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

In the format provided by the authors and unedited

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<u>Description of input data and sources of information</u>

To develop the spatial database of AEI, we first collected sub-national irrigated area statistics from multiple national and international sources. These sources included the FAO databases Aquastat[19] and FAOSTAT[18] and Historical Irrigation Data set (HID)[12] to obtain a large amount of irrigation statistics on AEI. Aquastat only reports data for years with national surveys at sub-national level. FAOSTAT contains AEI statistics only at national level for the survey years and also uses expert estimates to fill the gaps between those surveys. We also compared the statistics from HID database for years 2000 and 2005 with FAOSTAT estimates for the same year and made corrections to the input data for 2000 and 2005 if there was a difference between the two. FAOSTAT also corrects its data backwards in time, so this step was necessary in order to make the data consistent from the timesteps before 2005. For example, if for a specific country, FAOSTAT corrected its data for year 2005, we then revised the earlier data with the updated FAOSTAT statistics. Another international source that we used was Eurostat[20] - it reports data on AEI (irrigable land) for countries in the European Union at the NUTS2 sub-national level. We used the data available for countries for the years 2007, 2010, 2013 and 2016. At the time of updating the AEI data set, the data from Eurostat for 2016 was not complete for some of the countries, so a few modifications were made to acquire estimates for AEI for 2015 (described in Supplementary material). In addition to these international and global databases, we also used the data collected in national censuses, surveys, and statistical yearbooks for many countries, as these sources often contain information with greater spatial detail. We obtained reports and yearbooks from either the agricultural ministry websites or from other relevant governmental departments such as irrigation and water resources for the corresponding country (Supplementary Table S4).

To develop the spatial database of AEI, the sub-national irrigated area statistics were combined with georeferenced data on sub-national administrative boundaries taken from the Global Administrative Areas database (GADM)[54] version 3.6. For countries whose boundaries changed between years, we used administrative boundaries shapefiles sourced from their national ministries. We also used the global map of irrigated areas which contains the information of areas equipped with irrigation at 5 arcmin grid cell level around the year 2005[22]. We used this dataset as one of the inputs in our model to allocate (sub)national AEI statistics to grid cell level. The assumption is that irrigated areas are generally found in the regions that are already equipped with irrigation. History Database of the Global Environment (HYDE) (version 3.2)[55] from years 2000 to 2015 was used, containing information on cropland extent and pasture at 5 arcmin grid cell level. The dataset assigns the sub-national cropland statistics to grid cells based on two weighing maps: one based on satellite imagery from ESA for year 2010, and the other one considers urban built-up areas, protected areas, population density, soil suitability for crops, extent of coastlines and river plains, slope, and annual mean temperature.

To calculate the AEI changes from 2000 to 2015 in different water stress categories, we used the monthly maps of blue water stress (BWS) and green water stress (GWS)[58]. These monthly maps contain the spatial information of croplands that are facing blue water stress or green water stress at 5 arcmin resolution around the year 2000. These maps were created by first identifying croplands affected by GWS, and monthly GWS was calculated by the ratio between irrigation blue water requirements and crop water requirements. Croplands with monthly GWS >0.1 was considered to be facing GWS. Following this, monthly BWS was calculated as the ratio between blue water consumption and renewable blue water availability, and therefore, BWS occurs when this ratio is greater than 1 (total blue water consumption exceeds blue water availability).

**Methods used to harmonize data from different sources**

Because we acquired irrigation statistics of AEI from many different sources at different temporal and spatial resolutions and so the definitions of the variable of interest AEI were inconsistent and varied among different sources, which resulted in inconsistencies within the datasets. Therefore, to combine and make the global dataset consistent, it was important to harmonize the data. To do this, we employed a two-step procedure following Siebert et al. (2015)[23]: (i) data type harmonizing and (ii) temporal harmonizing. These procedures are briefly described below. Table SY contains the detailed description of all procedures used, data sources and assumptions made for each country and time step.

***Data type harmonizing*** was performed when the definition of irrigated land in statistics differed from the definition of AEI used in this study. For many countries for which statistics came from national sources (e.g., reports, yearbooks, websites), the definition of irrigated land either differed from AEI or was not available. In the cases where the definition was different and typically referred to AAI (e.g., China, India, US), we scaled the data to the Aquastat or FAOSTAT estimates by using a conversion factor and applied it to the sub-national data (state, district, county, or municipality). We calculated the conversion factor by dividing the total national AEI (from FAOSTAT/Aquastat) by the reported national AAI for the reference year (equation [1]). We then multiplied the conversion factor for the reference year with the sub-national AAI data to obtain the sub-national AEI data. In this conversion, we assumed that the ratio between AEI and AAI reported in the original source remains the same across sub-national units.

$$Conversion\ Factor_{reference\ year} = \frac{Reported\ AEI}{Reported\ AAI} \qquad [1]$$

For other countries for which AAI was reported, we used the maximum value of AAI reported for different years around the reference years 2010 and 2015. For example, we used the sub-national Eurostat data for irrigable area for years 2007, 2010, 2013 and 2016. We calculated the AEI at sub-national (NUTS2 unit) level by taking the maximum of irrigable area. We calculated the AEI by taking the maximum of irrigable area of 2007, 2010 and 2013 to get AEI for 2010, and maximum of irrigable area of 2010, 2013 and 2016 to get AEI for the year 2015. We used this method because the data corresponding to years 2007, 2013 and 2016 are from sample surveys, where only a sample of farmers get interviewed, and the data is extrapolated. On the other hand, the 2010 data is from a full agricultural census survey. We assumed that for each NUTS2 unit, the maximum reported in these three years will be the AEI around the year 2010 and 2015. This assumption is reasonable because the AEI likely cannot drastically decrease in a short amount of time. Therefore, using the maximum areas can correctly represent the AEI as compared to farm sample surveys.

***Temporal Harmonizing*** was carried out when the time steps of the input data did not exactly correspond with the predefined time steps. Specifically, we linearly interpolated the data between available years to match the year with the exact study year. This exercise was carried out at both national and sub-national levels. For example, for Russia, we obtained sub-national AEI data for the census years 2006 and 2016 from their agricultural ministry, but we couldn't locate any information on AEI for years 2010 and 2015. In order to obtain the national AEI data for 2010 and 2015, we interpolated between the national totals for years 2006 and 2016. After that, we used the resulting national AEI values and the proportions of AEI from years 2006 and 2016 to proportionately distribute the AEI to the subnational units for the years 2010 and 2015.

## Downscaling of irrigation statistics to 5 arcmin resolution

Following Siebert et al. (2015), the database of subnational AEI statistics for each country for time steps 2010 and 2015 was downscaled to 5 arcmin resolution based on georeferenced administrative boundaries. The objective of this was to spatially allocate AEI from the sub-national statistics to each 5 arcmin grid cell, so that the sum of AEI assigned to grid cells was equal to the AEI of subnational statistics for the corresponding sub-national 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 some administrative units, the AEI is larger than the sum of cropland and pasture extent in a specific year. To account for these inconsistencies, we followed the downscaling approach developed by Siebert et al. (2015) to maximize the consistency with the sub-national irrigation statistics and the HYDE dataset (Supplementary Table S1).

For the recent years 2010 and 2015, the AEI is allocated to the grid cells where irrigated land was found in the later years. Specifically, the downscaling process starts with the most recent year of the timesteps i.e., 2015 and goes back in time until the year 2000. This process followed a ten-step procedure (adapted from Siebert et al, 2015) which was repeated for each sub-national statistical unit and for each year in the time series (Table S1). The maximum irrigation area $IRRI_{max}$ is calculated for each step and grid cell according to the criterion described in Fig. 6. With each procedural step and criterion, the $IRRI_{max}$ increased by considering additional areas outside the irrigated land extent allotted in the previous step. All steps and criterion follow an assumption that (a) irrigated areas in earlier years are more likely to occur in places where irrigated areas are located at present; (b) irrigation of cropland is more likely than that of pastureland; and (c) irrigation of pasture is more likely than that of non-agricultural land.

The downscaling process maximizes consistency with sub-national irrigation statistics (which we report in the main results) for each grid cell based on the input provided. In the gridded product maximizing consistency with historical irrigation statistics, AEI can exceed the sum of cropland and pasture extent. Therefore, AEI reported in sub-national irrigation statistics for an administrative unit was fully allocated to grid cells within that unit. Two modifications have been made to the downscaling methodology described in Siebert et al., 2015. First, step S7 (Table S1) was additionally included to constrain expansion of irrigated land in countries with rapid increase of irrigated land between 2005 and 2015 to regions where AEI was mapped in year 2005. Second, the downscaling procedure for years 2015, 2010 and 2005 used version 5 of the Global Map of Irrigation Areas[22] as starting point for the downscaling ($IRRI_{t+1}$ in Table S1) while for year 2000 the result of the downscaling in year 2005 was used.

In many administrative units, the downscaling procedure terminated in the first step, since for most of the countries, AEI was lower in the previous years as compared to the present. Therefore, $IRRI_{max}$ calculated in the first step was reduced to match the reported AEI for the respective administrative unit. We performed the reduction half in relative terms (equal fraction of cell specific $IRRI_{max}$) and half in absolute terms (equal area in each grid cell) (see example below). This resulted in many grid cells with AEI as 0, and therefore, the number of irrigated grid cells decreased in the hindcasting process (i.e., moving backwards in time). When the sum of $IRRI_{max}$ (i.e., sum of AEI of all grid cells) in the administrative unit calculated in a specific step was less than the AEI reported for that administrative unit, the AEI for each grid cell was set to $IRRI_{max}$ and the process continued to the next step. When the sum of $IRRI_{max}$ in the administrative unit exceeded the reported AEI_SU, the procedure terminated. Half of the increment in AEI is allotted to the grid cells in relative terms and the other half as an area equal for each grid cell (explained in detail below in an Example).

**Table S1.** Illustration of downscaling process to assign irrigated area to specific grid cells (from Siebert et al. 2015). Steps 1-7 were performed only in grid cells containing AEI in the time step before (year 2000) or in the Global Map of Irrigation Areas (years 2015, 2010, 2005) while steps 8-10 were performed also for grid cells not irrigated in the Global Map of Irrigation Areas or the time step before.

| | **Maximizing consistency with sub-national irrigation statistics (AEI_SU)** |
|---|---|
| S1 | $IRRI_{max}$ = Min ($IRRI_{t+1}$, CROP) |
| S2 | $IRRI_{max}$ = Min ($IRRI_{t+1}$, CROP+PAST) |
| S3 | $IRRI_{max}$ = Min ($IRRI_{t+1}$, LAND) |
| S4 | $IRRI_{max}$ = $IRRI_{t+1}$ |
| S5 | $IRRI_{max}$ = Max ($IRRI_{t+1}$, CROP) |
| S6 | $IRRI_{max}$ = Max ($IRRI_{t+1}$, CROP+PAST) |
| S7 | $IRRI_{max}$ = LAND |
| S8 | $IRRI_{max}$ = CROP if $IRRI_{t+1}$ =0<br>$IRRI_{max}$ = $IRRI_{max}$ from S6 if IRRI $_{t+1}$ >0 |
| S9 | $IRRI_{max}$ = Max ($IRRI_{t+1}$, CROP+PAST) |
| S10 | $IRRI_{max}$ = Max ($IRRI_{t+1}$, LAND) |

**Variable definitions**

$IRRI_{t+1}$ Irrigated area in the previous time step (t+1) assigned to the grid cell (ha)

$IRRI_t$ Irrigated area (t) assigned to the grid cell in the current time step (t) of the hindcasting (ha) => result of the downscaling

CROP Cropland in the grid cell in the current time step (t) according to the historical land use data set (ha)

PAST Pasture land in the grid cell in the current time step (t) according to the historical land use data set (ha)

LAND Land area of the grid cell (ha)

$IRRI\_ADM_{t+1}$ Irrigated area in the previous time step (t+1) of the hindcasting for the whole administrative unit (ha)

$IRRI\_ADM_t$ Irrigated area in the current time step (t) of the hindcasting for the whole administrative unit (ha)

Example of the downscaling procedure:

**For simplicity, we assumed that the administrative unit consists of 2 grid cells only.**

***Information at the beginning of the downscaling:***

| Grid cell A | | Grid cell B | | Whole administrative unit (A + B) | |
|---|---|---|---|---|---|
| $IRRI_{t+1}$ | 20 | $IRRI_{t+1}$ | 80 | $IRRI\_ADM_{t+1}$ | 100 |
| CROP | 40 | CROP | 60 | $IRRI\_ADM_{t}$ | 160 |
| PAST | 80 | PAST | 40 | | |
| LAND | 200 | LAND | 200 | | |
| $IRRI_t$ | ? | $IRRI_t$ | ? | | |

***Calculation of the maximum area available for irrigation in steps S1-S10 (maximizing similarity to GMIA5):***

| Rule | $IRRI_{max}$ A | $IRRI_{max}$ B | $IRRI_{max}$ total |
|---|---|---|---|
| S1: $IRRI_{max}$ = Min ($IRRI_{t+1}$, CROP) | 20 | 60 | 80 |
| S2: $IRRI_{max}$ = Min ($IRRI_{t+1}$, CROP+PAST) | 20 | 80 | 100 |
| S3: $IRRI_{max}$ = Min ($IRRI_{t+1}$, LAND) | 20 | 80 | 100 |
| S4: $IRRI_{max}$ = $IRRI_{t+1}$ | 20 | 80 | 100 |
| S5: $IRRI_{max}$ = Max ($IRRI_{t+1}$, CROP) if $IRRI_{t+1} > 0$ | 40 | 80 | 120 |
| S6: $IRRI_{max}$ = Max ($IRRI_{t+1}$, CROP+PAST) if $IRRI_{t+1} > 0$ | 120 | 100 | 220 |
| S7: IRRImax = LAND | 200 | 200 | 400 |
| S8: $IRRI_{max}$ = CROP if $IRRI_{t+1} = 0$ or $IRRI_{max}$ from S6 if $IRRI_{t+1} > 0$ | 120 | 100 | 220 |
| S9: $IRRI_{max}$ = Max ($IRRI_{t+1}$, CROP+PAST) | 120 | 100 | 220 |
| S10: $IRRI_{max}$ = Max ($IRRI_{t+1}$, LAND) | 200 | 200 | 400 |

=> The allocation procedure terminates in **S6** because the sum of $IRRI_{max}$ in both grid cells becomes larger than $IRRI\_ADM_t$ (220>160).Finally, the values 60 ha and 100 ha (total 160 ha) are used for grid cells A and B respectively.

In the first step S1, $IRRI_{max}$ is calculated as the minimum of AEI in the previous time step ($IRRI_{t+1}$) and total cropland (CROP) in the grid cell in the current time step. If the sum of AEI within the grid cells is below the reported total AEI of the corresponding administrative unit in the current time step, the procedure continues to S2. In S2, $IRRI_{max}$ is calculated by taking a minimum of AEI in the previous time step ($IRRI_{t+1}$) (process in going back in time)and the sum of the cropland and pasture (CROP+PAST) in the grid cell in the current time step. At this point, the $IRRI_{max}$ total is 100, which is less than 160 ($IRRI\_ADM_t$). In step S3, $IRRI_{max}$ is calculated as the minimum of $IRRI_{t+1}$ and the total land area of the grid cell (LAND). In step S4, $IRRI_{max}$ is set equal to the AEI of grid cell in previous time step ($IRRI_{t+1}$). In step S5, $IRRI_{max}$ is calculated as the maximum of $IRRI_{t+1}$ and cropland in the grid cell, if $IRRI_{t+1}$ is greater than zero. Now, the AEI allocated to grid cells A and B is 40 and 80, with a total of 120. In step S6, $IRRI_{max}$ is calculated as the maximum of $IRRI_{t+1}$ and the total of cropland and pasture in the grid cell. At this stage, the AEI for A and B is 120 and 100 respectively, and the total goes above the total AEI for the admin unit (220 > 160). Therefore, the procedure terminated in step S6, and so now we have AEI assigned to cell A = 40 ha, and AEI cell B = 80 ha.

The total is 120 ha, and 40 ha still needs to be distributed among these two grid cells. Now, half of the increment (20 ha) is assigned relative to the AEI existing after S5 and half of the increment (20 ha) is assigned as an absolute extent equal for all grid cells. The calculation of the scaling factor for the relative increment is done as follows.

$$\begin{aligned} & \mathit{Relative\ increment} \\ & \qquad = \mathit{AEI\ in\ grid\ cell\ at\ terminating\ step} \\ & \qquad \times \frac{\mathit{Total\ AEI\ left\ to\ assign\ as\ relative\ increment}}{\mathit{Total\ AEI}} \end{aligned}$$

Therefore, for grid cell A, relative increment = 40*(20/120) = 6.67, and for grid cell B, it is 80*(20/120) = 13.33. After adding the relative increment, the total AEI for grid cells A and B is 46.67 ha and 93.33 ha respectively, and the total is 140 ha. Next, we are still left with 20 ha, and that will be allocated using absolute increment, which is calculated by:

$$\mathit{Absolute\ increment} = \frac{\mathit{Total\ AEI\ left\ to\ assign\ as\ absolute\ increment}}{\mathit{Number\ of\ grid\ cells}}$$

Absolute increment will be 20/2 = 10 ha. After this, a check is required for each grid cell, to see if the total AEI is less than or equal to $IRRI_{max}$ calculated for S6. For cell A: $56.67 \leq 120$, is correct, but for cell B: $103.3333 > 100$, which is not okay. Therefore, AEI in cell B will be constrained to IRRImax and the difference will be redistributed in equal parts to all the other grid cells (in this example to grid cell A). So finally, we will have the $IRR_{It}$ in grid cell A is 60 ha, and $IRR_{It}$ in grid cell B is 100 ha.

## Supplementary Tables and Figures

**Table S1 Countries with largest net positive and net negative changes in area equipped for irrigation (AEI).** Estimates are based on AEI version with Meier et al.[46] as a base map.

| Country | AEI net change (Mha) | Percent net change (%) |
|---|---|---|
| China | 13.3 | +23 |
| 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 |

**Table S2. Countries with largest net area equipped for irrigation (AEI) expansion in already water stressed regions.** BWS stands for blue water stress and is defined as the condition when renewable surface and groundwater availability (i.e., total availability after accounting for environmental flows) is insufficient to meet irrigation water demand. GWS in turn stands for green water stress and is defined as the condition when rainfall is insufficient to meet a crop's water requirement and supplementary irrigation is needed. Estimates are based on AEI version with Meier et al.[46] as a base map.

| Country | Unsustainable expansion (% of gross expansion) | Net AEI change in BWS or BWS+GWS regions (Mha) |
|---|---|---|
| India | 78 | 6.5 |
| China | 37 | 4.0 |
| Iran | 67 | 1.1 |
| Bangladesh | 91 | 1.0 |
| Australia | 63 | 1.1 |
| Thailand | 80 | 0.8 |
| Pakistan | 90 | 0.8 |
| Vietnam | 47 | 0.5 |
| Egypt | 93 | 0.3 |
| Indonesia | 21 | 0.3 |
| Algeria | 39 | 0.3 |

**Table S3. Country-level summary of AEI change, and (un)sustainable expansion and decline from 2000 to 2015 based on the FAO-GMIA version.** Water stressed regions are defined as the regions already experiencing blue water stress in the year 2000. Countries are sorted in descending order based on absolute net AEI change (first column).

| COUNTRY | AEI CHANGE 2000-2015 (HA) | DECLINE IN WATER STRESSED REGIONS (HA) | DECLINE IN NON WATER STRESSED REGIONS (HA) | EXPANSION IN WATER STRESSED REGIONS (HA) | EXPANSION IN WATER STRESSED REGIONS (%) | EXPANSION IN NON WATER STRESSED REGIONS (HA) |
|---|---|---|---|---|---|---|
| AFGHANISTAN | 9,000 | 0 | 0 | 7,059 | 78 | 1,941 |
| ALBANIA | 13,397 | 0 | 0 | 3,133 | 23 | 10,264 |
| ALGERIA | 626,447 | -23,414 | -26,300 | 232,114 | 34 | 444,047 |
| ANGOLA | 6,000 | 0 | -15 | 0 | 0 | 6,015 |
| ANTIGUA AND BARBUDA | 250 | 0 | 0 | 0 | 0 | 250 |
| ARGENTINA | 334,517 | -147,122 | -43,325 | 85,698 | 16 | 439,267 |
| ARMENIA | -5,074 | -460 | -4,615 | 0 | 0 | 0 |
| AUSTRALIA | 1,482,317 | -122,258 | -232,657 | 1,053,518 | 57 | 783,714 |
| AUSTRIA | 25,759 | 0 | -1,147 | 0 | 0 | 26,906 |
| AZERBAIJAN | -23,895 | -42,783 | -32,531 | 15,039 | 29 | 36,380 |
| BAHRAIN | -60 | 0 | -60 | 0 | 0 | 0 |
| BANGLADESH | 1,079,776 | -1,227 | -347 | 993,353 | 92 | 87,997 |
| BARBADOS | 400 | 0 | -149 | 0 | 0 | 549 |
| BELARUS | -87,046 | 0 | -87,254 | 0 | 0 | 208 |
| BELGIUM | -8,100 | 0 | -9,743 | 0 | 0 | 1,643 |
| BELIZE | 500 | 0 | 0 | 124 | 25 | 376 |
| BENIN | 10,742 | 0 | 0 | 0 | 0 | 10,742 |
| BHUTAN | -8,172 | -83 | -8,728 | 0 | 0 | 639 |
| BOLIVIA | 175,434 | -7,301 | -67,382 | 0 | 0 | 250,117 |
| BOTSWANA | 1,061 | 0 | 0 | 0 | 0 | 1,061 |
| BRAZIL | 3,553,077 | -37,541 | -643,307 | 193,122 | 5 | 4,040,803 |
| BULGARIA | -148,223 | -7,625 | -144,535 | 161 | 4 | 3,776 |
| BURKINA FASO | 30,000 | 0 | 0 | 4,110 | 14 | 25,890 |
| BURUNDI | 1,570 | 0 | 0 | 0 | 0 | 1,570 |
| CAMBODIA | 123,669 | 0 | 0 | 101,539 | 82 | 22,131 |
| CAMEROON | 3,346 | 0 | 0 | 1,608 | 48 | 1,738 |
| CANADA | 191,026 | -529 | -57,398 | 57,988 | 23 | 190,965 |
| CAPE VERDE | 540 | 0 | 0 | 0 | 0 | 540 |
| CHAD | 4,000 | -15 | -258 | 1,776 | 42 | 2,497 |
| CHINA | 12,827,602 | -3,779,941 | -3,548,010 | 7,332,044 | 36 | 12,823,509 |
| COLOMBIA | 189,995 | 0 | -5 | 6,170 | 3 | 183,830 |
| COSTA RICA | -6,000 | -850 | -5,172 | 0 | 0 | 22 |
| CROATIA | 27,486 | 0 | -1 | 0 | 0 | 27,487 |

| | | | | | | |
|---|---|---|---|---|---|---|
| CUBA | -310,000 | -201,372 | -108,628 | 0 | 0 | 0 |
| CYPRUS | -9,550 | -2,675 | -7,422 | 0 | 0 | 547 |
| CZECH REPUBLIC | -47,837 | 0 | -49,658 | 0 | 0 | 1,821 |
| DENMARK | 33,254 | 0 | -86 | 0 | 0 | 33,341 |
| DJIBOUTI | -11 | 0 | -11 | 0 | 0 | 0 |
| DOMINICA | 200 | 0 | 0 | 0 | 0 | 200 |
| DOMINICAN REPUBLIC | 32,000 | 0 | 0 | 17,097 | 53 | 14,903 |
| ECUADOR | -11,659 | -1,859 | -9,800 | 0 | 0 | 0 |
| EGYPT | 331,130 | -20,339 | -1,275 | 278,622 | 79 | 74,123 |
| EL SALVADOR | 200 | 0 | -19 | 15 | 7 | 204 |
| ERITREA | -590 | -41 | -596 | 0 | 0 | 47 |
| ESTONIA | 1,367 | 0 | -2 | 0 | 0 | 1,369 |
| ETHIOPIA | 1,349 | 0 | -1 | 1,199 | 89 | 150 |
| FIJI | 1,000 | 0 | 0 | 0 | 0 | 1,000 |
| FINLAND | 16,220 | 0 | -212 | 0 | 0 | 16,432 |
| FRANCE | 241,354 | -6,161 | -68,730 | 34,844 | 11 | 281,401 |
| FRENCH GUIANA | -1,100 | 0 | -1,100 | 0 | 0 | 0 |
| GAMBIA | 2,851 | 0 | 0 | 1,342 | 47 | 1,509 |
| GEORGIA | -24,000 | -2,027 | -21,980 | 0 | 0 | 7 |
| GERMANY | 177,004 | 0 | -31,407 | 0 | 0 | 208,410 |
| GHANA | 31,100 | 0 | 0 | 0 | 0 | 31,100 |
| GREECE | 216,687 | -3,890 | -16,908 | 139,119 | 59 | 98,366 |
| GRENADA | 1,800 | 0 | 0 | 0 | 0 | 1,800 |
| GUADELOUPE | 3,740 | 0 | 0 | 0 | 0 | 3,740 |
| GUAM | -112 | 0 | -112 | 0 | 0 | 0 |
| GUATEMALA | 208,000 | -5,266 | -12,671 | 48,928 | 22 | 177,009 |
| GUINEA | 86 | 0 | -60 | 0 | 0 | 146 |
| GUYANA | -7,000 | 0 | -7,015 | 0 | 0 | 15 |
| HAITI | 5,000 | 0 | 0 | 1,777 | 36 | 3,223 |
| HONDURAS | 10,000 | 0 | 0 | 1,561 | 16 | 8,439 |
| HUNGARY | 23,426 | 0 | -44,387 | 1,942 | 3 | 65,871 |
| INDIA | 8,485,008 | -4,840,017 | -1,361,730 | 12,098,849 | 82 | 2,587,906 |
| INDONESIA | 1,220,880 | 0 | -8 | 266,471 | 22 | 954,417 |
| IRAN | 1,730,000 | -34,372 | -21,203 | 1,120,279 | 63 | 665,295 |
| ISRAEL | 18,990 | -463 | -399 | 12,989 | 65 | 6,862 |
| ITALY | 374,735 | -19,267 | -51,790 | 76,848 | 17 | 368,943 |
| JAMAICA | 5,700 | 0 | -15 | 0 | 0 | 5,715 |
| JAPAN | -308,200 | -1,312 | -306,888 | 0 | 0 | 0 |
| JORDAN | 18,345 | -1,941 | -1,433 | 14,758 | 68 | 6,961 |
| KAZAKHSTAN | -1,413,745 | -830,168 | -840,730 | 124,582 | 48 | 132,570 |

| | | | | | | |
|---|---|---|---|---|---|---|
| KENYA | 65,452 | -8,901 | -10,947 | 10,304 | 12 | 74,995 |
| KOSOVO | 28,094 | 0 | -3,093 | 0 | 0 | 31,186 |
| KUWAIT | 11,032 | 0 | 0 | 8,222 | 75 | 2,810 |
| KYRGYZSTAN | -26,550 | -18,635 | -7,914 | 0 | 0 | 0 |
| LAOS | 14,465 | 0 | -1 | 2,344 | 16 | 12,122 |
| LATVIA | 547 | 0 | -19 | 0 | 0 | 565 |
| LEBANON | 17,387 | 0 | 0 | 10,587 | 61 | 6,800 |
| LESOTHO | 342 | 0 | 0 | 0 | 0 | 342 |
| LIBERIA | -150 | 0 | -165 | 0 | 0 | 15 |
| LIBYA | -70,000 | -62,666 | -7,334 | 0 | 0 | 0 |
| LITHUANIA | -2,515 | 0 | -2,585 | 0 | 0 | 70 |
| MACEDONIA | 200 | -82 | -7 | 81 | 28 | 208 |
| MADAGASCAR | -291 | -27 | -1,186 | 192 | 21 | 730 |
| MALAWI | 35,563 | 0 | 0 | 14,136 | 40 | 21,427 |
| MALAYSIA | 15,014 | 0 | -51 | 2,654 | 18 | 12,411 |
| MALI | 144,209 | 0 | 0 | 87,785 | 61 | 56,424 |
| MALTA | 2,200 | 0 | 0 | 0 | 0 | 2,200 |
| MARTINIQUE | -1,040 | 0 | -1,040 | 0 | 0 | 0 |
| MAURITANIA | -10 | -12 | 0 | 0 | 0 | 2 |
| MAURITIUS | -4,591 | 0 | -5,075 | 0 | 0 | 484 |
| MEXICO | 289,727 | -45,297 | -63,572 | 328,960 | 83 | 69,636 |
| MICRONESIA | 300 | 0 | 0 | 0 | 0 | 300 |
| MOLDOVA | -77,279 | -17,905 | -59,374 | 0 | 0 | 0 |
| MONTENEGRO | 187 | 0 | -154 | 0 | 0 | 341 |
| MOROCCO | 87,361 | 0 | -69 | 71,164 | 81 | 16,266 |
| MOZAMBIQUE | -148 | 0 | -506 | 0 | 0 | 358 |
| MYANMAR | 338,135 | -202,011 | -51,028 | 291,412 | 49 | 299,762 |
| NAMIBIA | 427 | 0 | 0 | 0 | 0 | 427 |
| NEPAL | 232,393 | -1,572 | -462 | 146,971 | 63 | 87,457 |
| NETHERLANDS | 29,430 | 0 | -62,952 | 0 | 0 | 92,383 |
| NEW CALEDONIA | 1,000 | 0 | -185 | 0 | 0 | 1,185 |
| NEW ZEALAND | 187,581 | 0 | -16,417 | 3,588 | 2 | 200,410 |
| NICARAGUA | 136,612 | 0 | 0 | 10,070 | 7 | 126,542 |
| NIGER | 26,652 | -6 | 0 | 12,436 | 47 | 14,222 |
| NIGERIA | 34,809 | 0 | 0 | 11,330 | 33 | 23,479 |
| NORTHERN MARIANA ISLANDS | 100 | 0 | 0 | 0 | 0 | 100 |
| NORWAY | -39,661 | 0 | -39,661 | 0 | 0 | 0 |
| OMAN | 21,360 | -2,308 | -196 | 6,188 | 26 | 17,677 |
| PAKISTAN | 542,352 | -830,382 | -392,964 | 1,535,091 | 87 | 230,607 |
| PALESTINA | 4,000 | -673 | 0 | 1,419 | 30 | 3,254 |

| | | | | | | |
|---|---|---|---|---|---|---|
| PANAMA | -10,541 | -816 | -9,725 | 0 | 0 | 0 |
| PARAGUAY | 73,000 | 0 | 0 | 0 | 0 | 73,000 |
| PERU | 889,527 | -227 | -721 | 55,747 | 6 | 834,728 |
| PHILIPPINES | 3,790 | -2,601 | -90,442 | 6,282 | 6 | 90,552 |
| POLAND | 134,050 | 0 | -17,938 | 0 | 0 | 151,988 |
| PORTUGAL | -215,010 | -127,920 | -93,705 | 4,199 | 63 | 2,417 |
| PUERTO RICO | -11,822 | 0 | -16,343 | 0 | 0 | 4,521 |
| QATAR | 8,000 | 0 | 0 | 2,457 | 31 | 5,543 |
| REUNION | 430 | 0 | -78 | 0 | 0 | 508 |
| ROMANIA | -2,181,830 | -519,730 | -1,664,342 | 0 | 0 | 2,242 |
| RUSSIA | -1,997,722 | -306,948 | -1,713,359 | 2,065 | 9 | 20,521 |
| RWANDA | 1,100 | 0 | 0 | 0 | 0 | 1,100 |
| SAINT KITTS AND NEVIS | 12 | 0 | 0 | 0 | 0 | 12 |
| SAINT LUCIA | -321 | 0 | -321 | 0 | 0 | 0 |
| SAINT VINCENT AND THE GRENADINES | -1,000 | 0 | -1,000 | 0 | 0 | 0 |
| SÃO TOMÉ AND PRÍNCIPE | 300 | 0 | 0 | 0 | 0 | 300 |
| SAUDI ARABIA | -272,908 | -165,520 | -107,388 | 0 | 0 | 0 |
| SENEGAL | 12,388 | 0 | -33 | 12,158 | 98 | 264 |
| SERBIA | 38,858 | 0 | -20,077 | 0 | 0 | 58,935 |
| SEYCHELLES | 18 | 0 | 0 | 0 | 0 | 18 |
| SIERRA LEONE | -370 | -28 | -367 | 0 | 0 | 24 |
| SLOVAKIA | -116,320 | 0 | -116,320 | 0 | 0 | 0 |
| SLOVENIA | 1,530 | 0 | 0 | 0 | 0 | 1,530 |
| SOMALIA | -3 | -327 | -82 | 227 | 56 | 180 |
| SOUTH AFRICA | 120,057 | -293,974 | -108,900 | 96,436 | 18 | 426,495 |
| SOUTH KOREA | -73,865 | 0 | -73,865 | 0 | 0 | 0 |
| SOUTH SUDAN | 30,928 | 0 | 0 | 19,449 | 63 | 11,479 |
| SPAIN | 283,288 | -47,668 | -45,909 | 229,008 | 61 | 147,856 |
| SRI LANKA | 60,000 | 0 | 0 | 26,231 | 44 | 33,769 |
| SUDAN | -828 | -828 | 0 | 0 | 0 | 0 |
| SURINAME | 8,820 | 0 | 0 | 0 | 0 | 8,820 |
| SWAZILAND | 140 | -2 | 0 | 94 | 66 | 48 |
| SWEDEN | 28,468 | 0 | -4 | 0 | 0 | 28,472 |
| SWITZERLAND | 13,597 | 0 | -1,080 | 0 | 0 | 14,677 |
| SYRIA | 75,338 | -5,546 | -7,782 | 75,609 | 85 | 13,058 |
| TAIWAN | -50,895 | -2,774 | -66,834 | 728 | 4 | 17,986 |
| TAJIKISTAN | 32,626 | -17,024 | -34,752 | 52,893 | 63 | 31,508 |
| TANZANIA | 147,062 | -6,651 | -30,808 | 29,645 | 16 | 154,877 |
| THAILAND | 825,000 | -654,081 | -276,251 | 1,399,219 | 80 | 356,113 |

| | | | | | | |
|---|---|---|---|---|---|---|
| TIMOR-LESTE | 3,000 | 0 | -151 | 0 | 0 | 3,151 |
| TOGO | -300 | 0 | -300 | 0 | 0 | 0 |
| TRINIDAD AND TOBAGO | 2,000 | 0 | -180 | 0 | 0 | 2,180 |
| TUNISIA | 81,937 | 0 | 0 | 57,446 | 70 | 24,491 |
| TURKEY | 146,889 | -30,886 | -74,574 | 88,555 | 35 | 163,793 |
| TURKMENISTAN | 280,572 | -10,840 | -2,880 | 286,698 | 97 | 7,594 |
| UGANDA | 1,990 | 0 | 0 | 0 | 0 | 1,990 |
| UKRAINE | -238,116 | -509,967 | -564,900 | 387,730 | 46 | 449,021 |
| UNITED ARAB EMIRATES | -126,206 | -110,976 | -28,072 | 6,831 | 53 | 6,011 |
| UNITED KINGDOM | -47,604 | -1,198 | -112,446 | 0 | 0 | 66,039 |
| UNITED STATES | -274,280 | -2,374,799 | -1,417,708 | 1,474,318 | 42 | 2,043,909 |
| UZBEKISTAN | 70,141 | -387,750 | -30,011 | 464,071 | 95 | 23,831 |
| VENEZUELA | 444,014 | -12,652 | -21,519 | 101,863 | 21 | 376,322 |
| VIETNAM | 945,701 | 0 | -3 | 421,484 | 45 | 524,220 |
| VIRGIN ISLANDS, U.S. | -85 | 0 | -85 | 0 | 0 | 0 |
| YEMEN | 203,312 | -54,990 | -25,848 | 113,744 | 40 | 170,406 |
| ZIMBABWE | 1,487 | 0 | 0 | 163 | 11 | 1,324 |
| WORLD | 32,119,482 | -18,891,965 | -16,544,125 | 32,365,064 | | 35,190,508 |

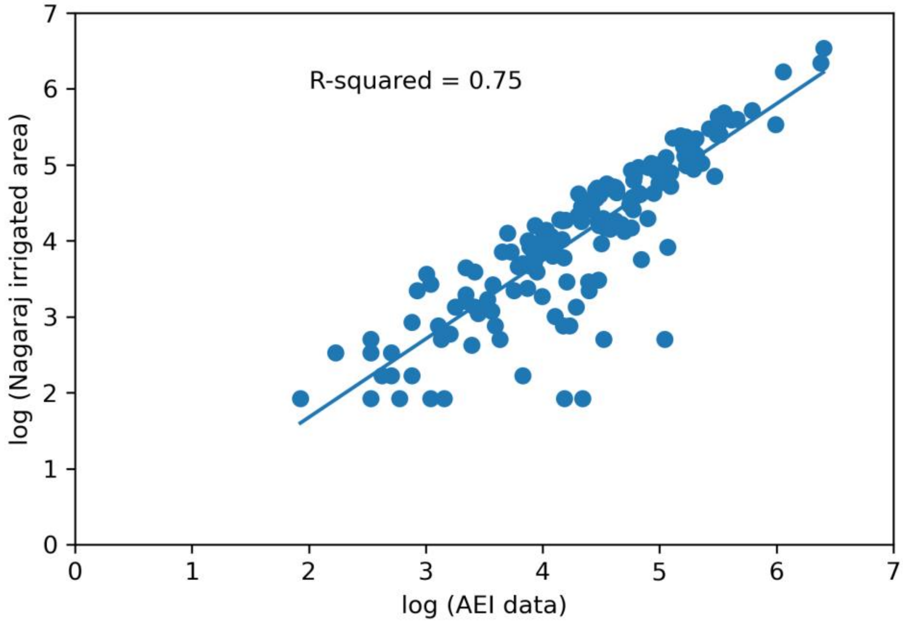


**Figure S1**. Comparison of global low intensity irrigated area and AEI for the year 2015. Each point is a country. The Nagaraj et al.[14] maps have different classes (0=not irrigated; 1=low-to-medium irrigated; 2=highly irrigated) but do not provide continuous values. As such, this product could be directly compared to our maps. To examine agreement with our maps to the extent possible, we categorized our AEI maps based on the Nagaraj definitions of low-to-medium irrigated pixels (1%-20% of a pixel's area is irrigated) and highly irrigated pixels (>20% of a pixel's area is irrigated).

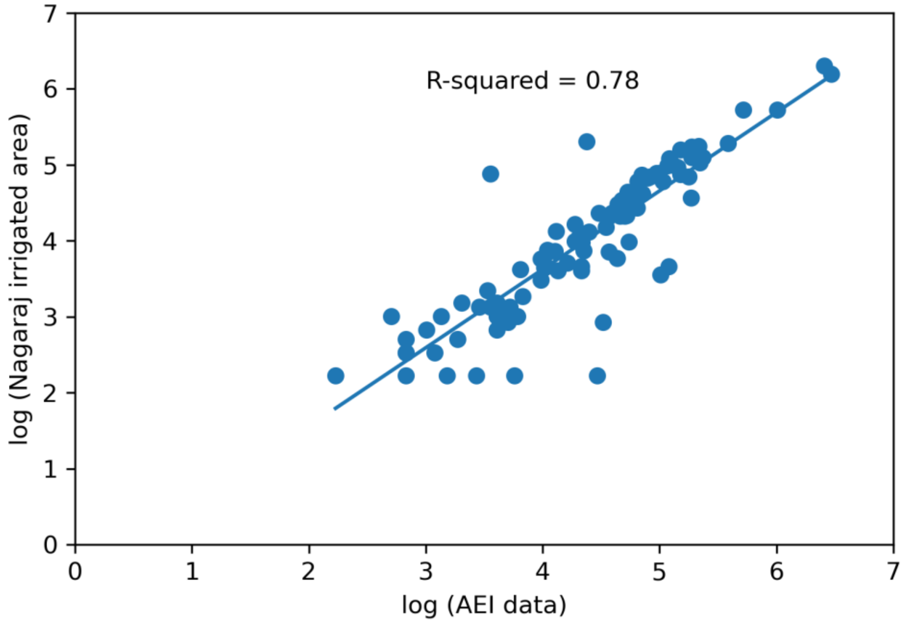


**Figure S2**. Comparison of global high intensity irrigated area[14] and AEI for the year 2015. Each point is a country. The Nagaraj et al.[14] maps have different classes (0=not irrigated; 1=low-to-medium irrigated; 2=highly irrigated) but do not provide continuous values. As such, this product could be directly compared to our maps. To examine agreement with our maps to the extent possible, we categorized our AEI maps based on the Nagaraj definitions of low-to-medium irrigated pixels (1%-20% of a pixel's area is irrigated) and highly irrigated pixels (>20% of a pixel's area is irrigated).

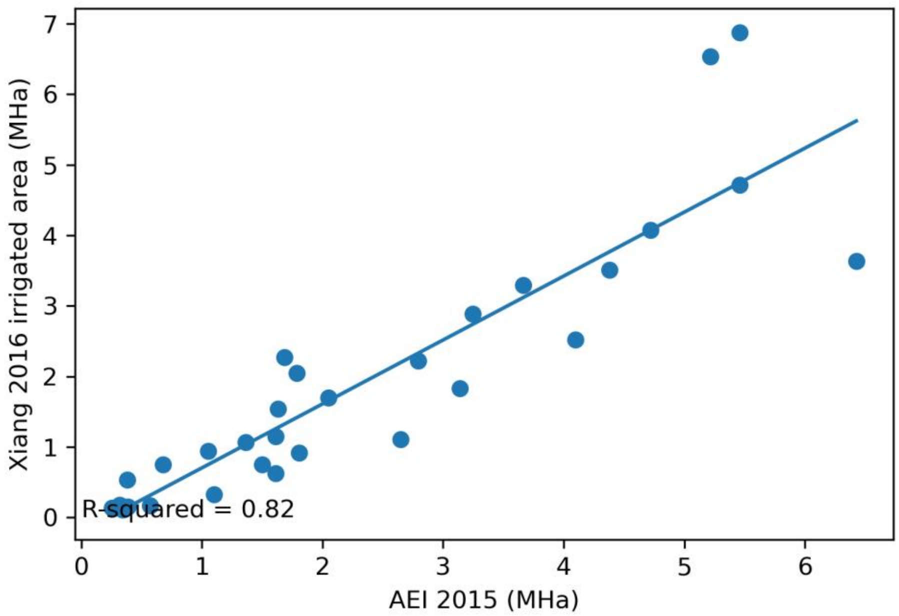


**Figure S3**. **Comparison of province-wise AEI and irrigated area for China[56] for year 2015.** Each point is a province.

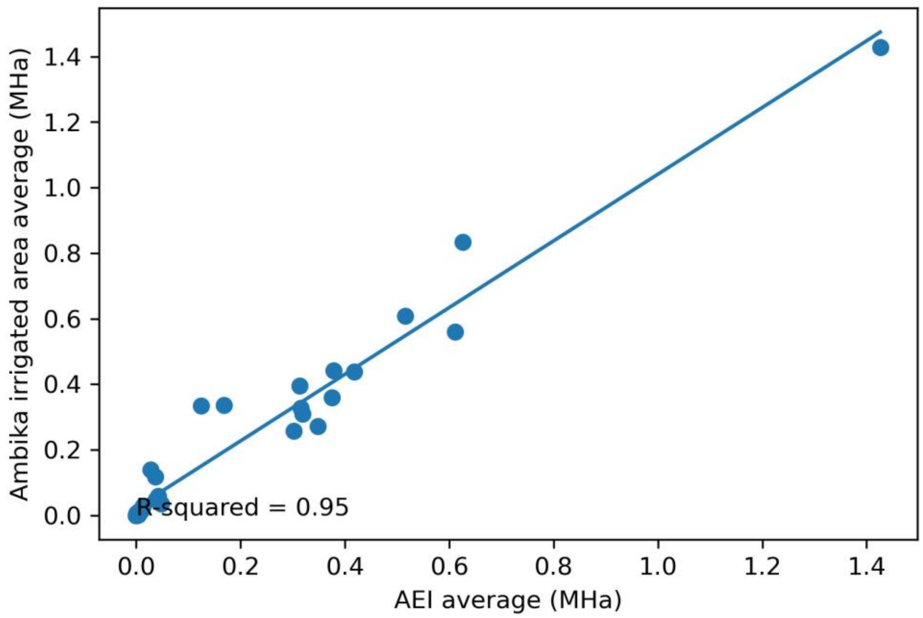


**Figure S4**. **Comparison of state-wise average of AEI and irrigated area[17] for India for years 2000-2010.** Each point is a state.

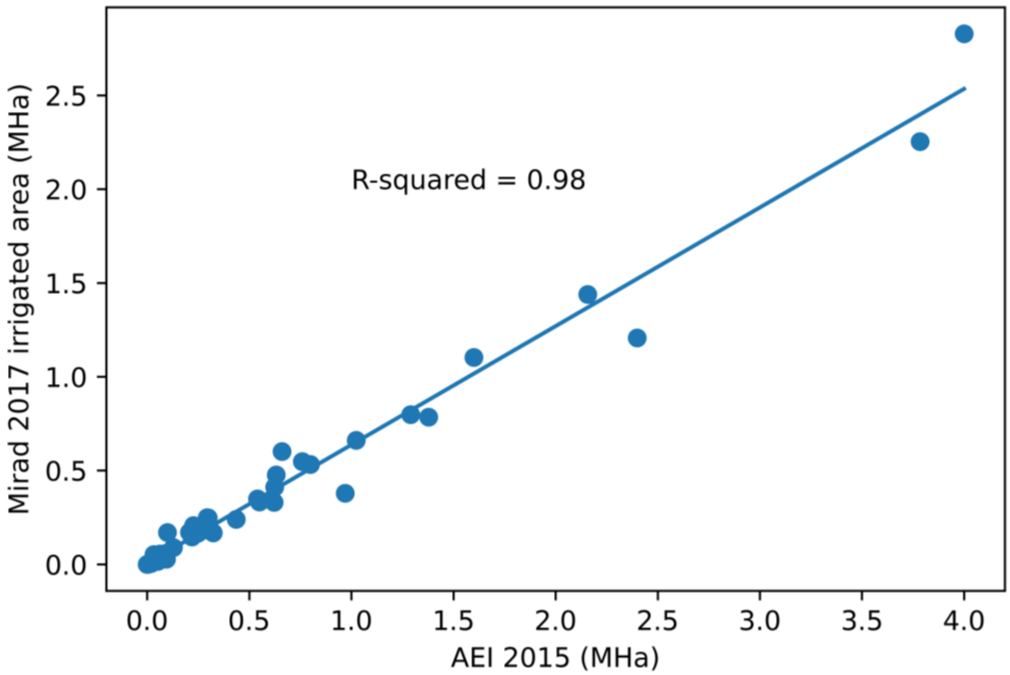


**Figure S5**. **Comparison of state-wise AEI and irrigated area for United States[57] for year 2015.** Each point is a state.

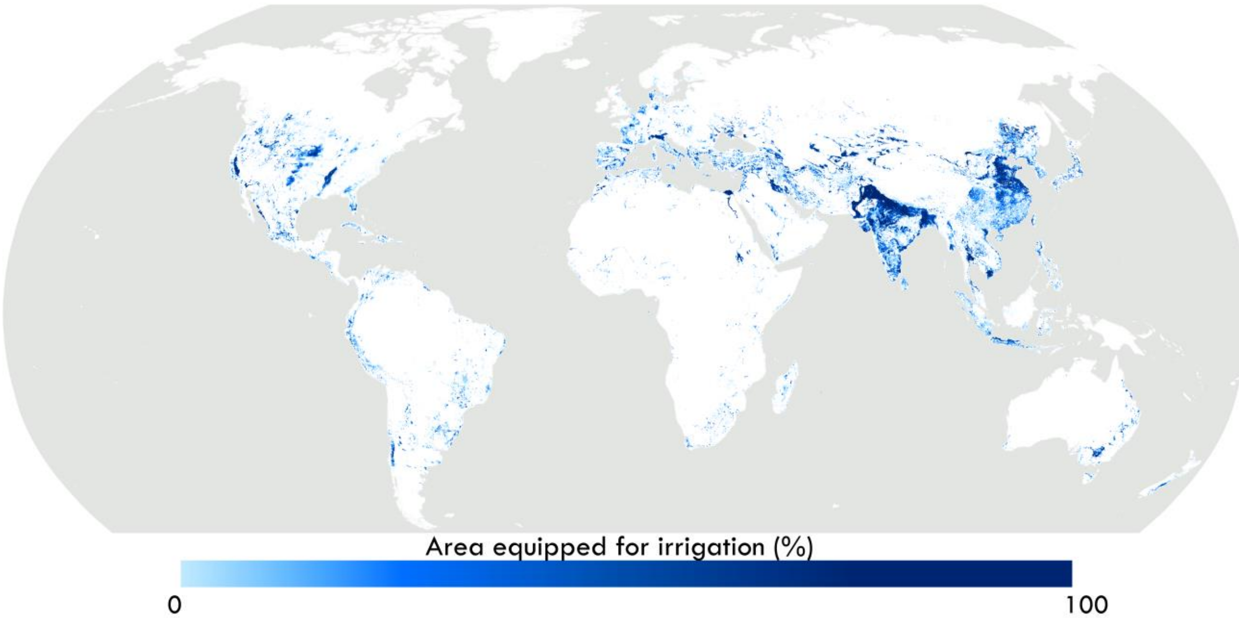


**Figure S6**. **Global map of area equipped for irrigation (AEI) in 2015.** Each 5 arc-min pixel is shown as percentage of land equipped for irrigation. Estimates are based on the AEI version with Meier et al.[46] as a base map (see Methods).

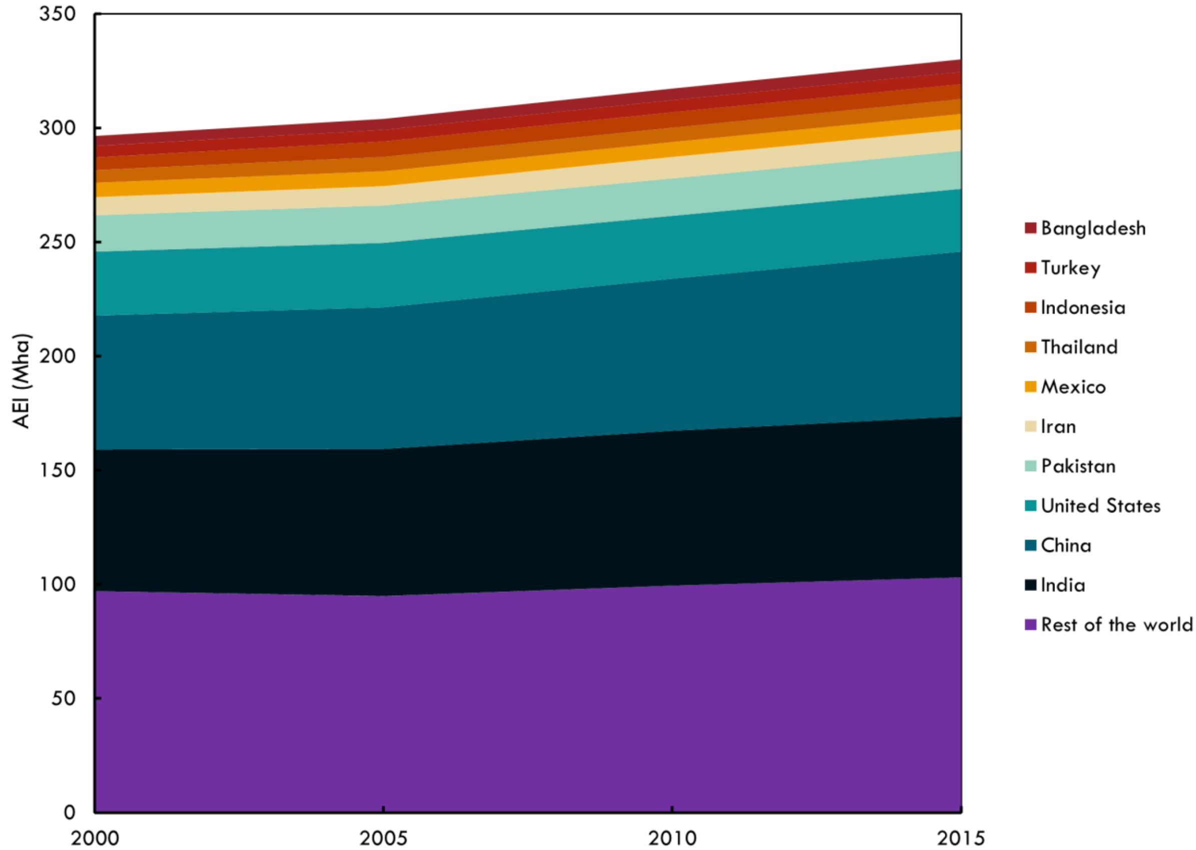


**Figure S7. Area equipped for irrigation (AEI) for major countries between 2000 and 2015.** Countries are ordered in ascending order based on their year 2000 AEI. Estimates are based on AEI version with Meier et al.[46] as a base map.

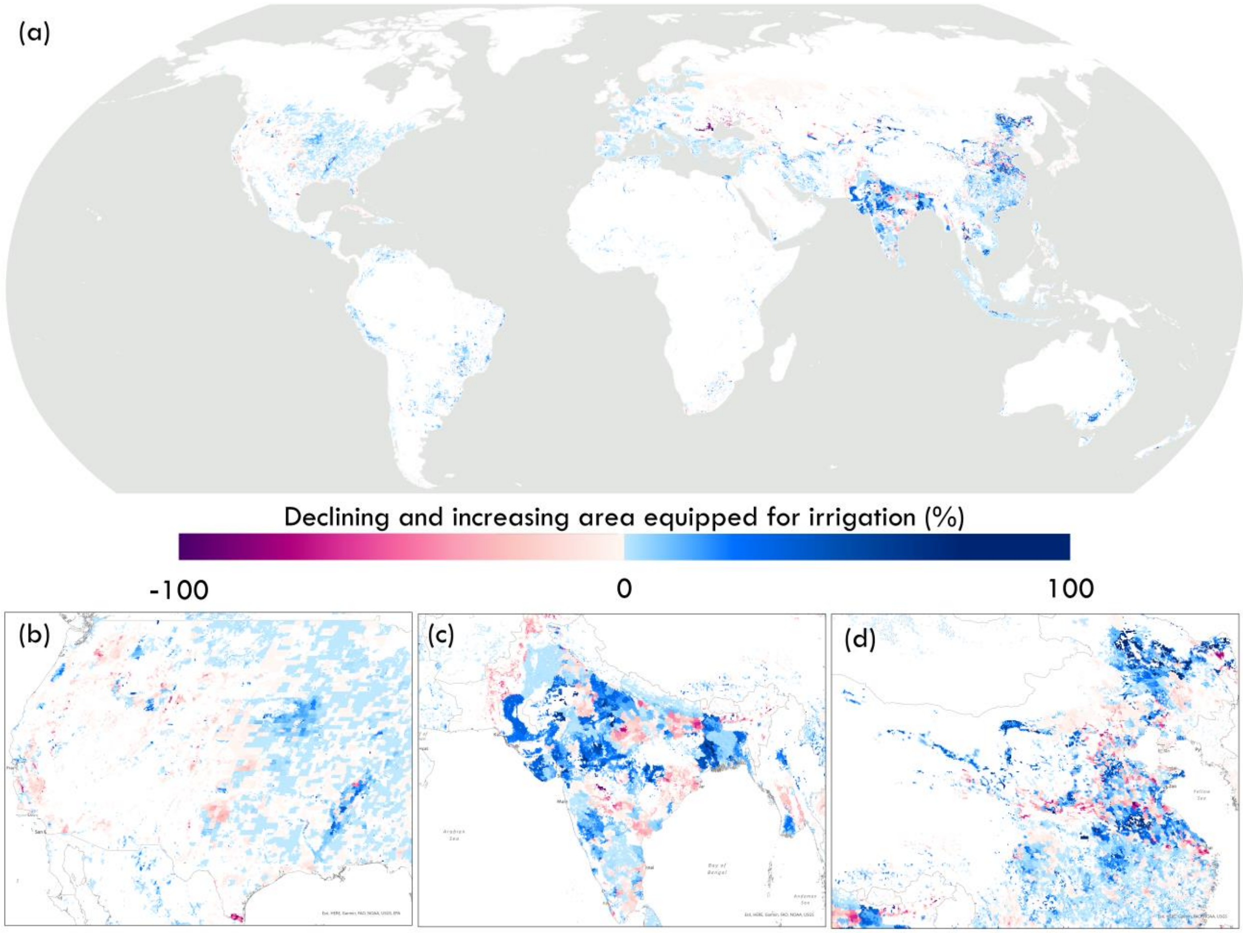


**Figure S8. Global changes in area equipped for irrigation (AEI) from 2000 to 2015**. (a) Areas of expansion are shown in blue, and areas of decline are shown in purple as percentage change in AEI. (b-d) Insets show the western US, India, and eastern China. Estimates are based on the AEI version with Meier et al.[46] as a base map.

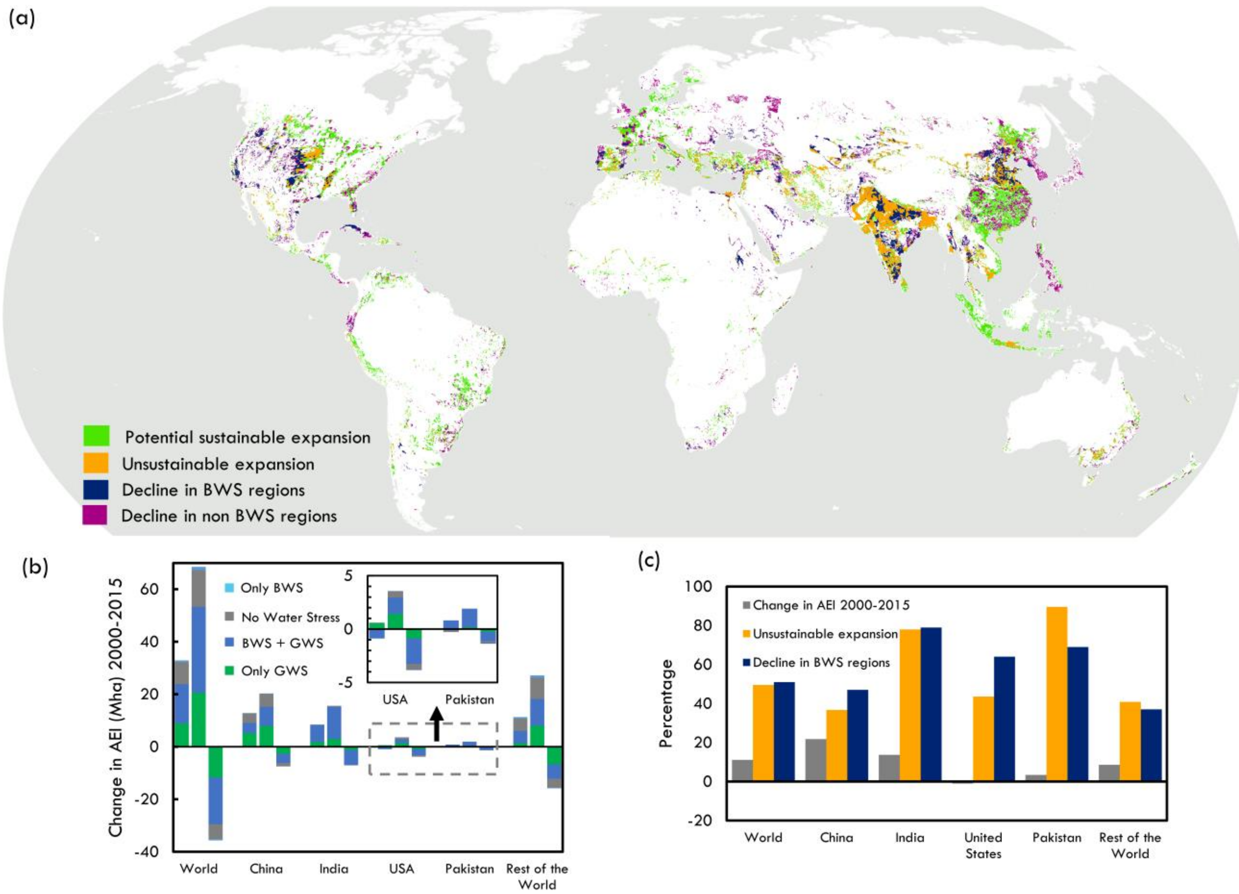


**Figure S9. Sustainability of 21st century area equipped for irrigation (AEI) changes.** Green water stress (GWS) is defined as the condition when rainfall is insufficient to meet a crop's water requirement and supplementary irrigation is needed. Blue water stress (BWS) is defined as the condition when renewable surface and groundwater availability (i.e., total availability after accounting for environmental flows) is insufficient to meet irrigation water demand. (a) Map showing four categories for AEI change: potentially sustainable expansion (i.e., in areas of green water stress (GWS) or no water stress), unsustainable expansion (i.e., in areas of blue water stress (BWS) or BWS+GWS), decline in BWS regions, decline in non-BWS regions. Blue water resources are relatively abundant in areas with only GWS or with no water stress (i.e., there is not BWS); a full accounting of changes in crop-specific water demand under irrigation expansion is necessary to comprehensively determine whether conditions of water stress continue to be avoided in these areas of potentially sustainable expansion. Only pixels with >1% of their area occupied by AEI are shown. (b) Change in AEI from 2000 to 2015 by water stress category for major countries. (c) Percentage change in net AEI change from 2000 to 2015, percentage of unsustainable expansion of AEI (i.e., in areas of BWS) and percentage of decline in BWS regions. Estimates are based on the AEI version with Meier et al.[46] as a base map.