Uncertainties in global climate and water models challenge future estimates of crop water use and sustainability

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Introduction

- The assessment of crop water needs and sustainability under future climates is crucial for coping with predicted water scarcity and devising strategies to ensure global food security.
- Among the various indicators that have been developed to quantify crop water requirements and sustainability, this study focuses on the Water Footprint (*WF*)[1] and the Water Debt repayment time (*WD*)[2].
- Global water and climate models provide input variables needed for such assessments. However, different models generally provide divergent estimates of precipitation, potential evapotranspiration and renewable freshwater rates – which in turn greatly affect the final estimations of crop water requirements[3].
- Thus, a multi-model evaluation is needed to evaluate future crop water requirements, their sustainability, and how uncertainties embedded in different global models propagate into such estimates.

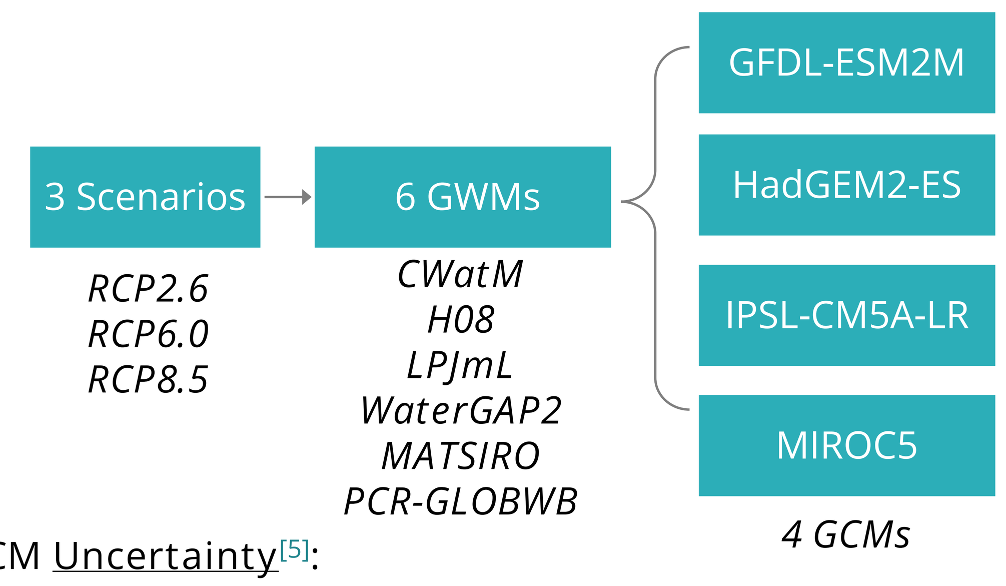
Objectives

- Quantify how uncertainties from global climate and water models propagate into crop water use (WF) and sustainability (WD), from local to regional and global scales.
- Evaluate future changes in blue and green water requirements and sustainability for the most produced crops worldwide, and identification of critical hotspots characterized by unsustainable water use.

Methods

Data sources and Uncertainty analysis

ISIMIP Data[4]: 3 future scenarios (RCPs), 6 Global Water Models (GWMs), and 4 Global Climate Models (GCMs)



GCM Uncertainty[5]:

- For each GCM, compute the *average* across all GWMs:

$$\bar{V}_j = \frac{1}{N}\sum_{i=1}^{N=6} V_{ij} \quad (j = 1, \dots, 4)$$

where V represents the variable of interest (e.g., WF or WD), i indexes the GWMs and j indexes the GCMs.

- Evaluate *range (Max – Min)* across all:

$$U_{GCM} = \max_j [\bar{V}_j] - \min_j [\bar{V}_j]$$

GWM Uncertainty[5]:

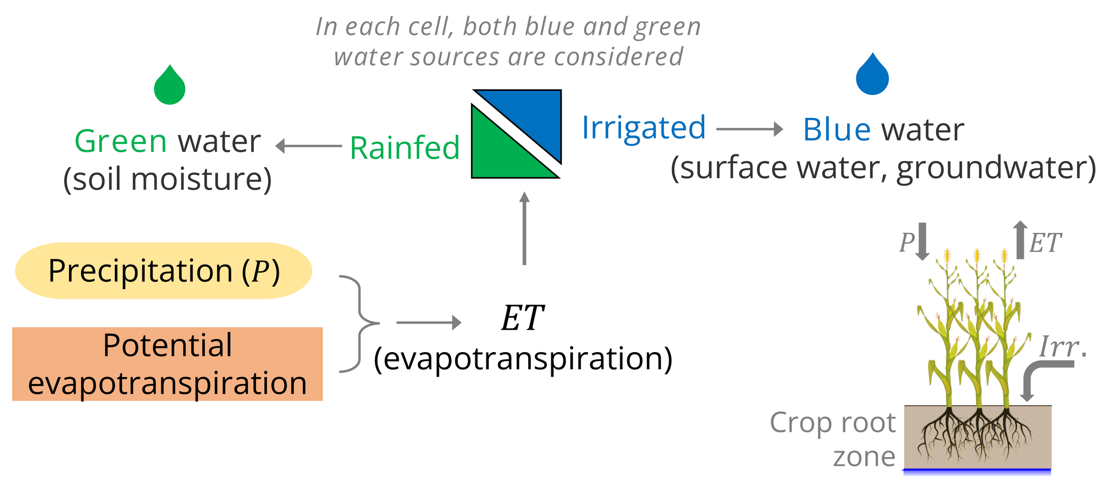
- $\bar{V}_i = \frac{1}{N}\sum_{j=1}^{N=4} V_{ij} \quad (i = 1, \dots, 6)$
- $U_{GWM} = \max_i [\bar{V}_i] - \min_i [\bar{V}_i]$

Fractional Uncertainty[6]:

- $F_V = \frac{\sqrt{U_{GCM} + U_{GWM}}}{\bar{V}}$

Evapotranspiration over a growing season

- Time period: historical (2000) + every 10 years from 2010 to 2090.
- 8 crops (≈ 60% of global harvested area [7]): *Barley, Maize, Potato, Rice, Sorghum, Soybeans, Sugarcane, Wheat*



Water requirements indicators

$$VWC_{c,s,l} = \frac{ET_{c,s,l}}{Yield_{c,l}}$$

(virtual water content [m³/ton])

$$WF_{c,s,l} = VWC_{c,s,l} \cdot Prod_{c,l}$$

(water footprint [m³])

How much water is used?

$$WD_{c,s,l} = \frac{VWC_{c,s,l}}{A_l \cdot R_{s,l}}$$

(water debt [yr])

Surface runoff (R_{sr}), Groundwater recharge (R_{gw})

Root zone soil moisture (R_{sm})

How long will it take to renew the local water resources?

GCM outputs
GWM outputs

c = crop
s = water source (blue/green)
l = location

Results

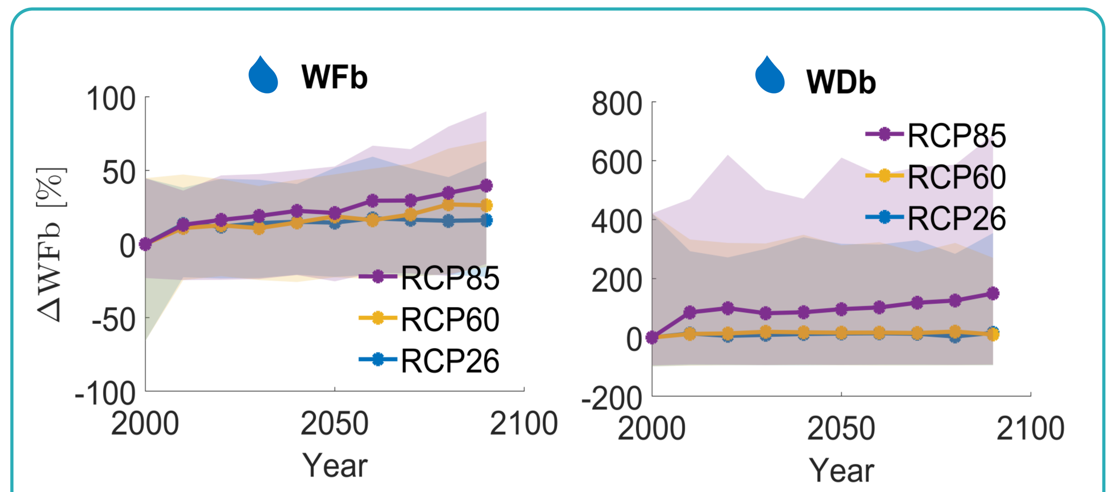


Fig. 1. Temporal variation of global blue WF and WD (all 8 crops). Solid lines are average values across all models, shaded areas denote the uncertainty range.

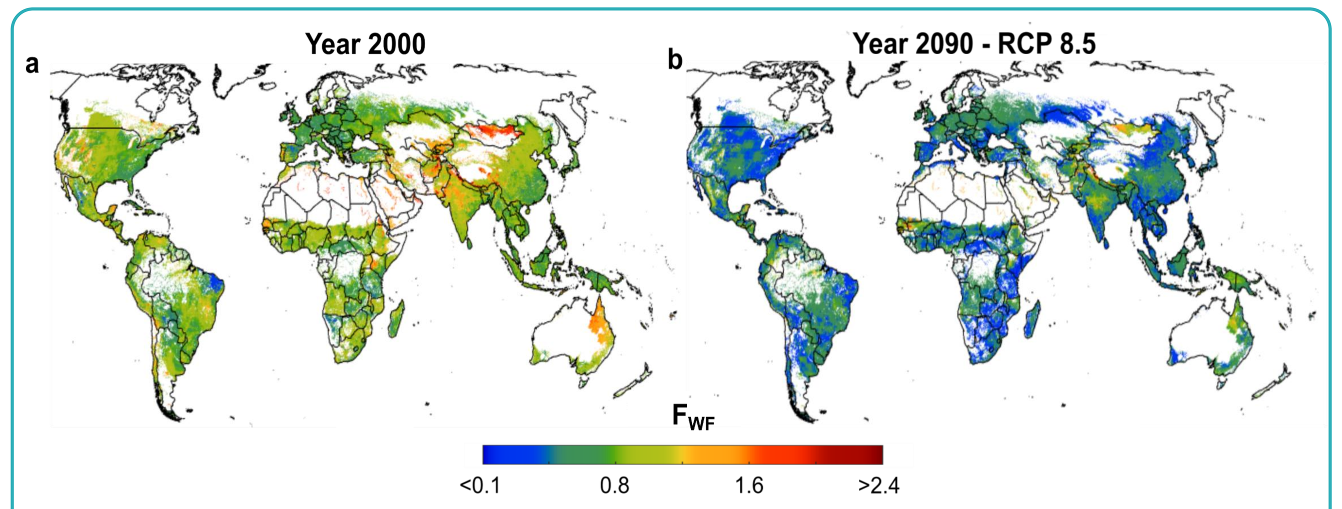


Fig. 2. Fractional uncertainty F of total water footprint ($WF = WF_b + WF_g$) for the reference year 2000 (a) and year 2090 under RCP 8.5 (b).

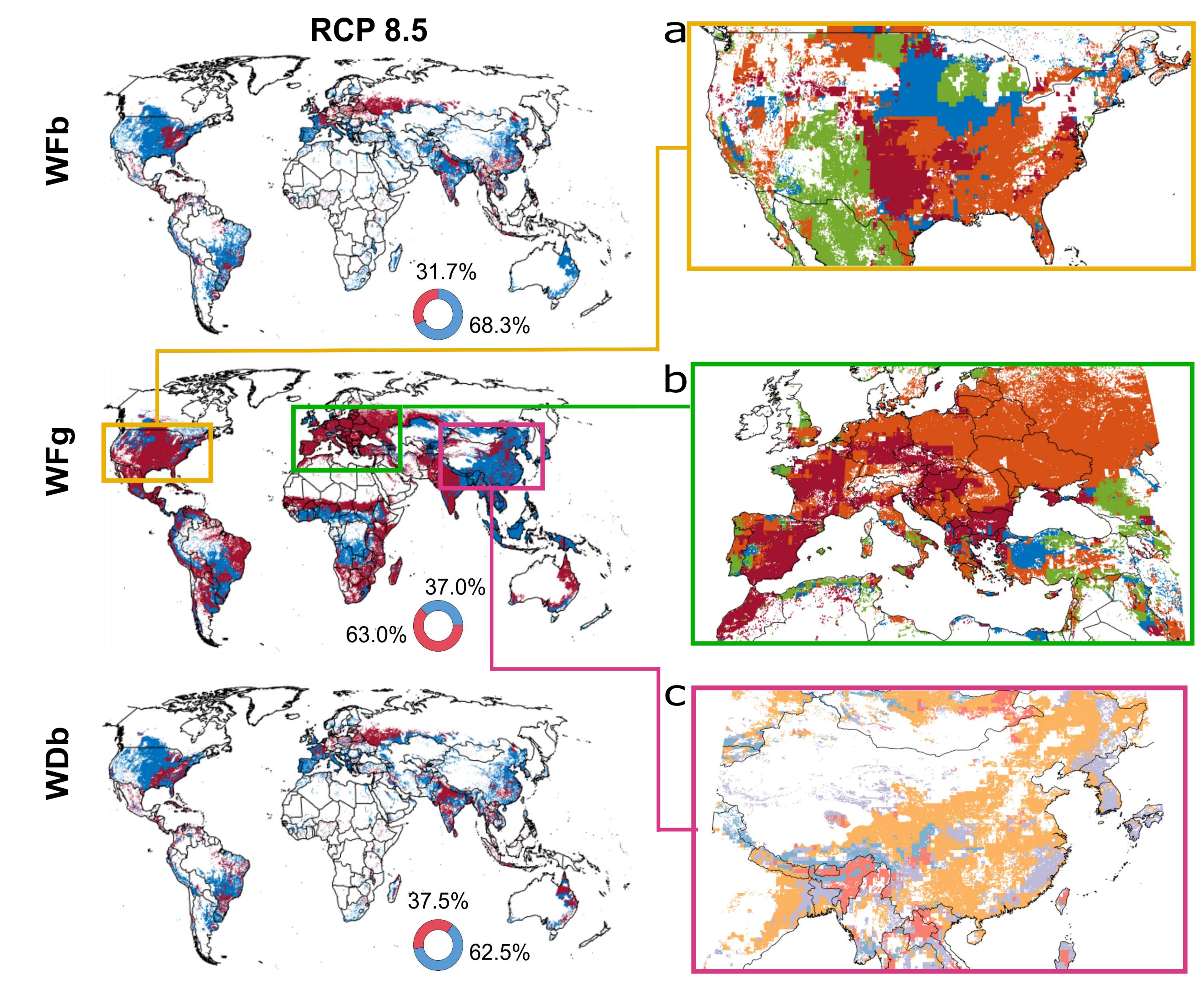
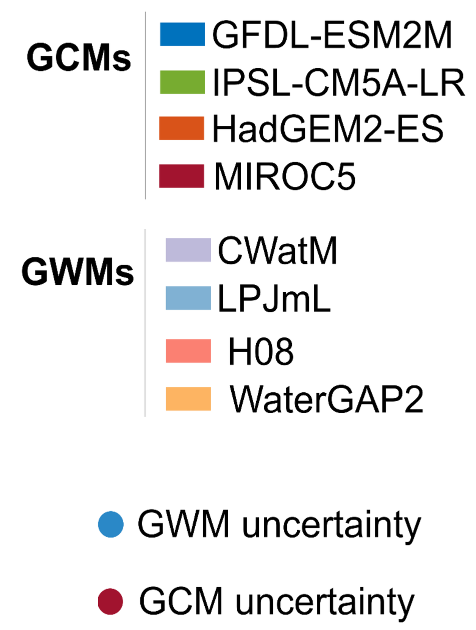


Fig. 3. Global scale dominant source of uncertainty between GWMs (light blue) and GCMs (red), for blue water footprint WF_b, green water footprint WF_g, and blue water debt WD_b (year 2090, RCP8.5). Doughnut charts show the global area proportion of each source. The three insets associated with WF_g feature macro-areas for which the dominant source of uncertainty is further examined by highlighting the corresponding GCMs (a,b) and GWMs (c).



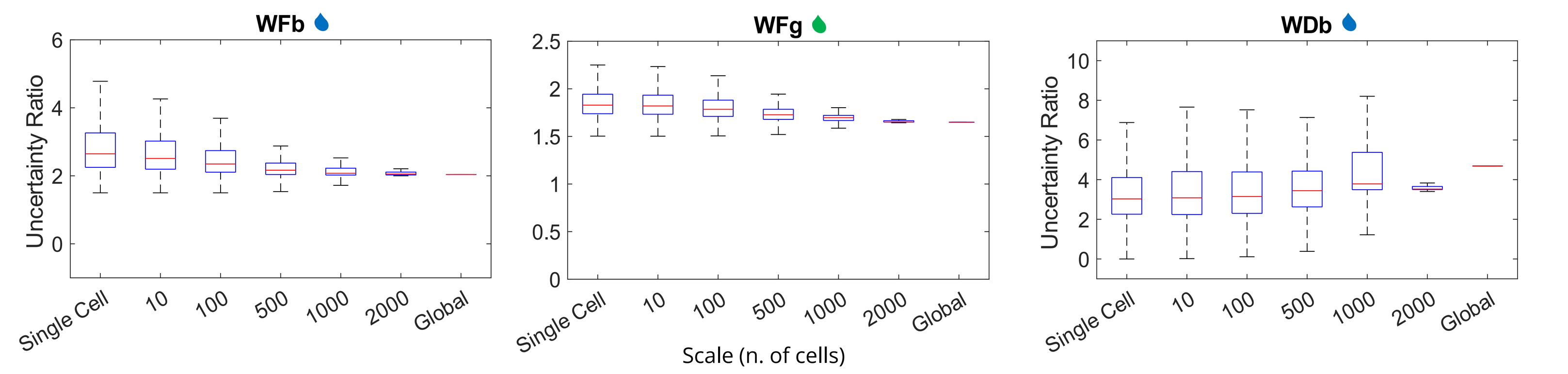


Fig. 4. Variation of uncertainty as a function of scale (i.e., number of grid cells for spatial aggregation of results). The uncertainty ratio (computed as the range of the variable of interest divided by its mean value) decreases with the size of the region of interest for WF, highlighting the higher uncertainty in local results compared to regional/global averages.

Conclusion

- Globally, deviations in green and blue WFs from the multi-model averages range between ±10% and ±30%, respectively (Fig. 1). These uncertainties become significantly larger as the spatial scale of analysis is decreased (Fig. 4).
- Disagreement across GWMs dominates global uncertainty for blue crop water use and sustainability, while variability in GCMs contributes more to uncertainty in green WF under severe climate change scenarios (RCP8.5) – Fig. 3.
- The analysis highlights the need for ensemble approaches to produce robust and reliable projections of crop-water requirements.

References

[1] Mekonnen et al., Hydrology and Earth System Sciences (2011)
[2] Tuninetti et al., Water Resources Research (2019)
[3] Bonetti et al., Environmental Research Letters (2022)
[4] The Inter-Sectoral Impact Model Intercomparison Project [https://www.isimip.org/]
[5] Pokhrel et al., Nature Climate Change (2021)
[6] Orlowsky and Seneviratne, Hydrology and Earth System Sciences (2013)
[7] Portmann et al., Global Biogeochemical Cycles (2010)

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