Global Changes in Agricultural Water Demand Driven by Climate and Crop Area Change

Lingli Ye [1,2], Ying Guo [2,*], Yafang Zhang [3], Chao Zhao [4,5,6,*], Min Liu [7], Jing Wang [1] and Yanjun Shen [2]

[1] School of Life Sciences, Institute of Life Science and Green Development, Hebei University, Baoding, Hebei 071002, China

[2] Hebei Key Laboratory of Agricultural Water-Saving, Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, Chinese Academy of Sciences, Shijiazhuang 050021, China

[3] Artificial Intelligence College, Tianjin Electronic Information College, Tianjin 300350, China

[4] China Meteorological Administration Xiong'an Atmospheric Boundary Layer Key Laboratory, Xiong'an New Area 071800, China

[5] Hebei Key Laboratory of Meteorology and Ecological Environment, Shijiazhuang 050021, China

[6] Hebei Institute of Meteorological Sciences, Shijiazhuang 050021, China

[7] Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Sciences, Shijiazhuang 050061, China

[*]Corresponding author: Ying Guo, +86 311 85872248; Chao Zhao

E-mail: guoy@sjziam.ac.cn; zhaochao-1980@163.com

Table S1. Data information in this research

Data type	Data sources	Data elements	Data usage
NCEP-DOE Reanalysis 2 (2.5° × 2.5°)	https://psl.noaa.gov/data/gridded/data.ncep.reanalysis2.html	Daily max/min temperature, wind speed, precipitation, relative humidity, and solar radiation	Computation of reference evapotranspiration and daily correction of crop coefficients
Crop coefficient reference	https://www.fao.org/4/x0490e/x0490e00.htm	Crop coefficient values under standard conditions	Standard crop coefficient reference
Köppen-Geiger climate classification (0.5° × 0.5°)	https://koeppen-geiger.vu-wien.ac.at/	Climate zones (A–E types)	Regional division for crop phenology modeling
Crop Planting Calendar	http://www.sage.wisc.edu	Sowing dates, harvesting dates, total growth period lengths for 19 crops	Crop growth calibration
Growth period lengths for different stages	FAO Irrigation and Drainage No. 24	Growth period lengths for wheat, maize, soybean stages (region-specific)	Stage-specific correction of crop coefficients

FAOSTAT	http://www.fao.org/faostat	National annual crop area data for wheat, maize, soybean	Temporal scaling of crop area over 1980–2017
MIRCA2000 (5 arc-minutes, ~0.083°)	https://www.uni-frankfurt.de/45218031/Data_Download_Center_for_MIRCA2000	Gridded crop area data (irrigated and rainfed) for wheat, maize, soybean	Spatial allocation of crop distribution

The correction of crop coefficients (K_c) needs to consider different growth stages of the crop and specific climatic conditions.

The crop coefficient for the initial stage (K_{cini}) was corrected based on the frequency of precipitation and the atmospheric evapotranspiration capacity, which was expressed as ET_0 [1].

Table S2. Approximate values of K_{cini} for moderately wet processes (10–40 mm) and moderately textured soils

Frequency of wetting time	Atmospheric evaporation capacity (ET_0 mm/d)			
	1~3	3~5	5~7	>7
< 1 week	1.2~0.8	1.1~0.6	1.0~0.4	0.9~0.3
= 1 week	0.8	0.6	0.4	0.3
> 1 week	0.7~0.4	0.4~0.2	0.3~0.2	0.2~0.1

The K_c for the mid- and end-growth stages (K_{cmid} and K_{cend}, respectively) were corrected by considering minimum relative humidity, wind speed and plant

height. The formula for correcting K_{cmid} is as follows [1]:

$$K_{cmid} = K_{cmid(A)} + [0.04(u - 2) - 0.04(RH_{min} - 0.45)]\left(\frac{h}{3}\right)^{0.3} \quad \text{(S1)}$$

where $K_{cmid(A)}$ denotes the crop coefficient for the mid-growth stage under the standard conditions provided by the FAO; u, the average wind speed in the mid-growth stage (m/s), with a range of 1m/s ≤ u ≤ 6m/s; RH_{min}, the average daily minimum phase humidity in the mid-growth stage, with a range of 20% ≤ RH_{min} ≤ 80%; and h, the crop average height in the mid-growth stage (m), with a range of 0.1m ≤ h ≤ 10m.

During the late stages of crop growth, when K_{cend} < 0.45, it is considered permissible for the crop to naturally wither in the field without requiring additional adjustments. When K_{cend} ≥ 0.45, this value is regarded as a prerequisite for fresh harvesting or pre-drying harvesting, with K_{cend} being corrected according to Eq. (S1).

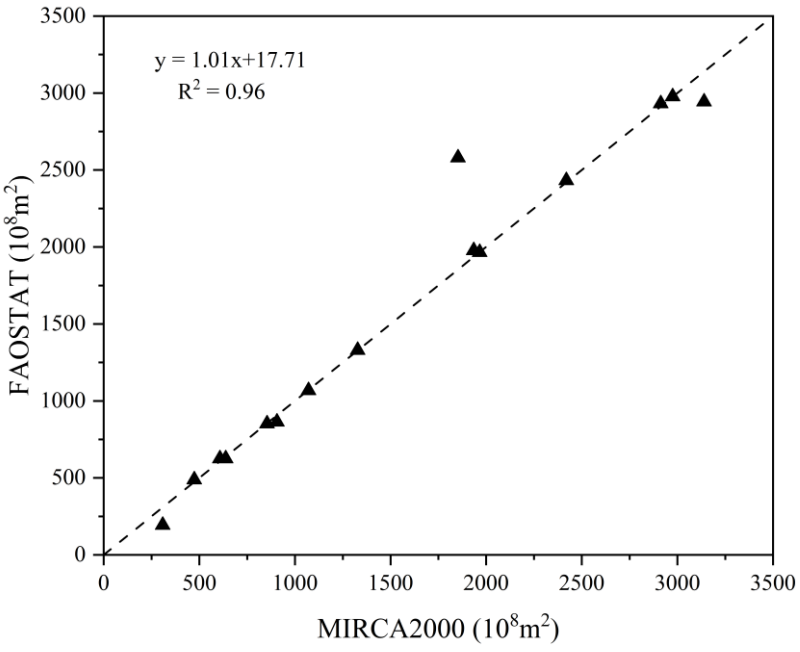


Figure S1. Correlation analysis between FAOSTAT and MIRCA2000 planting

areas of three major crop producing countries

Mann–Kendall trend

The global trends in the ET_c of major crops were analysed using the Mann–Kendall (M–K) trend test [2,3]. For the time series $X = \{x_1, x_2, ..., x_n\}$, the standard normal variable Z is given using the following equation [4]:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} Sgn(x_j - x_i) \quad \text{(S2)}$$

where *Sgn* is a sign function defined as follows:

$$\text{Sgn} = \begin{cases} 1, x_j > x_i \\ 0, x_j = x_i \\ -1, x_j < x_i \end{cases} \quad \text{(S3)}$$

when $n \geq 8$; the statistic S follows approximately a normal distribution with mean 0 and variance V(S):

$$V(S) = \frac{n(n-1)(2n+5)}{18} \quad \text{(S4)}$$

$$Z = \begin{cases} \frac{S-1}{\sqrt{V_s}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{V_s}} & S < 0 \end{cases} \quad \text{(S5)}$$

When the absolute value of the calculated standard normal variable Z exceeds a certain threshold (e.g. 1.64 corresponding to a confidence level of 95%), it indicates that there is a substantial trend change in the time series at a set confidence level. Positive and negative values of Z reflect an upwards and downwards trend, respectively. In this study, a confidence level of 95% was used as the minimum criterion for determining a significant trend.

linear regression

The World Meteorological Organization recommends simple linear regression for identifying trends in evapotranspiration and climate variables [5].

This method determines whether a linear trend exists by analysing the relationship between time (x) and the target variable (y) using least-squares linear regression:

$$y = a + b \cdot x + \varepsilon \quad \text{(S6)}$$

where a and b are parameters and ε is the regression residual.

The trend value b is defined as the regression gradient of the least-squares linear function of the inter-annual variability of variables of interest and reflects the rate of change of y on a time scale of x.

$$b = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad \text{(S7)}$$

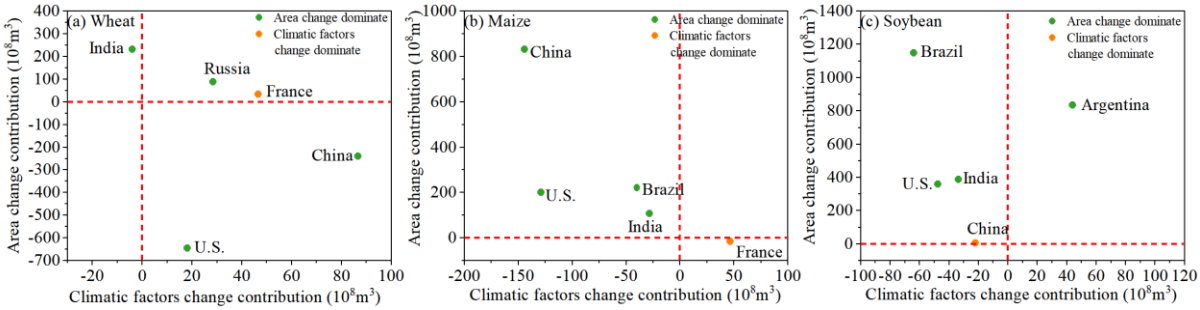


Figure S2. Contribution of climatic factors and crop area changes to changes in the total global CWR in major producing countries from 1980 to 2017

References:

1. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements-FAO Irrigation and Drainage Paper 56. *Fao, Rome* **1998**, *300*, D05109.
2. Mann, H.B. Non-Parametric Tests against Trend. *Econometrica* **1945**, *13*, 245.
3. Kendall, M.G. Rank Correlation Measures. **1975**.

4. Modarres, R.; da Silva, V. de P.R. Rainfall Trends in Arid and Semi-Arid Regions of Iran. *J. Arid Environ.* **2007**, *70*, 344–355.
5. Mitchell, J.M.; Dzerdzeevskii, B.; Flohn, H.; Hofmeyr, W.L.; Lamb, H.H.; Rao, K.N.; Wallen, C.C. Climate Change, WMO Technical Note No. 79. *World Meteorol. Organ.* **1966**.