation expansion can boost agricultural productivity and feed up to 1.4 billion more people, although more water storage will be needed (62). However, in areas with physically available renewable blue water resources, irrigation can be blocked by a variety of socioeconomic and political factors that cause the so-called agricultural economic water scarcity (6). These regions tend to lack the capacity to afford the costs to develop irrigation infrastructure using the available renewable blue water resources (6, 46).

Conclusions

Global warming is expected to increase the intensity and frequency of extreme weather events, leading to unpredictable water availability and exacerbating water scarcity. These disrupting weather patterns are expected to negatively affect rain-fed crops, which largely depends on rainfall and soil moisture. To evaluate the extent to which global warming will affect crop yields and food security worldwide, it is important to understand how climate change will reshape the extent and intensity of water scarcity. This study quantifies global agricultural GWS under baseline and future warmer climates. We define GWS when precipitation cannot meet CWR. We find that around half of global rain-fed croplands currently face GWS. Such extent will increase to 67 and 75% under 1.5°C and 3°C warmer climates. Increased GWS will mostly occur in the United States, Russia, Ukraine, and Brazil and will affect food production for 1.23 and 1.45 billion people under 1.5°C and 3°C warming. However, adopting climate solutions that aim to better manage green water can reduce the extent of rain-fed croplands facing GWS by 71 and 54 Mha under 1.5°C and 3°C warmer climates, leading to an increase in calorie production of 630 and 670 million people, respectively. These findings demonstrate that wise agricultural technology and engineering have the potential to contribute to global food and water security.

Materials and methods

We use the climate output from earth system models from the CMIP5 archive to quantify GWS under baseline, 1.5°C warmer, and 3°C warmer climates with respect to the preindustrial era. First, the climate projections obtained from CMIP5 are fed into the WATNEEDS crop water model to assess CWR and BWR. Second, CWR and BWR are used to assess for each month of the year global GWS at 5 arcminute by 5 arcminute resolution. Third, we quantify the extent, duration, and timing of GWS. Fourth, we quantify the number of people fed over croplands facing GWS and test the sensitivity of our results to different GWS thresholds. Last, we quantify the potential of green water management solutions to alleviate future GWS and increase food security over rain-fed croplands. While irrigated croplands may also be experiencing a shortage of green water, they are more intensively managed, and thus less sensitive to climate vagaries (35). Therefore, we aim to assess GWS over rain-fed croplands because they are the croplands that will be more affected by water stress under climate change.

Assessment of GWS

GWS is assessed per grid cell at 5 arcminute by 5 arcminute resolution (or ~10 km at the equator). GWS is calculated as the ratio between irrigation BWR (or green water deficits) and CWR. CWR is the amount of water needed by a crop to avoid water-stressed crop growth. BWR is the amount of blue water needed by a crop to meet CWR when there is a deficit of green water. Rain-fed croplands face GWS when soil moisture (or green water) cannot meet CWR. Following Rosa et al. 2020 (6), we define GWS as follows:

$$\mathrm{GWS} = \frac{\mathrm{BWR}}{\mathrm{CWR}}. \quad (1)$$

Croplands face GWS when this ratio is greater than 0.2 (i.e. when the rainfall regime is unable to meet at least 80% of CWR or crops have a 20% water deficit). We then test the robustness of our results by defining GWS when the ratio is greater than 0.1 or 0.3 or crops have a 10 and 30% water deficit. These values are depicted with interval bars whenever necessary and represent an upper and lower bound estimate of GWS under different climate conditions. Our results assume that a given crop will face GWS if the ratio between BWR and CWR is greater than a critical value of 0.2. Under this level of water stress, crops decrease yields and farmers usually deploy, where feasible, irrigation (63, 64).

Assessment of BWR and CWR

For each crop and scenario, CWR and BWR are assesed using the WATNEEDS crop water model (see Chiarelli et al. 2020 (37) for a detailed description). The model calculates CWR and BWR for 26 crop classes or 130 primary crops or 100% of global crop production implementing a daily time-step using a soil water balance during each crop growing season. We run the WATNEEDS model using precipitation and evaporation data under baseline, 1.5°C warmer, and 3°C warmer climates and using cropland extent from the MIRCA2000 data set (38). The MIRCA2000 data set provides global monthly irrigated and rain-fed crop areas for 26 crop classes or 130 primary crop species (38).

Climatic data

We use historical monthly observational climatic data sets for the baseline scenario (1996–2005 period). Potential reference evapotranspiration of 0.5° × 0.5° resolution is obtained from the University of East Anglia's Climate Research Unit Time Series (CRU TS version 4.01) (65). Precipitation of 50°N to 50°S at 0.05° × 0.05° resolution is downloaded from Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS version 2.0) (66). Precipitation data of 0.5° × 0.5° resolution for the remaining latitudes are taken from the National Oceanic and Atmospheric Administration's Climate Prediction Center Global Unified Gauge-Based Analysis of Daily Precipitation data set (67). All gridded data sets were resampled to a 5 arcminute (0.08333°) spatial resolution, the resolution of the GWS assessment and MIRCA2000 data set.

For future climate forcing, we use global monthly evapotranspiration and precipitation outputs of three global climate models (GFDL-ESM2M, HadGEM2-ES, and MIROC-ESM-CHEM) and three hydrological models (LPJmL, H8, and WATERGAP2) from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) under representative concentration pathway (RCP) 8.5 (36). RCP8.5 refers to the highest emission scenario if the society does not take efforts to reduce greenhouse gas emissions. The three global climate models are selected with the rationale that GFDL-ESM2M, HadGEM2-ES, and MIROC-ESM-CHEM reflect the wettest, average, and driest climate scenarios in terms of predicted global precipitation patterns (16, 68). Therefore, we obtained 18 outputs of climate and hydrological model combinations, nine for 1.5°C wamer and nine for 3°C warmer climates.

The global mean temperature in year 2022 is estimated to be 1.15°C above the average temperature of the late 19th century, from 1850 to 1900, a period often used as a preindustrial baseline for global temperature targets (69). The global mean temperature in the baseline period is estimated to be 0.6°C above the preindustrial era (69). The times when the three selected global climate models used in the study (GFDL-ESM2M, HadGEM2-ES, and MIROC-ESM-CHEM) are projected to reach 1.5°C and 3°C warmer climate conditions with respect to preindustrial era are 2011–42 and 2047–86, respectively (16).

Previous studies have revealed systematic error or bias in global climate model simulations due to simplified physics and thermodynamic processes, numerical schemes, and incomplete knowledge of climate system processes (70). In addition, different models have divergent historical behaviors due to different assumptions and set-up paramenters, especially land use, aerosol, and clouds (71). Hence, it is important to bias-correct the raw climate model outputs obtained from CMIP5 to produce bias-corrected climate projections that are better fit for agricultural modeling. Here, we implement a widely used bias correction practice, which aims to correct the projected CMIP5 potential evapotranspiration outputs using the difference between the simulations and historical data produced by CRU over the baseline climate conditions (period 1996–2005) (16). The similar calculation is done for precipitation to obtain bias-corrected precipitation projections. This bias correction method ensures that the projected variables have the same monthly climatology as the historical obsevations (16, 72).

Climate observations and future forcing are first downscaled to 5 arcminute by 5 arcminute to match the spatial resolution of crop species distributions procuded by MIRCA2000 data sets. Then, they are fed into the WATNEEDS crop water model (37) to assess monthly irrigation BWR and CWR, which are then used to assess agricultural GWS. Results are presented using the mean of the ensemble of the nine simulations for each warming scenario. In our assessment, we use growing stages for year 2000, as provided by the MIRCA2000 data set. We focus on GWS assessment over a rain-fed cropping system using the latest avaiable irrigation data updated to year 2015 (42). Here, we define irrigated croplands as croplands with an area > 5% equipped for irrigation (42). We assess monthly GWS by averaging the results of 18 climate and hydrological model combinations under 1.5°C and 3°C warming scenarios. We do not account for the impact of severe droughts due to the use of a combination of monthly climate model outputs. This approach may not capture extreme events that occur on short periods, such as a daily timescale.

Assessment of calorie production

For each crop, calorie production is assessed as the product of crop yield (tons per hectare), crop-harvested area (hectares), and calorie content of each crop (kilocalories per tons). Rain-fed crop yields are taken from Monfreda et al. 2008 (73). Crop-specific calorie content is taken from D'odorico et al. 2014 (74). Crop-harvested areas are taken from Portmann et al. 2010 (38). The FAO reports that reduction in relative crop yields is linearly correlated with water deficit, with slightly different coefficients across different crops over the growing season, e.g. 1.0 for winter wheat, 0.9 for sorghum, 1.25 for maize, and 0.85 for soybean (12, 45). Such linear relationship can be explained by the coupling of plant growth (i.e. photosynthesis) and transpiration regulated by stomatal behavior (45, 75, 76) and has been used in previous studies to estimate crop yield losses due to GWS (6, 12, 16, 57). To avoid further assumptions in applying our calculations on the global scale, we use a 1-to-1 relationship between crop yield losses and biophysical water deficit or GWS, e.g. GWS of 0.2 leads to 20% yield losses. We then assess the number of people that can be potentially fed considering a global average diet of 3,343 vegetal kcal per capita per day. This value accounts for food waste, food losses, the use of crops for direct human consumption, and crop used for feed-fed livestock production (6, 16).

Supplementary material

Supplementary material is available at *PNAS Nexus* online.

Funding

The authors declare no funding.

Author contributions

L.R. conceived and designed the study; L.H. and L.R. wrote the paper and performed the analyses.

Data availability

The geospatial extent of green water scarcity under different climates is available in the following Zenodo repository: https://doi.org/10.5281/zenodo.7187381.

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