ENVIRONMENTAL SCIENCES

Global agricultural economic water scarcity

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Water scarcity raises major concerns on the sustainable future of humanity and the conservation of important ecosystem functions. To meet the increasing food demand without expanding cultivated areas, agriculture will likely need to introduce irrigation in croplands that are currently rain-fed but where enough water would be available for irrigation. "Agricultural economic water scarcity" is, here, defined as lack of irrigation due to limited institutional and economic capacity instead of hydrologic constraints. To date, the location and productivity potential of economically water scarce croplands remain unknown. We develop a monthly agrohydrological analysis to map agricultural regions affected by agricultural economic water scarcity. We find these regions account for up to 25% of the global croplands, mostly across Sub-Saharan Africa, Eastern Europe, and Central Asia. Sustainable irrigation of economically water scarce croplands could feed an additional 840 million people while preventing further aggravation of blue water scarcity.

INTRODUCTION

The global growth in food demand is placing unprecedented pressure on the land and water resources of our planet. Water and nutrients are important key biophysical factors determining food production (*1*). While advances in technology have allowed humanity to economically produce massive quantities of nitrogen fertilizers (*2*), water still remains a critical input limiting global food production (*3*). To halt agricultural expansion and meet the increasing demand for food commodities, agricultural production will likely have to intensify by expanding irrigation to water-limited croplands that are currently rain-fed (*4*). In some regions of the world, the expansion of irrigation will likely put under additional stress water bodies and aquifers that are already depleted (*5*), rising concerns about Earth's ability to feed humanity with its limited freshwater resources (*6*).

Water scarcity refers to a condition of imbalance between freshwater availability and demand where freshwater demand exceeds availability (*7*). Water scarcity represents a multidimensional state of human deprivation characterized by lack of access to affordable and safe water to satisfy societal needs or a condition in which these needs are met at the expenses of the environment (*8*). While water scarcity may affect entire regions, it is the most vulnerable and poor people that suffer the most severe consequences (*9*). This fact points to the strong role played by economic and institutional factors as determinants of water scarcity. Therefore, water scarcity is generally considered both from the perspective of its physical constraints and economic determinants.

Physical water scarcity affects both blue and green water (i.e., water from water bodies or aquifers and soil moisture, respectively; see Box 1). In the case of crop production, green water scarcity (GWS) corresponds to a condition in which the rainfall regime is unable to meet the crop water requirements (CWRs) (Box 1). That is, for at least part of the year, irrigation is needed to prevent water-limited crop growth. Blue water scarcity (BWS) occurs in croplands facing GWS if the available renewable blue water resources are not sufficient to meet the irrigation water requirements. In this context, renewable blue water resources are defined as the water resources that can be withdrawn from aquifers and surface water bodies without causing either groundwater depletion or loss of environmental flows—the stream flows that need to be maintained to preserve aquatic habitats (*10*–*12*). In case of BWS, farmers can either practice sustainable irrigation without completely meeting the CWR (i.e., "deficit irrigation") or meet these requirements through unsustainable irrigation practices at the expenses of environmental flows and/or groundwater stocks (Box 1).

Blue water has been at the center of the water scarcity debate because it underlies the emerging competition between water uses for societal and environmental needs (*13*–*19*). BWS is increasingly perceived as a global socioenvironmental threat (*20*) that has been associated with questions about food security and energy security (*3*). Moreover, Target 6.4 of the Sustainable Development Goals (SDGs) explicitly addresses BWS with the goal of ensuring adequate blue water resources for humans and ecosystems. Conversely, GWS has received much less attention although ~65% of global crop production is contributed by green water (*21*–*24*). A management plan for green water is still missing in the SDG agenda (*25*). Even less studied is the case of economic water scarcity (EWS).

While GWS and BWS refer to conditions of physical water scarcity associated with insufficient freshwater availability to meet human needs (*8*, *26*), EWS has been defined as the condition in which renewable blue water resources are physically available but lack of economic and institutional capacity limits societal ability to use that water (*8*, *27*, *28*). An early definition of EWS is one that described countries that have adequate renewable water resources to meet current and projected water requirements but need to make massive improvements in their water development programs to be able to use their freshwater resources (*27*). The technocratic, hydraulic engineering perspective that has dominated the "hydraulic mission" of the 20th century has pushed infrastructural development as the main determinant of water development (*29*). Hence, the lack of infrastructural development has been at the center of the conceptualization of EWS (*30*). However, this "old water governance" approach has been exposed for its inability to deal with fast-changing sociohydrological conditions and often criticized for doing more harm than good to the environment and the society. Emerging research

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Box 1. Concepts and definitions about agricultural economic water scarcity.

Water consumption: The volume of abstracted water that is evapotranspired.
Green water: Root-zone soil moisture that is available for uptake by plants.
Blue water: Fresh water in surface and groundwater bodies available for human use.
Green water scarcity: When green water is insufficient to sustain unstressed crop production and irrigation is needed to boost yields. GWS can be defined as the ratio between irrigation water requirement (or "green water deficit") and the total CWR (*4*).
Irrigated agriculture: When there is GWS and crop production is enhanced by irrigation (blue) water.
Sustainable irrigation: When renewable blue water availability is sufficient to sustain crop production and while preventing loss of environmental flows and depletion of freshwater stocks (*4*,*10*).
Blue water scarcity: When irrigation is unsustainable and renewable blue water availability is insufficient to sustainably meet CWR. In these cases, irrigation impairs environmental flows and depletes freshwater stocks. BWS has been defined as the ratio between societal blue water demand and renewable blue water availability (*26*,*58*).
Agricultural economic water scarcity: When there is GWS but no BWS. There is renewable blue water to irrigate but lack of economic or institutional capacity. Agricultural economically water scarce croplands are underperforming rain-fed croplands suitable for sustainable irrigation expansion.
Total water scarcity: When there are GWS, BWS, and lack of economic or institutional capacity.
Deficit irrigation: An irrigation practice whereby blue water supply is reduced below maximum levels and crops are grown under mild water stress conditions with minimal effects on yields.

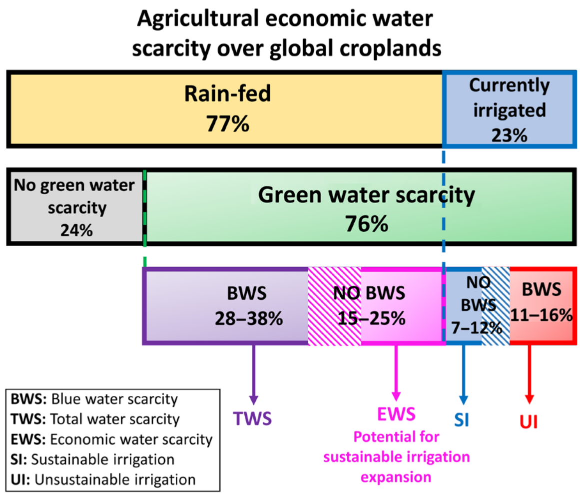

Fig. 1. Conceptual framework and extent of agricultural EWS. Percentages represent fraction of the global cultivated area in each category. Shading indicates croplands affected by blue water scarcity (BWS) that can be sustainably irrigated with deficit irrigation. These areas are then reclassified as suitable for sustainable irrigation [i.e., with no blue water scarcity (NO BWS)], considering different deficit irrigation scenarios. Lack of irrigation in these areas is interpreted as agricultural EWS. See Box 1 for concepts and definitions about agricultural EWS.

agendas on adaptive water governance (*31*), the political ecology of water (*32*), water justice (*33*), and community (*34*) debates how institutional, political, and power dynamics are ultimately affecting the relationship between access and restriction and possession and dispossession of water resources. Hence, the understanding of EWS needs to consider the variety of sociopolitical factors that interact at different scales. For example, maintaining a focus on the global scale, we see that there is a fundamental gap in the way the notion of EWS has been integrated in agricultural development so far (*27*).

We here define and introduce the original concept of "agricultural economic water scarcity" as the condition whereby croplands exposed to GWS are not irrigated although a sufficient amount of renewable blue water resources for irrigation is locally available. These conditions occur for instance as a result of a variety of socioeconomic and political factors that impede irrigation. To date, little attention has been given to the analysis of this phenomenon and its role in the global geography of water scarcity.

Here, we first develop and apply a monthly agrohydrological model to quantify and map croplands affected by agricultural GWS, BWS, and EWS. By doing so, we first provide a comprehensive, spatially explicit, global assessment of agricultural EWS (Fig. 1). We, first, identify croplands affected by GWS and estimate their irrigation water requirements with an evapotranspiration model coupled with a soil water balance analysis. We use a simple comparison between irrigation water requirements and local water availability to investigate to what extent rain-fed croplands affected by GWS are also prone to BWS. Because farmers might not always irrigate at maximum potential in areas affected by BWS, we also considered two deficit irrigation scenarios, where 80 and 50% of full irrigation water requirements are applied to crops (also named as 20 and 50% irrigation deficit, respectively). These deficit irrigation scenarios are investigated only if and where they do not entail the depletion of groundwater resources or environmental flows. We then identify economically water scarce lands as those rain-fed areas where irrigation water requirements can be sustainably met either completely or through deficit irrigation, but irrigation is still missing. Further, we calculate the maximum volume of renewable blue water resources that would be consumed to support crop production in cultivated lands affected by GWS but not prone to BWS. This water includes current sustainable irrigation water consumption and the additional water that would be needed to expand irrigation into rain-fed areas affected by EWS. We lastly estimate the additional calorie produced and number of people that can be fed from sustainable irrigation expansion over economically water scarce croplands.

Our results improve the understanding of how agricultural EWS affects water and food security globally. The application of the concept of agricultural EWS has the potential to inform water and food security policies at global, regional, national, and local scales and to provide new insights to achieve global sustainability targets.

RESULTS

Exposure to GWS and BWS

We develop a spatially explicit integrated mapping of GWS, BWS, and EWS across the global croplands for 130 primary crops (or nearly 100% of global crop production) for the 1996–2005 period using

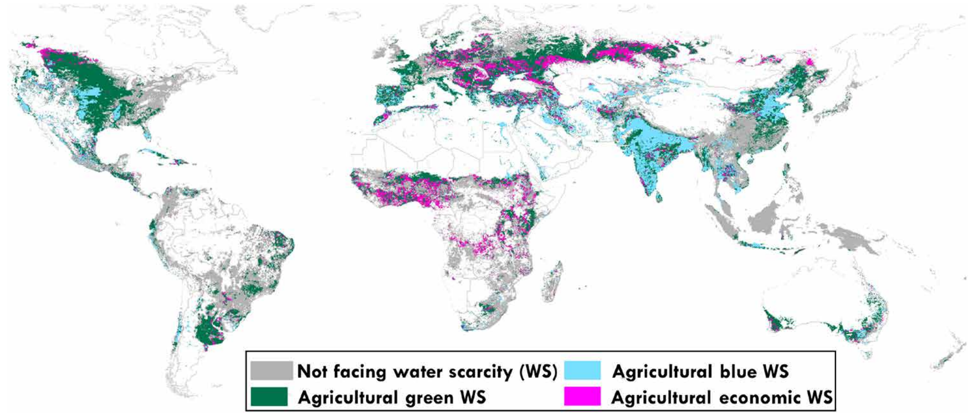

Fig. 2. The geography of global agricultural water scarcity. The map shows the global distribution of agricultural GWS, BWS, and EWS across global croplands. In the map, shown are croplands facing at least 1 month of water scarcity per year.

monthly climate forcing (Fig. 2). The exposure to water scarcity strongly varies with geographic location and month of the year (Fig. 3). We find that 76% of global croplands (or 69% of global rain-fed calorie production) face GWS for at least 1 month a year and 42% experience GWS for 5 months a year (Fig. 1).

We estimate that current green water consumption over croplands is 5406 km^3 $year^{-1}$ (tables S2 to S5). To avoid crop growth under water-stressed conditions as a result of GWS, global croplands would require an additional 2860 km^3 $year^{-1}$ of blue water consumption. That is, this is the global irrigation water requirement without accounting for the limits imposed by sustainability needs. Presently, 23% of global cropland areas are irrigated, consuming 1083 km^3 $year^{-1}$ of blue water resources. Irrigation currently provides 34% of global calorie production (calculated as the difference between irrigated and rain-fed production over irrigated lands) or 40% if calculated as the total production from irrigated lands. Major irrigated regions in the United States (High Plains and the Central Valley of California), Mexico, Spain, North China, Australia (the Murray-Darling Basin), India, and Pakistan consistently face BWS for several months during their crops' growing seasons (Fig. 3 and fig. S1). In those months, irrigation water requirements can only be met with an unsustainable use of water resources.

We find a widespread reliance of food production on irrigated regions affected by BWS. Sixty-eight percent of the global irrigated croplands face BWS for 1 month a year and 37% experience BWS for 5 months during the year. We estimate that 22% of global calorie production is exposed to at least 1 month of BWS during the growing season and that 56% (611 km^3 $year^{-1}$) of global irrigation volumes are applied on unsustainably irrigated lands (Fig. 4). We also analyze to what extent deficit irrigation would be sustainable even in currently irrigated areas affected by BWS. We find that water applications with a 20 and 50% irrigation deficit could be sustainably carried out in 7% (0.01 billion hectares) and 33% (0.05 billion hectares) of the currently irrigated lands affected by BWS, respectively (Fig. 4 and fig. S2).

Exposure to agricultural EWS

The widespread reliance on unsustainable irrigation, combined with longer dry spells, and more erratic rainfalls is of particular concern for local and global food security. The expansion of irrigation over economically water scarce lands could be an important adaptation strategy to climate change, contributing to a more reliable and resilient crop production.

We find that 15% (0.14 billion hectares) of global croplands are exposed to agricultural EWS, while 16% of the cultivated lands are currently unsustainably irrigated. Considering current crop types and growing seasons, the expansion of irrigation to lands affected by EWS would increase global blue water consumption for irrigation by 10% (+105 km^3 $year^{-1}$), thereby allowing for a 6% increase in global calorie production (0.76×10^{15} kcal), which would be sufficient to feed 620 million people (Fig. 4). Because rain-fed production usually allows for only one growing season per year, we find that 43% (0.06 billion hectares) of economically water scarce croplands face agricultural EWS for only 1 month in the course of its rain-fed growing season and 86% is exposed to agricultural EWS for 3 months during its rain-fed growing season (Fig. 3). We illustrate these differences in greater detail in figs. S1 and S3.

By applying a 20 and 50% irrigation deficit, the extent of economically water scarce croplands would increase (fig. S4). With a 20% irrigation deficit, it is possible to further expand sustainable irrigation to an additional 5% of global croplands (+0.05 billion hectares) (Fig. 4). This expansion of sustainable irrigation would feed an additional 160 million people, while increasing irrigation water consumption by 50 km^3 $year^{-1}$. By applying a 50% irrigation deficit, an additional 5% of global croplands could be irrigated sustainably to produce food for 60 million more people. Therefore, in a 50% irrigation deficit scenario, up to 25% of global croplands are found to be exposed to agricultural EWS (Fig. 1). In this scenario, sustainable irrigation expansion over underperforming rain-fed (i.e., economically water scarce) lands could increase food production to feed about 840 million people.

We also determined the extent of croplands facing total water scarcity (Fig. 1 and Box 1). In these rain-fed croplands, irrigation expansion would be unsustainable (i.e., it contributes to groundwater depletion or loss of environmental flows) even in the two deficit irrigation scenarios discussed above. Depending on these scenarios, we find that 28 to 38% of global croplands are exposed to total water scarcity (Fig. 1). Over these agricultural regions, trade-offs among the opportunity to increase food production through irrigation expansion, the cost of irrigation infrastructure, and the sustainable use of blue water resources should be evaluated.

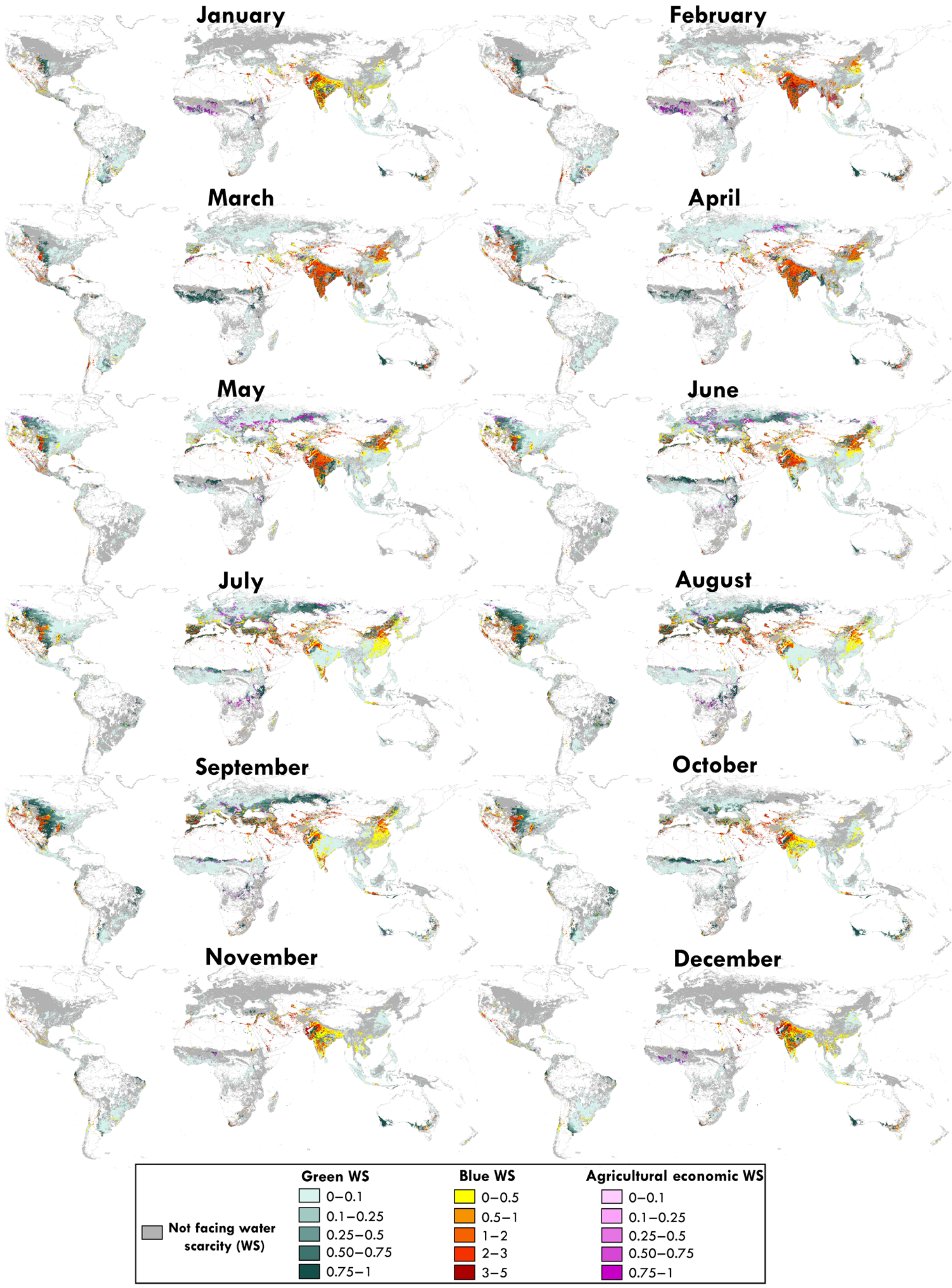

Fig. 3. Monthly agricultural GWS, BWS, and EWS over global croplands.

Regional hot spots of agricultural EWS

Agricultural EWS tends to concentrate in low-income countries with large yield gaps, likely due to the lack of capacity to invest in the irrigation infrastructure needed to meet CWR using the available renewable blue water resources. Expectedly, in both high-income and arid regions, there are less agricultural economically water scarce croplands where irrigation expansion can be used to increase food production (Fig. 5).

Two-thirds of agricultural economically water scarce croplands are located in Sub-Saharan Africa, Eastern Europe, and Central Asia (Fig. 5). In Sub-Saharan Africa, a region currently sparsely irrigated, irrigation expansion over economically water scarce croplands—combined with the adoption of sustainable deficit irrigation practices—would produce enough food to feed an additional 189 to 235 million people while requiring an additional 38 to 61 km^3 of irrigation water (~24 to 96% increase with respect to current irrigation water consumption). In Eastern Europe and Central Asia, the expansion of irrigation in regions affected by EWS—combined with the adoption of sustainable deficit irrigation practices—would produce enough food to feed an additional 317 to 417 million people using 40 to 77 km^3 of irrigation water (Fig. 5).

Opportunities for irrigation expansion differ markedly by country (see the Supplementary Materials for detailed country-specific data). Maximizing crop production by expanding irrigation over economically

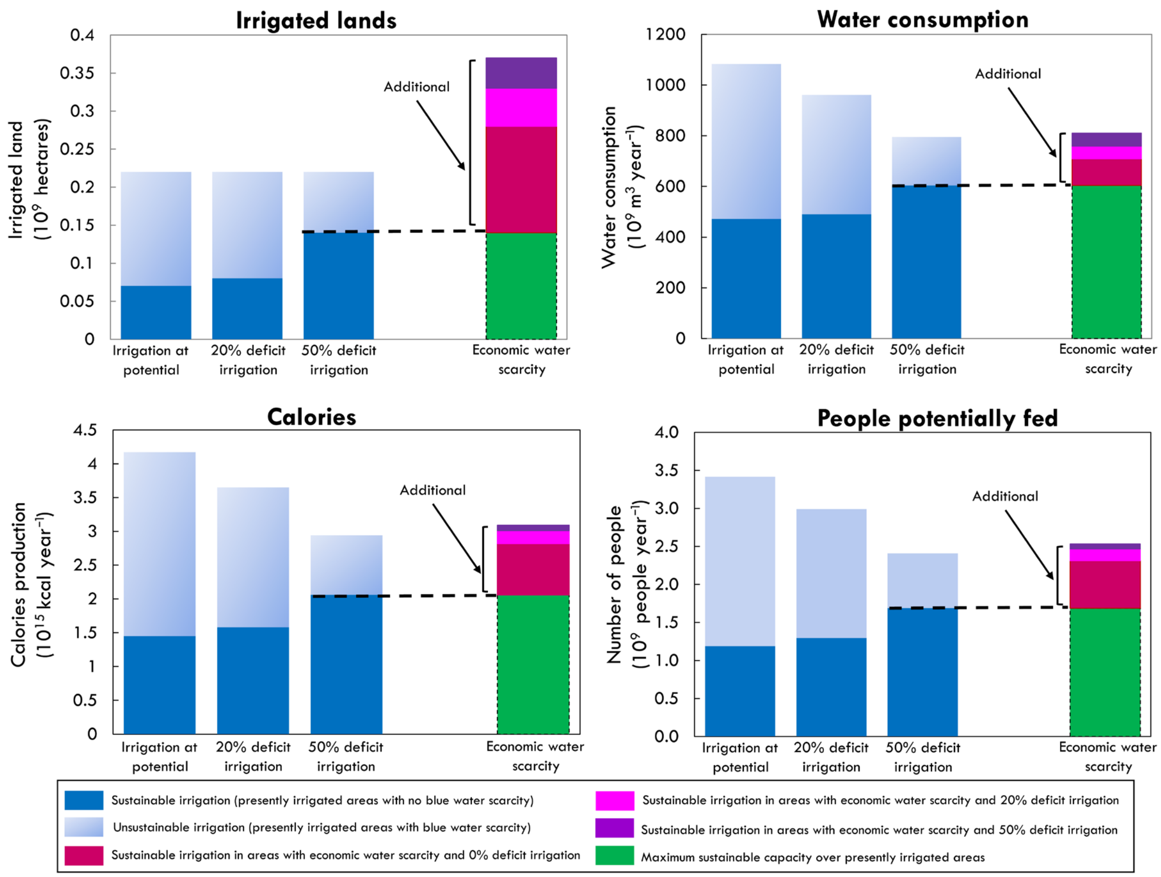

Fig. 4. Global irrigated land, blue water consumption, calorie production, and people potentially fed in presently irrigated areas (see the three blue columns to the left), and in croplands facing agricultural EWS (column to the right). Maximum sustainable capacity over currently irrigated areas (green bars) is obtained in the 50% deficit irrigation scenario. Additional sustainable irrigation can be obtained by expanding irrigation to agricultural economic water scarce rain-fed areas and adopting deficit irrigation in rain-fed croplands affected by BWS.

water scarce croplands would increase by at least one-third the current total calorie production in 19 low-income countries. About half of the increase in global calorie production associated with irrigation expansion over economically water scarce croplands would be contributed by only five countries—namely, Nigeria, Ukraine, Russia, Romania, and Kazakhstan—where vast cropland areas are affected by agricultural EWS. Nigeria, a country with rapid population growth, has the potential to increase food production and feed an additional 87 to 98 million people by expanding irrigation to agricultural economic water scarce areas. Ukraine, Russia, and Romania also have good opportunities to increase food production for an additional 84 to 119 million, 67 to 88 million, and 33 to 39 million people, respectively. With an increase in food production in agricultural economic water scarce lands, net food importing countries, many in Sub-Saharan Africa, could reduce their reliance on international food trade and therefore their exposure to socioenvironmental shocks in food supply systems (*35*).

DISCUSSION

Building on previous efforts that assessed GWS and BWS (*4*, *10*, *17*, *24*), our study maps and quantifies the productivity potential of sustainable irrigation expansion into rain-fed croplands that are economically water scarce. Sustainable irrigation expansion has the potential to increase food production without degrading terrestrial and aquatic habitats by claiming uncultivated land or environmental flows. Sustainable irrigation is also an adaptation strategy to climate change, which creates more reliable and resilient food production than solely rain-fed croplands. Our monthly assessment allows us to estimate also the maximum amount of blue water resources that can be consumed by humanity across the global croplands. We estimate that while at most 810 km^3 $year^{-1}$ of blue water resources can be consumed for sustainable irrigation worldwide, humanity is currently consuming 1083 km^3 $year^{-1}$, thereby overshooting the planetary boundary for water (Fig. 4). While 0.10 to 0.15 billion hectares of agricultural land are facing unsustainable irrigation for at least 1 month per year, we find that 0.14 to 0.23 billion hectares of rain-fed croplands (mostly in Sub-Saharan Africa, Eastern Europe, and Central Asia) are suitable for sustainable irrigation but they are not irrigated because of agricultural EWS.

The use of irrigation to complement green water deficits has boosted agricultural production in many regions worldwide, making irrigation a crucial factor in global food security. However, this practice is largely exposed to BWS. We estimated that 2.23 billion people, corresponding to 22% (2.72×10^{15} kcal $year^{-1}$) of global food production, rely on unsustainable uses of blue water resources. If current unsustainable irrigation were to be totally eliminated, then a combined adoption of sustainable irrigation deficit practices

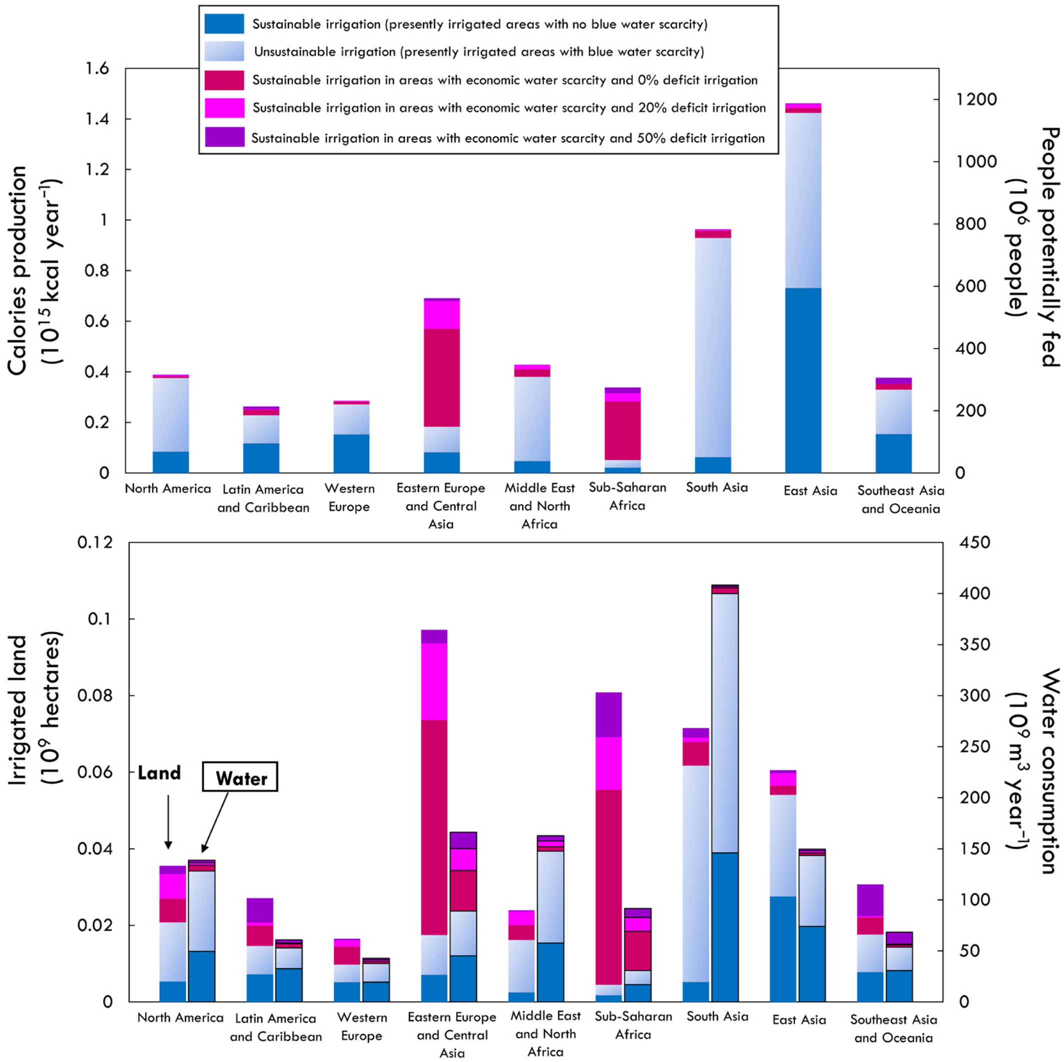

Fig. 5. Regional distribution of calorie production, people potentially fed, irrigated land, and blue water consumption over agricultural economic water scarce croplands. The figure shows (i) current (sustainable and unsustainable) land, water, and calorie produced in irrigated lands considering irrigation at maximum potential; and (ii) additional land, water, and calorie that could be sustainably produced in economically water scarce lands also considering deficit irrigation scenarios. Results are represented by considering croplands facing at least 1 month of BWS and agricultural EWS along the year. Note that calorie production and people potentially fed are proportional.

and sustainable irrigation expansion over economically water scarce croplands would contribute to 13% (1.64×10^{15} kcal year^{-1}) of global calorie production or produce food enough to feed 1.34 billion more people (Fig. 4). Because water availability and crop water demand have a large intra-annual variability, the construction of small and sometimes temporary reservoirs built to store excess run-off in the course of the year could retain enough water to bridge seasonal water deficits. A previous study, at the annual scale and under the same assumptions, has shown that sustainable irrigation expansion into rain-fed croplands could produce 1.57×10^{15} kcal year^{-1} (or food for about 1.28 billion people) more than the monthly assessment (*4*). This means that in the presence of adequate water storage to mitigate the effects of seasonal BWS, there would be an increase in food production (3.21×10^{15} kcal year^{-1}), which would be enough to sustainably offset the loss of calorie production in the event that unsustainable irrigation practices were eliminated.

Most likely, the construction of local water storages will allow intermediate conditions between these two limit scenarios to be achieved. Of course, the enhancement of agricultural productivity on underperforming croplands is only one of the possible options available to feed humanity while meeting environmental goals. On the consumption side, food waste reduction (*36*), moderating reliance on first generation biofuels, reducing meat consumption, and improving resource use efficiency (*37*) can be adopted to sustainably reduce food demand while improving water and food security without requiring an increase in production (*3*). Moreover, investing in girls' education and expanding people's access to family planning are other valuable strategies that could be adopted to limit population growth and reduce future food demand (*38*).

Opportunities to ease green water deficits

Nearly half of the economically water scarce croplands are exposed to GWS for only 1 month a year. In these areas, investments in irrigation might not be justified by the limited increase in crop production that would result from irrigation in such short water deficit periods. Therefore, it is important to consider less costly and environmentally more suitable "soft" approaches to reducing crops' exposure to water stress (*39*). These approaches are nature-based solutions that allow for a sustainable intensification of agriculture in target areas while maximizing climate resilience and minimizing resource demands and environmental impacts (*40*). For instance, it is possible to retain more green water in the soil by reducing soil evaporation with appropriate low-cost land and water management options (*25*, *41*). Contour stone bund, pitting, and terracing are indigenous farming techniques that increase soil moisture by enhancing infiltration rates and reducing surface runoff (*25*, *41*). Mulching and no-till farming can also improve infiltration of precipitation in the soil and reduce evaporation by lowering soil temperature due to shading (*42*). Agroforestry and agrivoltaics, combing agriculture with forestry or solar panels, can decrease croplands exposure to sunlight and therefore reduce evaporation rates while increasing productivity (*38*, *43*). Replacing water-intensive crops with less water consuming crops can also reduce exposure to GWS (*44*). The removal of weeds can further reduce nonproductive green water consumption (*41*). The implementation of these approaches could provide enough rainwater to bridge a month-long GWS.

For longer green water deficits, however, irrigation infrastructure is necessary to enhance crop productivity. In areas affected by only short periods of GWS, the construction of small, decentralized water harvesting and storage facilities is often seen as an economically more viable option than the construction of large dams and centralized irrigation systems (*45*). Collecting run-off in small human-made storage systems such as ponds and tanks and in natural storage systems (e.g., managed aquifer recharge) can effectively alleviate green water deficits (*46*). Moreover, these solutions are more likely to serve small-scale farmers in economically water scarce lands by reducing the capital and operational costs of storage with respect to large centralized irrigation systems (*47*).

CONCLUSIONS

With continuing growth in food demand and limited potential for cropland expansion, sustainable irrigation becomes an increasingly important strategy to ensure a reliable and resilient global supply of food in a changing climate. This study maps global agricultural EWS at unprecedented spatial and temporal resolution. We determine agricultural economic water scarce lands where investments in sustainable irrigation have the possibility to increase food production by expanding irrigation over currently rain-fed croplands. We find that 22% global calorie production happens under conditions of BWS. While irrigation currently consumes 1083 km^3 $year^{-1}$ of blue water resources, we estimate that only 810 km^3 $year^{-1}$ of blue water resources can be consumed sustainably by the global croplands. We estimate that cultivated lands affected by agricultural EWS account for 15 to 25% of the global croplands and could be irrigated sustainably contributing to future food security. A sustainable irrigation expansion into these areas could increase global food production by 6 to 8% and feed an additional 620 to 840 million people while avoiding agricultural expansion into natural ecosystems. The findings of this study show that wise agricultural governance and interventions have the potential to contribute to global food and water security without negatively impacting natural ecosystems. Investigating and explaining the nexus, interlinkages, and trade-offs between environmental sustainability and human well-being are fundamental to orientate rural development toward a more sustainable trajectory.

MATERIALS AND METHODS

Assessment of GWS, BWS, and EWS

Water scarcity was assessed per month per grid cell at 5 arc min by 5 arc min resolution (or ~10 km at the equator). Monthly GWS was expressed as the ratio between irrigation blue water requirements (BWRs) (or green water deficits) and CWR. Crops face GWS when rain-fed conditions cannot meet the CWR. We define the green water (GWS) as the ratio (*4*)

$$GWS = \frac{BWR}{CWR}$$

Because areas with small levels of crop water deficit do not require irrigation, we classify as water scarce those regions with a GWS of >0.1.

Monthly BWS was calculated as the ratio between current blue water consumption (WC_{CURR}) and renewable blue water availability (WA). BWS occurs when total blue water consumption exceeds blue water availability or when the following ratio is greater than 1 (*17*)

$$BWS = \frac{WC_{CURR}}{WA} > 1$$

Monthly EWS was calculated over croplands currently not equipped for irrigation and facing GWS but no BWS. Therefore, EWS was defined as the ratio between total blue water consumption under yield gap closure (WC_{GAP}) and renewable blue water availability (WA)

$$EWS = \begin{cases} \text{currently not equipped for irrigation} \\ \text{facing green water scarcity} \\ \frac{WC_{GAP}}{WA} < 1 \end{cases}$$

Assessment of green and blue water consumption

We used a global process-based crop water model to calculate the CWR for 130 primary crops or 26 crop classes (or nearly 100% of global crop production) for the 1996–2005 period using monthly climate forcing while keeping the spatial extent of global croplands fixed to the MIRCA2000 dataset (*48*). This model has been extensively used to assess spatially explicit CWR (*4*, *10*, *49*). CWR is the amount of water needed by a crop to satisfy its evapotranspirative demand and to avoid water-limited plant growth. CWR can be satisfied by precipitation (i.e., green water) and supplemented through blue water (or irrigation) (blue water requirement, BWR, or irrigation water requirement) if precipitation is insufficient to meet the entire CWR. The model calculates a crop-specific CWR (millimeters per year) using a daily soil water balance during each crop's growing season (*4*, *10*, *49*).

In every grid cell, the current irrigation water consumption ($WC_{IRR,CURR}$) was calculated multiplying crop-specific BWR by the irrigated harvested area of that crop in the year 2000 (*48*). To assess green water consumption, we multiplied crop-specific green water consumption calculated by the model by the rain-fed harvested area of that crop in year 2000 (*48*). For each crop, we also assessed irrigation water consumption at yield gap closure by multiplying crop-specific

BWR by the rain-fed harvested area of that crop in year 2000 (*48*). Water consumption at yield gap closure—the difference between current and attainable yields (*50*)—is the additional irrigation water necessary to avoid water-limited plant growth and therefore reach the maximum crop productivity (or "close the yield gap") in rain-fed croplands (*4*). Yield gap closure can be achieved by avoiding biophysical deficiencies that constrain crop growth and are not addressed by current management practices, including irrigation and fertilizer applications (*1*). However, this study focuses on limitations arising from water scarcity.

Monthly current total blue water consumption (WC_{CURR}) was assessed by summing monthly current irrigation water consumption ($WC_{IRR,CURR}$) and monthly estimates of industrial and municipal blue water consumption. This analysis was repeated to assess monthly total blue water consumption under yield gap closure (WC_{GAP}), where we assumed constant consumption from industrial and municipal uses. Industrial and municipal blue water consumption for the 1996–2005 period was taken from Hoekstra and Mekonnen (*51*). For each month of the year, we considered a 10-year average for the 1996–2005 period. WC_{CURR} and WC_{GAP} at 5 arc min by 5 arc min resolution were aggregated to 30 arc min by 30 arc min resolution, the resolution of the renewable blue water availability analysis (WA).

Assessment of renewable blue water availability

Renewable blue water availability (WA) (30 arc min by 30 arc min resolution) was evaluated following Mekonnen and Hoekstra (*17*) as the difference between blue water flows generated in that grid cell and environmental flow requirements. Renewable blue water availability accounts for surface water and groundwater volumes that are recharged through the hydrological cycle (*4*). Long-term (circa year 2000) monthly blue water flows were assessed from local runoff estimates obtained from the Composite Runoff V1.0 database (*52*) and were calculated using the upstream-downstream routing "flow accumulation" function in ArcGIS. Environmental flow requirements were assessed using the Variable Monthly Flow (VMF) method (*53*). The VMF method estimates environmental flow requirements taking into account the seasonality of flow regimes. Once assessed, BWS at 30 arc min by 30 arc min resolution was disaggregated at 5 arc min by 5 arc min resolution, the resolution of the rain-fed and irrigated harvested areas datasets (*48*).

Assessment of calorie production

For each of the 26 crop classes, current 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). Current and maximized crop yields were taken from Monfreda *et al.* (*54*) and Mueller *et al.* (*1*), respectively. Calorie content for each crop was taken from D'Odorico *et al.* (*55*). Crop harvested areas were taken from Portmann *et al.* (*48*). We considered a linear relation between crop yields and biophysical water deficit (*56*), assuming that irrigated production decreases by 20 and 50% under a 20 and 50% irrigation deficit scenario, respectively. We assessed the number of people that can be potentially fed considering a global average diet of 3343 vegetal kcal per capita per day (*4*).

Uncertainties, assumptions, and limitations

The complexity of a global analysis lends itself to a scenario-based approach and to the use of suitable assumptions. First, our model does not consider future potential changes in crops and cropping practices that could result from the development of irrigation infrastructure, nor does it consider the economic viability of new irrigation projects. For example, while it might be technically possible to expand irrigation over economically water scarce lands in Western Europe and North America, from the standpoint of economic evaluations, it might be unfeasible because of the low return on investment relative to the cost of irrigation infrastructure (Fig. 4). Increasing crop productivity might not always be the preferred option, considering other local socioeconomic or environmental factors that our biophysical model is unable to account for (e.g., regional water and land management policies, transboundary water rights, and political instability). Second, irrigation infrastructure might also include new water storage to meet water demand during the dry season. Thus, the access to new water storage would affect our agricultural economic and BWS assessment at the monthly scale. Third, we assessed intra-annual agricultural water scarcity based on long-term renewable water availability data. Interannual variations in water availability, however, may lead to year-to-year fluctuations in the global patterns of water scarcity that are not investigated in this study (*57*). Fourth, this study did not account for the fact that many of the assessed agricultural economic water scarce regions require not only additional irrigation water but also an improvement in nutrient supply (e.g., through manure or industrial fertilizers) to achieve maximum yields (*1*). Fifth, we assumed that irrigated crop yields decrease linearly with the reduction in irrigation water applied under deficit irrigation scenarios. This approach is widely implemented in global studies aiming to assess changes in yields under deficit irrigation (*5*). However, we acknowledge that each crop variety has different responses to water-stressed crop growth. Moreover, the 20 and 50% deficit irrigation thresholds were chosen as an intermediate and extreme value of deficit irrigation that can be applied to crops. Sixth, water scarcity depends also on the quality of water resources because water of poor quality is not suitable for irrigation. In this study, we assessed agricultural EWS only as a function of the available water quantity without considering water quality. Seventh, our study assesses sustainable irrigation based on the amount of water evapotranspired by crops, and therefore, it does not need to account for the efficiency of the irrigation systems, which needs to be considered in studies that use water withdrawals in their analyses. Eighth, we assumed that staple crops and cash crops are all irrigated under the same conditions. However, we acknowledge that the flexibility in irrigation water applications varies between crops depending on the costs or effects associated with water-stressed crop growth (*19*). Last, given the global scope of this study, we assessed environmental flows using the VMF method (*53*). However, we acknowledge that, depending on the scale of the analysis, environmental flow requirements could be defined differently to account for watershed-specific attributes of the hydrologic regime that are crucial to the maintenance of aquatic habitats. These are all assumptions, limitations, and uncertainties that can be accepted within the current study scale and objective, which is to introduce the idea of agricultural EWS, a method to measure it, and its potentials for global sustainable intensification of agriculture.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/6/18/eaaz6031/DC1

View/request a protocol for this paper from *Bio-protocol*.

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