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Half of twenty-first century global irrigation expansion has been in water-stressed regions

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The expansion of irrigated agriculture has increased global crop production but resulted in widespread stress on freshwater resources. Ensuring that increases in irrigated production occur only in places where water is relatively abundant is a key objective of sustainable agriculture and knowledge of how irrigated land has evolved is important for measuring progress towards water sustainability. Yet, a spatially detailed understanding of the evolution of the global area equipped for irrigation (AEI) is missing. In this study, we used the latest subnational irrigation statistics (covering 17,298 administrative units) from various official sources to develop a gridded (5 arcmin resolution) global product of AEI for the years 2000, 2005, 2010 and 2015. We found that AEI increased by 11% from 2000 (297 Mha) to 2015 (330 Mha), with areas of both substantial expansion, such as northwest India and northeast China, and decline, such as Russia. Combining these outputs with information on green (that is, rainfall) and blue (that is, surface and ground) water stress, we also examined to what extent irrigation has expanded unsustainably in places already experiencing water stress. We found that more than half (52%) of the irrigation expansion has taken place in areas that were already water-stressed in the year 2000, with India alone accounting for 36% of global unsustainable expansion. These findings provide new insights into the evolving patterns of global irrigation with important implications for global water sustainability and food security.

The global population is projected to increase to over 10 billion people by 2050 (ref. 1) and food production will need to increase substantially to meet the associated food demand of the growing population[2]. Because increasing the amount of cropland area would mean the conversion of forests and other ecosystems[3], intensifying agriculture on existing croplands by sustainably increasing irrigation and other inputs is a promising potential alternative[4,5]. While irrigated areas account for 24% of croplands, roughly 40% of global food production is from irrigated croplands[6,7]. In addition, over 90% of humanity's consumptive water use is used for irrigated agricultural production[8]. Depending on the relative water demand and availability in a location, this extensive water use can alter the water cycle, deplete aquifers and surface water bodies[9], increase water stress[10] and escalate competition for freshwater resources[11]. Given the critical role that irrigation will probably play in meeting future food demand and the highly heterogeneous nature of water availability and demand, it is essential to understand how spatial

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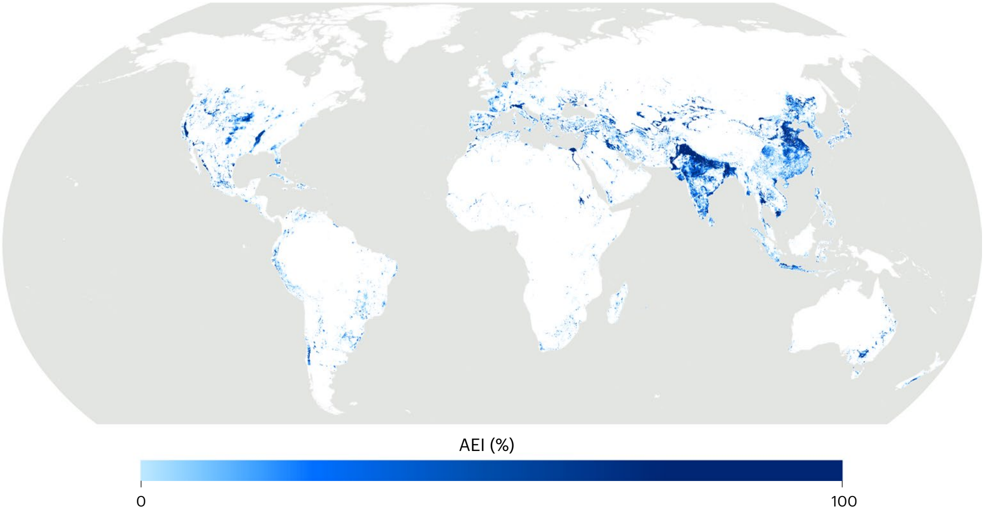

Fig. 1 | Global map of area equipped with irrigation (AEI) in 2015. Map of global AEI showing areas of high potential irrigation activity. Each 5 arcmin pixel shows the percentage of AEI. Only pixels having 1% AEI or higher are shown. Basemap from GADM[54].

patterns of global irrigation have recently evolved and to evaluate whether these changes have tended to occur in locations where water resources are relatively abundant or scarce.

Several global and regional efforts have begun to address the challenges of mapping spatial patterns and temporal trends in irrigation. Datasets on the extent of irrigated land have been developed at global[12] and regional[13] scales, but these analyses do not have the spatio-temporal coverage to evaluate the (un)sustainability of irrigation changes since the start of the century. A growing number of studies have also attempted to map irrigated areas at global or national scales using satellite imagery and remotely sensed data[13–15]. While these studies often provide fine spatial resolution, the resultant maps are not necessarily consistent with irrigation statistics and do not include areas that were equipped for irrigation but not actively in use in the year of the assessment[13,14,16]. Other databases[17–19] offer greater temporal coverage but for coarse national or subnational units, limiting their utility in spatially explicit assessments of irrigation changes with respect to regions experiencing water scarcity. While all of these efforts have provided valuable insights into aspects of either spatial patterns or temporal trends of global irrigation, there remains a critical need for information on the global irrigated area that is both spatially and temporally detailed to examine the sustainability of the evolution of irrigated areas in the twenty-first century. Specifically, a global assessment of whether changes in irrigated area have occurred in locations where conditions of water scarcity already existed is still missing, which could shed new light on the extent to which investments in irrigation infrastructure across the world's croplands have taken into account the state of water availability and sustainability in a particular location.

In this study, we quantified the water sustainability of changes in the global area equipped for irrigation (AEI) since the start of the century. To do so, we first gathered national and subnational irrigation statistics from the year 2000 through to 2015 for 243 countries (consisting of 17,298 administrative units) from international databases, national agricultural censuses and government reports. This focus on AEI, as opposed to the area actually irrigated, is advantageous for examining broader temporal trends and minimizing the errors of harmonizing different agricultural census reference years across countries. We then combined these data with global gridded maps of cropland[20], pastureland[20] and irrigated area[21] into a spatial allocation and downscaling model[12] to develop global gridded (5 arcmin) maps of AEI for the years 2000, 2005, 2010 and 2015. Where there was temporal and spatial overlap, we compared our maps with existing gridded products. Assessing the spatial patterns of AEI expansion and decline, we overlaid global maps of blue (that is, surface and ground) and green (that is, rainfall) water stress[22] to evaluate the fraction of AEI changes that have occurred in water-stressed regions (that is, unsustainable) since the start of the century. This new understanding of the sustainability of recent changes in global irrigation could point to areas that have had success in sustainable irrigation expansion and inform strategies to address undesirable water scarcity outcomes.

Results

Changing patterns of global irrigation

We found that the global AEI in the year 2015 was 329 Mha (Fig. 1), with Asia dominating, accounting for 222 Mha (68%) of the total AEI, followed by North America (37 Mha, 11%) and Europe (31 Mha, 9%). China (72 Mha), India (70 Mha) and the United States (28 Mha) alone accounted for more than half (52%) of the total global AEI.

We also estimated that the global AEI increased on net by 33 Mha (+11%) from the year 2000 (297 Mha; Fig. 2). This net increase was the result of a 65 Mha gross increase in AEI in some areas and a 32 Mha gross decrease in other areas (Fig. 3). Asia and South America observed the largest net increases in AEI of about 28 Mha (+14%) and 5.6 Mha (+49%), respectively, followed by Africa (1.8 Mha, +13%) and Oceania (1.7 Mha, +40%). The countries in which irrigation expanded (on net) the most were China (12.8 Mha) and India (8.5 Mha; Table 1 and Supplementary Table 3 for a full list of countries). A major reason behind this expansion is the increasing investment in irrigation projects to maintain food self-sufficiency[23,24]. AEI expansion was exceptionally large in relative terms in Brazil, where AEI more than doubled in the period 2000–2015 (Table 1).

In Europe, AEI decreased by 4.8 Mha overall (−13%), which is largely attributable to former centrally controlled irrigation infrastructure designed to serve very large irrigation schemes going out of operation and adverse economic conditions in Eastern European countries, for example, Romania[25] (−83%) and Russia[26] (−53%). Other countries, such as Japan (−11%) and Saudi Arabia (−16%), also saw substantial declines in the extent of irrigation (Fig. 2 and Supplementary Table 3), potentially due to a growing reliance on food imports[17]. Overall, these findings point to substantial shifts in irrigation patterns since the start of the century.

The state of water stress in areas of irrigation change

Of equal importance to shifts in AEI is the extent to which these shifts have occurred in locations where water resources are relatively abundant and can potentially support additional blue water demand without

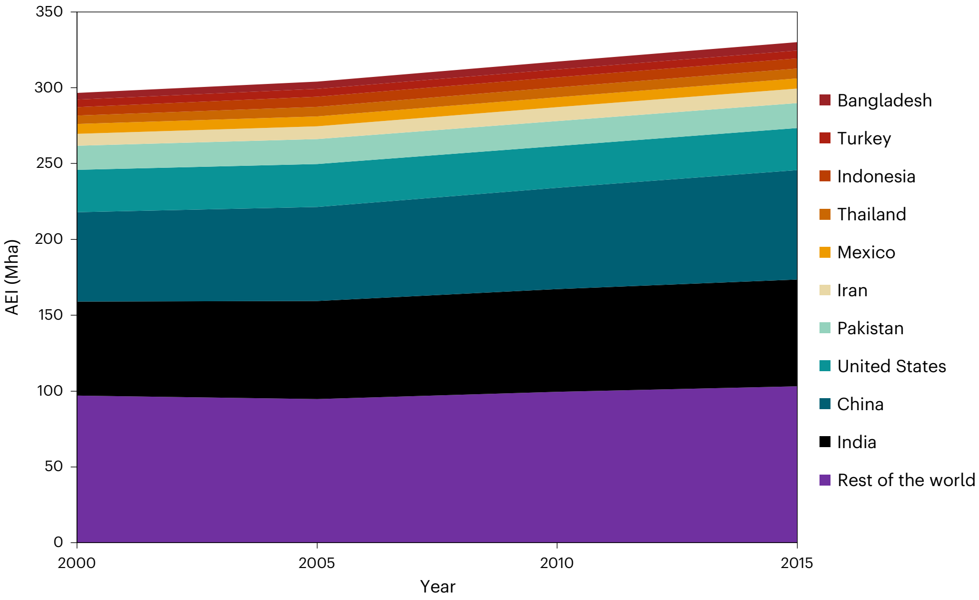

Fig. 2 | Area equipped for irrigation (AEI) for major countries between 2000 and 2015. The global AEI shows a net increase for the period 2000–2015. Countries are arranged in order of increasing AEI (top to bottom) in the year 2000.

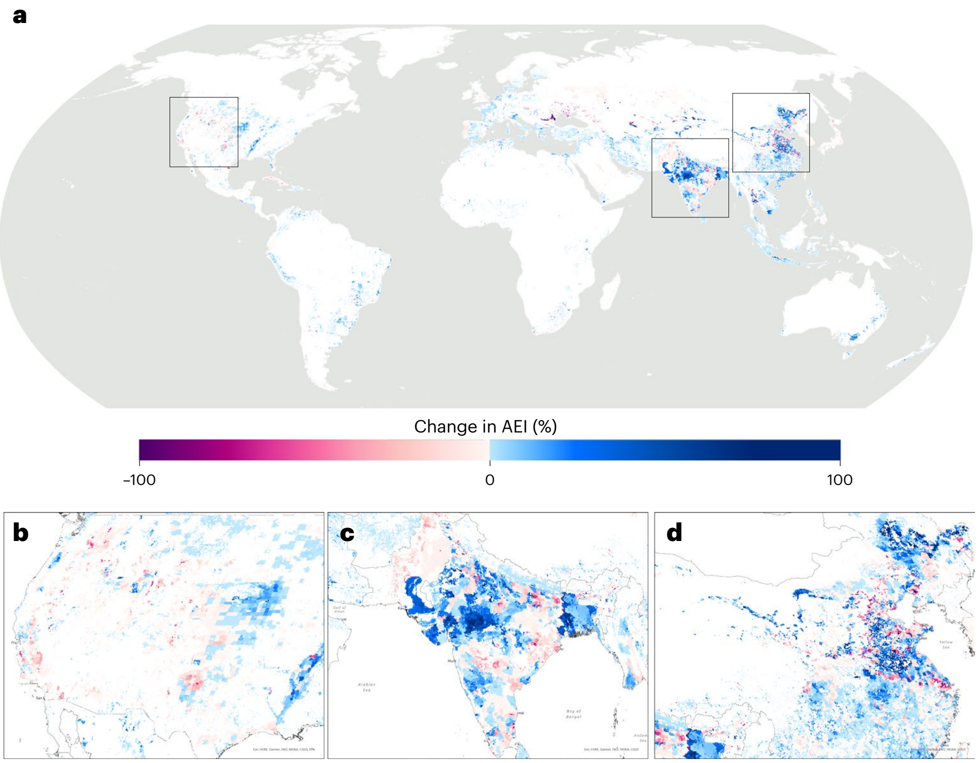

Fig. 3 | Global changes in AEI from 2000 to 2015. a, Global map showing areas that have experienced an increase in AEI and areas that have seen a decline in AEI. Areas of AEI expansion are shown in blue and areas of AEI decline are shown in purple as percentage changes. **b**–**d**, The insets in **a** show the western United States (**b**), India (**c**) and eastern China (**d**). Only pixels with 1% AEI or higher are shown. Basemap from GADM[54].

depleting streamflow or aquifers (that is, sustainable expansion). We assessed potentially sustainable AEI expansion by combining our spatio-temporal AEI database with information on global patterns of water stress. We define water stress as the condition in which consumptive demand (that is, withdrawals minus return flows) by all sectors exceeds freshwater availability[27]. Water stress can be the result of either green water stress (GWS), when rainfall is insufficient to meet a crop's water requirement and supplementary irrigation is needed, or blue water stress (BWS), when renewable surface and groundwater availability (that is, total availability after accounting for environmental flows) is insufficient to meet irrigation water demand. In the case of GWS, expansion of irrigation infrastructure can be a valuable strategy for buffering against variations in rainfall, provided that blue water resources are sufficiently available. In the case of BWS, expansion of irrigation infrastructure can lead to enhanced depletion of aquifers and streamflow.

Table 1 | Countries with the largest net positive and net negative changes in AEI

Country	AEI net change (Mha)	AEI net change (%)
China	12.8	+22
India	8.5	+14
Brazil	3.6	+113
Iran	1.7	+22
Australia	1.5	+41
Indonesia	1.2	+22
Bangladesh	1.1	+25
Vietnam	1.0	+26
Peru	0.9	+52
Thailand	0.8	+15
Japan	−0.3	−11
Cuba	−0.3	−36
Kazakhstan	−1.4	−40
Russia	−2.0	−53
Romania	−2.2	−83
Rest of the world	6.1	+5

Of the 65 Mha of gross irrigation expansion that we observed, 1.1 Mha occurred in regions with only BWS, 19 Mha occurred in regions with only GWS, 31.2 Mha occurred in regions with both BWS and GWS, and 13.9 Mha occurred in regions with no water stress (Fig. 4). This means that approximately 50% (1.1 + 31.2 Mha) of gross AEI expansion has been unsustainable, taking place in locations already experiencing some form of BWS (see country list in Table 2). We found consistent estimates when using an alternative base irrigation map[28] (68 Mha gross irrigation expansion, 47% of which is unsustainable; Supplementary Fig. 9 and Supplementary Table 2). Of the countries with the largest AEI in 2015, India and Pakistan have seen the most unsustainable expansion, with 86% (12.1 Mha) and 87% (1.53 Mha) of the gross expansion in AEI, respectively, taking place in locations that were already experiencing BWS. A substantial fraction of the AEI expansion in China (28%) and the United States (42%) was also unsustainable (Supplementary Table 3). Conversely, there were also countries in which most of the AEI expansion was sustainable (from the perspective of water resources), such as Brazil (3.4 Mha, 96% of the total expansion was sustainable), Indonesia (0.9 Mha, 76%), Peru (0.8 Mha, 94%), Italy (0.3 Mha, 85%) and France (0.2 Mha, 88%; Supplementary Table 3). In many places, we also observed substantial declines in AEI in areas that were previously experiencing unsustainable water demand (that is, under BWS conditions). Globally, the decline in AEI in water-stressed regions (BWS and BWS + GWS) totalled −15.4 Mha (51% of the total decline). The countries with the largest decreases in AEI in water-stressed regions included India (−4.8 Mha, 78%), China (−3.5 Mha, 52%) and the United States (−1.4 Mha, 63%; see Supplementary Table 3 for a full list). Taken together, all of these results demonstrate that both sustainable and unsustainable shifts in irrigation patterns have occurred across diverse geographies and contexts (and often within the same country) since the start of the century. These findings provide a critical understanding of whether and where irrigation trends have been on a sustainable trajectory (that is, in locations where water resources are relatively abundant) and highlight regions where interventions are most urgently needed to address unsustainable practices.

Discussion

Our findings shed new light on the extent to which shifts in irrigation have been sustainable since the start of the century. Globally, we found that AEI has expanded by 11% since 2000, a necessary and important step towards increasing food supply and buffering against rising climate variability. Most notably, the expansion of irrigation that we observed in sub-Saharan Africa and South and Southeast Asia has potential to help to address widespread and persistent malnutrition[29] and aid the productivity and adaptive capacity of the many smallholder farmers in these regions[30,31]. Yet, our analysis also demonstrates that in many places, irrigation expansion has occurred where water stress already existed, suggesting the further depletion of streamflow and aquifers in these locations. In all, these findings paint a mixed picture of progress towards global water sustainability and highlight deep differences in irrigation shifts both within and between countries.

The extent to which countries increase crop production through unsustainable irrigation expansion will also have important implications for the food self-sufficiency of nations as well as global food security, given the growing reliance of many countries on food imports[32]. Countries continuing to practise and expand irrigated agriculture in places where water is scarce subject themselves to an increasing likelihood that freshwater resources could become inaccessible (that is, groundwater table drawdown and streamflow depletion) and ultimately impose physical and/or economic limits on the levels of irrigated production[33]. For food-importing countries (for example, Saudi Arabia and South Africa), such a situation may cause local food production to falter and necessitate a growing reliance on food trade. For food exporters (for example, the United States and Australia), continued unsustainable irrigation practices could force a reduction in food exports to continue to meet domestic food demand. Sustainable irrigation is particularly important in these exporting countries as a failure of water resources would potentially have cascading effects on the nations to which they export food[34]. Thus, ensuring that irrigation expansion occurs only in those places where water resources are relatively abundant could avoid these undesirable outcomes. By quantifying the global patterns of irrigation change, our results can provide spatially detailed information on where targeted interventions are most urgently needed to avoid or reverse unsustainable irrigation expansion.

Despite the uncertainty inherent in such global mapping efforts, our analysis can also begin to point to areas where policies and investments have been successful in moving towards sustainable water resource management. Understanding the socio-political conditions that enabled and informed these examples of sustainable expansion can provide valuable insights for potential applications in other locations and contexts. While an estimated 3.8 billion additional people could be fed through irrigation expansion[35], our findings demonstrate that much of the irrigation expansion that has already taken place is compromising the long-term viability of freshwater resources. With 129 countries currently off-track to sustainably manage their water resources by 2030[36], urgent action is needed and sustainable irrigation will play a central role. To this end, our study enables the identification of opportunities to realize co-benefits (for example, increased food production, improved water sustainability and enhanced climate adaptation) and avoid trade-offs, a critical condition for achieving multiple Sustainable Development Goals (SDGs)[37]. In addition to quantifying the sustainability of changing global irrigation patterns and pointing to locations where expansion is advisable, our results can also provide the basis for evaluating a suite of potential solutions for reduced water consumption in irrigated croplands, including improved irrigation efficiencies paired with water consumption caps[38–40], switching to less water-intensive crops[41,42], soil water conservation[38] and selective fallowing[43,44].

While our study provides important advances in sustainable irrigation expansion, it would be prudent to consider the following four key caveats when using and interpreting our AEI database. First, the reported changes in irrigated areas are based on the best available information on global irrigation extent (that is, the Global Map of Irrigation Areas[21] and ref. 28). Thus, the magnitude of the estimated change in a particular location may vary depending on how these input

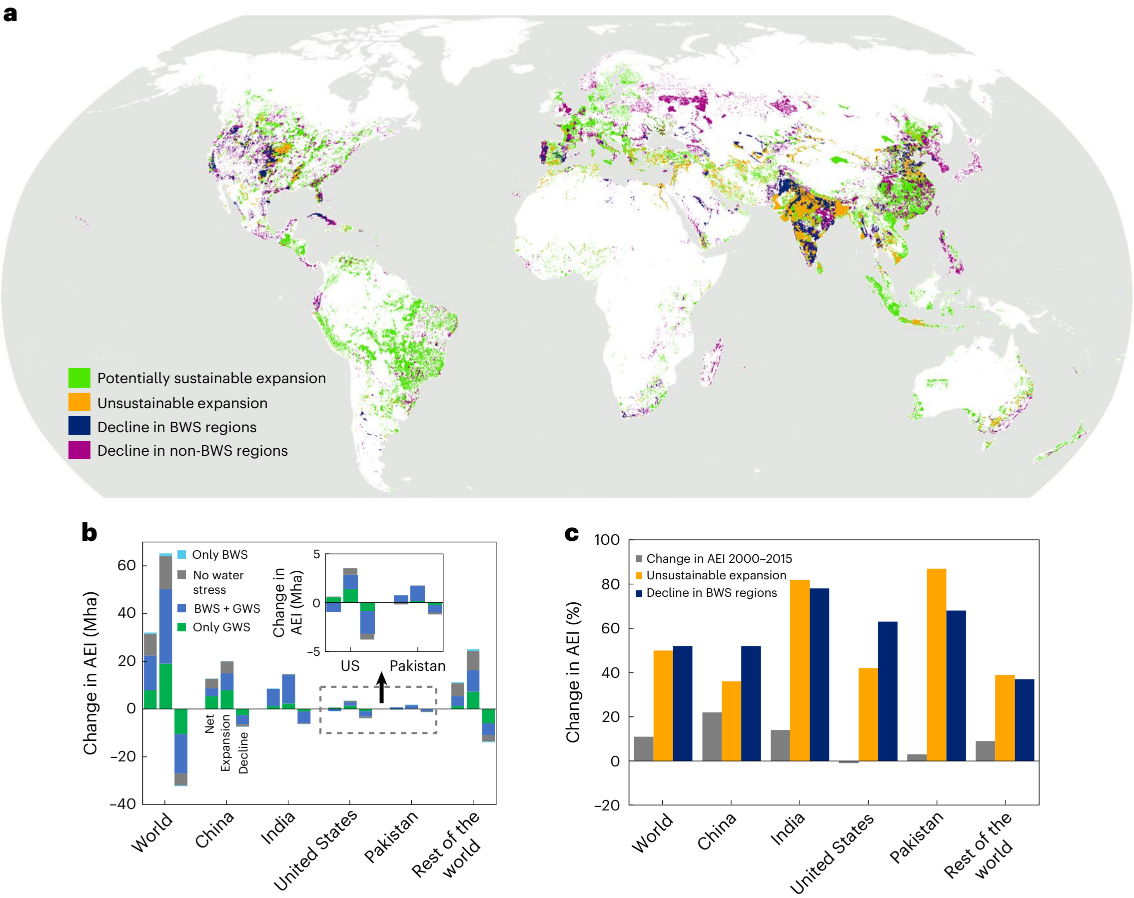

Fig. 4 | Sustainability of changes in AEI in the twenty-first century. a, Map showing four categories of AEI change: potentially sustainable expansion (that is, in areas of GWS or no water stress), unsustainable expansion (that is, in areas of BWS or BWS + GWS), decline in BWS regions and decline in non-BWS regions. Blue water resources are relatively abundant in areas with only GWS or with no water stress (that is, there is no BWS); a full accounting of changes in crop-specific water demand under irrigation expansion is necessary to comprehensively determine whether water stress continues to be avoided in these areas of potentially sustainable expansion. Only pixels with >1% of the area occupied by AEI are shown. **b**, Changes in net AEI as well as AEI expansion and decline from 2000 to 2015 by water stress category for major countries. **c**, Percentage change in net AEI from 2000 to 2015, percentage of unsustainable AEI expansion (that is, in areas of BWS) and percentage of AEI decline in BWS regions. Basemap in **a** from GADM[52].

Table 2 | Countries with the largest net expansion of AEI in already water-stressed regions

Country	Unsustainable expansion (% of gross expansion)	Net AEI change in BWS or BWS+GWS regions (Mha)
India	82	7.3
China	36	3.5
Iran	63	1.1
Bangladesh	92	1.0
Australia	57	0.9
Thailand	80	0.7
Pakistan	87	0.7
Vietnam	45	0.4
Egypt	79	0.3
Indonesia	22	0.2
Algeria	34	0.2

datasets define irrigation and for where. Furthermore, depending on the underlying global irrigated area map used, changes in AEI may not be captured in certain locations (for example, Brazilian Cerrado and India's Chhattisgarh and Odisha states) where new croplands have been established via land use change. Second, the changes in AEI that we investigated here may not perfectly mirror changes in the area that is actually irrigated. For instance, our estimates of declines in irrigated area may be muted in locations where irrigation infrastructure still exists but has been abandoned (for example, former Soviet states). This difference between AEI and actual irrigated area is less problematic when considering expansion as active investment in and development of expanded irrigation infrastructure suggests that the area is being actively used. Relatedly, we also note that our approach does not allow us to capture the finer temporal dynamics of actually irrigated areas, which can vary interannually and by season. Approaches to fuse data on AEI and area actually irrigated will be an important next step in better understanding global irrigation dynamics. Third, for a number of countries, for example, in sub-Saharan Africa, irrigation statistics are only available at the national level (Supplementary Table 4). As such, assessments of grid cell level changes in these places should be performed with caution[45]. For future versions of this AEI database, a combination of updates to global maps of irrigated extent as well as spatially disaggregated irrigation statistics for currently data-scarce nations will largely address these limitations. Fourth, our estimates of sustainable and unsustainable irrigation expansion depend on how water scarcity is defined and how crop water demand is estimated. As such, our approach is intentionally flexible to incorporate different definitions and estimations of global water stress. In areas where we estimated potentially sustainable expansion (that is, only GWS or no water stress), a full accounting of changes in crop-specific water demand under irrigation expansion would be necessary to comprehensively determine whether conditions of water stress continue to be avoided. Combined with the fact that BWS has increased with time[46], this suggests that our estimates for unsustainable irrigation expansion might be understated. In contrast, water stress may be overestimated in regions where the assessment of water resources has not accounted properly for interbasin transfers and water transfer by large-scale irrigation canal networks, for example, in India, Pakistan and the Nile Basin.

Our assessment provides critical information for quantifying and measuring the progress of global irrigated agriculture. The fine-scale spatial heterogeneity of changing irrigation patterns that we observed will probably have implications that propagate to subsequent food supply chain steps[47] and alter the entire food system[48]. Holistic and coordinated approaches to promoting irrigation that account for these interconnections have potential to maximize environmental and socio-economic co-benefits while minimizing trade-offs[49]. Yet, our study also clearly demonstrates that irrigation expansion continues to occur in water-stressed areas either because current efforts have been ineffective in defining or achieving water sustainability targets in many places or because the long-term sustainability of freshwater resources remains secondary to other societal priorities in these locations. Thus, ensuring that meeting the water demands of humanity—to increase food production and meet other needs—does not compromise other dimensions of sustainability is critical to moving beyond the shortcomings of the Green Revolution and meeting multiple SDGs.

Methods

Terminology

The main variable mapped in this study was AEI, defined as the area of land equipped with infrastructure to provide water to crops[50]. It includes areas equipped for surface irrigation, full or partial control irrigation, spate irrigation and equipped lowland areas[50], but excludes rainwater harvesting. Areas that are irrigated seasonally and switch between rainfed and irrigation farming were also included.

To define water stress, we followed the terminology of ref. 51 who defined water stress as the ratio of water used (that is, consumption) to total water availability.

Data sources

Subnational administrative boundaries were taken from the Global Administrative Areas database[52] (version 3.6). Information on the areas equipped for irrigation in the year 2005 came from the Global Map of Irrigation Areas (5 arcmin resolution)[21]. Data on cropland and pastureland for the years 2000 through to 2015 came from the History Database of the Global Environment (HYDE, version 3.2, 5 arcmin resolution)[20].

We acquired AEI statistics from three major international sources for all countries for the years 2000 onwards: FAOSTAT[17], AQUASTAT[18] and EUROSTAT[19], as well as from various national censuses (Supplementary Table 4). A few countries with large extents of irrigated area (that is, Canada, China, India and the United States) collect and report data only on area actually irrigated (AAI; Supplementary Table 4). As AEI refers to all land that is equipped with irrigation, we expect AAI to be lower or equal to the AEI of a country. AAI can be lower than AEI when part of the irrigation infrastructure is not used, as a result of rainfed crop cultivation, or simply because the land was not used for agriculture (left fallow). In these cases, we scaled the statistics on AAI to match reported AEI values.

To develop the spatial database of AEI, we first collected subnational irrigated area statistics from multiple national and international sources (Supplementary Table 4). Many of the irrigation statistics on AEI were taken from the Food and Agricultural Organization (FAO) databases AQUASTAT[18] and FAOSTAT[17] and the Historical Irrigation Dataset[12]. We also used data from EUROSTAT[19] (for the years 2007, 2010, 2013 and 2016), which reports data on AEI (irrigable land) for countries in the European Union at the Nomenclature of territorial units for statistics 2 subnational level. In addition to these international and global databases, we obtained data from the national censuses, surveys, reports and statistical yearbooks of many countries as these sources often contain information with greater spatial detail (Supplementary Table 4).

Following the methodology of ref. 12, we pre-processed the irrigation data using data-type and temporal harmonizing to eliminate inconsistencies in the irrigation statistics between information sources and across years. We used data-type harmonizing when the definition of irrigated land in statistics differed from the definition of AEI used in this study. We used temporal harmonizing when the time steps of the input data did not exactly correspond to the pre-defined time steps of this dataset. Specifically, we linearly interpolated the data between available years to match the year with the exact study year. This was carried out at both national and subnational levels (Supplementary Information).

Grid cell level downscaling

We then downscaled the cleaned global database of AEI to 5 arcmin resolution following ref. 12. The objective of this step was to spatially allocate AEI information from the subnational statistics to each 5 arcmin grid cell so that the sum of the AEI assigned to grid cells was equal to the AEI of the subnational statistics for the corresponding subnational administrative unit and year. This process was also meant to ensure that for each grid cell, the assigned AEI value was less than or equal to the sum of cropland and pasture area in that year. However, for certain administrative units, AEI was larger than the sum of cropland and pasture extent in a specific year. In these cases, we prioritized maximizing consistency with either subnational irrigation statistics or the HYDE dataset (see Supplementary Information for a detailed methodology and Supplementary Table 1). All calculations were repeated using the ref. 28 global map of the area actually irrigated (Supplementary Figs. 6–9 and Supplementary Tables 1 and 2).

Validation

Global AEI maps for 2015 were validated against the global irrigation map of ref. 14 (Supplementary Figs. 1 and 2), finding R^2 values of 0.56 for low-to-medium-intensity irrigation areas and 0.78 for high-intensity irrigation areas. The output AEI maps for 2015 were validated for China[53], India[16] and the United States[54] using remotely sensed data products, finding overall accuracies of 0.56, 0.58 and 0.91 at the pixel level, respectively. The low accuracies for China and India could be a result of differences in the scale of planting (smallholder farms are difficult to locate by remote sensing), the irrigation techniques used (flood or border irrigation are difficult to identify compared with sprinklers in the United States), topographic factors (complex terrains in China) and meteorological factors (a subtropical climate results in cloudy remotely sensed images). Furthermore, these remote sensing products suffer from either no ground truthing or validation (in the case of the India map[16], which prevents an estimation of map accuracy) and low levels of accuracy (reported overall accuracy = 0.62 in the case of the China map[53], which implies a large range of uncertainty), while the US product is well validated[54]. Despite the vastly different methods by which irrigation estimates are derived via remote sensing (through indirect measures of surface properties) or agricultural census (through farmer surveys), encouragingly, we found high agreement at more aggregated levels (Supplementary Figs. 2–4). Having validated our estimates against all other possible independent sources, we emphasize that our estimates (1) are based on the systematic processing of the best available statistical records of AEI for each country using a consistent terminology and methodology, (2) fall in the range of other well-established data products and (3) provide consistent information back to the year 1900 (which is unique and not possible to achieve through other methods such as remote sensing). These characteristics make our dataset ideally suited to address our research objective: to explore global-scale spatio-temporal trends in the development of irrigated land in relation to conditions of water stress.

Comparison of irrigation changes and water-stressed areas

The locations and magnitudes of AEI expansion and decline were identified by the difference between the AEI maps for each grid cell for the years 2000 and 2015. Subsequently, the resulting difference map was combined with maps (5 arcmin, for the year 2000) of existing monthly BWS and GWS, which account for irrigation, other societal water consumption and environmental flow requirements, taken from ref. 22. This enabled us to identify the locations where AEI expansion occurred under four categories of existing (that is, for the year 2000) water stress conditions: (1) both BWS and GWS, (2) BWS but no GWS, (3) GWS but no BWS and (4) no water stress. AEI expansion in the first two categories was defined as 'unsustainable' because they would exacerbate the depletion of surface water and groundwater resources[9]. The same steps were repeated for areas of AEI decline, where AEI decline in the first two categories was defined as 'potentially sustainable'. In other words, the most sustainable outcomes for changes in AEI would show AEI expansion in places where surface water and groundwater resources are relatively abundant and AEI decline in places where water resources are already relatively scarce. This water stress dataset was selected because of its agreement in terms of spatial resolution with this study's AEI maps (to avoid unnecessary aggregation or resampling), its coincidence with the beginning of the study period (to enable assessment of existing conditions of water stress), and its quantification of both monthly and annual water stress (to capture locations of seasonal unsustainable water demand). We note that our approach can readily incorporate alternative datasets quantifying global patterns of water stress or scarcity.

Data availability

All of the data used in this study are publicly available through https://zenodo.org/record/7809342 or upon request from the corresponding author.

Code availability

All of the code used in this study is available upon request from the corresponding author.

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Author contributions

P.M. and K.F.D. conceived the study. P.M., S.S., M.K. and K.F.D. designed all of the analyses. P.M., Q.D., T.A., L.M. and W.X. collected the data. P.M. and S.S. performed the analyses. P.M. and K.F.D. wrote the first draft of the paper. All authors contributed to the writing and revision of the paper.

Competing interests

The authors declare no competing interests.

Additional information

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