Authors' Response to Reviews of

Shifting water scarcities: Irrigation alleviates agricultural green water deficits while increasing blue water scarcity

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Review #1

The authors investigate how irrigation reshapes agricultural water stress worldwide by shifting pressure from green water scarcity (GWS) to blue water scarcity (BWS). They simulate crop water use with the global vegetation–crop model LPJmL at 0.5° daily resolution, contrasting a no-irrigation counterfactual (INO) with a limited-irrigation case (ILIM) where withdrawals are constrained to locally available blue water (including upstream inflow and reservoirs, but excluding long-distance transfers and fossil groundwater). GWS and BWS are then quantified with monthly indices.

The paper's key innovation is to treat GWS and BWS jointly, which yields clear global insights: irrigation alleviates GWS on 13% of cropland are but increases BWS by ~12%, concentrating the latter in some irrigation hotspot (e.g., in India and the Mediterranean basin). The estimates of blue water overuse are broadly consistent with published studies; however, the manuscript should explicitly state what is meant by "*water use*" (i.e., whether it refers to water consumption or to withdrawals). Moreover, it remains unclear whether renewable groundwater is explicitly included in the accounting of available blue water. Clarifying these points would strengthen the interpretation of overshoot volumes.

The manuscript is well written, the narrative is coherent, and figures, tables, and supplementary materials effectively support the analysis. Overall, this is a solid and valuable contribution; I recommend **minor revisions** focused on clarifying the treatment of renewable groundwater in the blue-water budget and related sensitivity.

We thank Dr. Lorenzo Rosa for reviewing our manuscript and for his positive evaluation of the paper. The constructive remarks and questions have been very valuable in refining our study. Below, we provide detailed responses and suggestions addressing each comment.

Specific comments:

**** lines 39-40**:** This sentence would benefit from bibliographic references; for example, Gleeson et al. (2020).

Gleeson, T., Wang-Erlandsson, L., Porkka, M., Zipper, S. C., Jaramillo, F., Gerten, D., ... & Famiglietti, J. S. (2020). Illuminating water cycle modifications and Earth system resilience in the Anthropocene. Water Resources Research, 56(4), e2019WR024957.

We will add the proposed reference.

****lines 115-116**:** Adding (S) and (D) to water supply and atmospheric demand, respectively, would make Eq. (1) clearer and more accessible to readers, since these symbols are not defined immediately afterward.

Thank you for this comment, we will add S and D accordingly to improve the clarity of Eq. (1).

Eq.3: In the ratio between the scaling factor and the potential canopy conductance, the division sign (—) is missing; please check.

We will add the division sign to the equation.

lines 145-147: Here too, it would be better to introduce the symbols in Eq.4 beforehand. The symbols for the water uses, even if intuitive, should be restated in the text for the sake of completeness.

We will add the symbols accordingly to the sentence introducing Eq. (4).

Moreover, could you please specify what is meant by "water use" in this study? Are you working with consumption or with withdrawals? For water-balance estimates of overuse, the relevant quantity is typically identified by the water consumption, as it represents the fraction removed from the system and not locally available for reuse (hence generally smaller than withdrawals). It would help to state this explicitly in the Methods.

Thank you for this valuable comment. In the original manuscript, we did not apply a consistent definition of water use: WU_{irr} was calculated with LPJmL and represents the total amount of irrigation water applied to the field. We will now recalculate WU_{irr} to consistently represent irrigation water consumption as follows:

$WU_{irr} = WD_{irr} + E_{conv} - RF_{blue}$ *(Eq. 5),*

where WD_{irr} represents *the applied irrigation water* which depends on the simulated irrigation system, E_{conv} *the evaporative conveyance loss* and RF_{blue} *the water return flow.*

The global average annual irrigation water consumption in our studied time period 2015-2019 is 1213 km^3yr^{-1}, very much in line with estimates calculated in other studies (e.g. Mc Dermid et al., 2024: 1195 +/- 99 km^3yr^{-1}). We assume that blue water stress will be influenced by this change and will decrease accordingly, as will be reflected in the newly calculated results.

lines 145-162: In these paragraphs, it is unclear why additional sectors such as livestock, electricity generation, and mining are not considered. In several regions these are as water-intensive as domestic and industrial uses. Please justify their exclusion (e.g., data gaps, scope) or discuss as a limitation.

Thank you for this important question. In our study, we used the dataset from Flörke et al. (2013) as input, which includes the water consumption of households, industry and livestock. In response to the reviews we propose to change the input and use a dataset by Huang et al. (2018) instead, which is more up-to-date and includes more sectors than Flörke et al. (2013). This dataset was created by spatially and temporally downscaling national (and U.S. state-level) sectoral water-withdrawal estimates from AQUASTAT and USGS, providing a monthly 0.5° gridded dataset for the period 1971–2010. It includes the sectors domestic, electricity generation (cooling of thermal power plants), livestock, mining, manufacturing and irrigation. For our updated analysis, we will use the data for the first five sectors as input to LPJmL (whereas consumptive water use for irrigation is computed internally).

We will update the Method section accordingly and further acknowledge data gaps and time coverage as limitations in the Discussion section and elaborate on how the inclusion of additional sectors and longer time periods could influence the results. We expect blue water stress to (slightly) decrease because global industrial water withdrawal estimates by Flörke et al. (2013) are higher than estimates by Huang et al. (2018).

It is not specified how the Flörke et al. (1950–2010) database covers the full simulation period, particularly after 2010. Were values held constant at 2010 levels thereafter, as in Rosa & Sangiorgio (2025) and Citrini et al. (2025)? This should be stated explicitly in the Methods and acknowledged as a limitation.

Thank you for highlighting this aspect. We will adjust the Method section and describe that with the new proposed dataset, values are held constant at 2010 levels.

Please clarify why renewable groundwater inflows to grid cells are not included in the blue-water budget (they appear to be excluded in Eq. 4 and Eq. 5). If intentionally omitted, explain the rationale and, in the Discussion section, the implications for overuse estimates.

We will re-evaluate whether withdrawal from the established groundwater buffer is possible for this analysis and discuss our decision in the revised manuscript.

It would help to add a brief note on the routing module: how upstream–downstream relationships among cells are represented when computing overuse, including whether deficits are calculated locally or propagated, and any reservoir/return-flow assumptions.

The routing module represents upstream–downstream relations through the predefined river network, where discharge flows between grid cells with a constant flow velocity and via cascaded linear reservoirs (Schaphoff et al., 2018). Water deficits are calculated locally in each cell, but propagate downstream because reduced outflow from an upstream cell decreases available discharge for all downstream cells. Return flows from irrigation losses are assumed to percolate into the soil and subsequently contribute to surface runoff, which is added to the local surface water and routed downstream. Reservoirs further modify these interactions by storing, buffering, and releasing water according to their operating rules, thereby altering both local and downstream water availability. We will explain these points in the revised Method section.

****Lines 155-156**:** Stenzel et al.'s approach to estimating blue-water overuse appears closely aligned with earlier assessments of unsustainable water use (e.g., Mekonnen & Hoekstra, 2016; Mekonnen & Hoekstra, 2020; Citrini et al., 2025; Rosa & Sangiorgio, 2025 and many others). It would strengthen the manuscript to situate the method explicitly within this literature (briefly clarifying similarities and differences) and, where feasible, to prioritize citations to peer-reviewed, published studies.

Citrini, A., Sangiorgio, M., & Rosa, L. (2025). Global multi-model trends of unsustainable irrigation under climate change scenarios. Environmental Research Letters, 20(10), 104011.

Mekonnen, M. M., & Hoekstra, A. Y. (2016). Four billion people facing severe water scarcity. Science advances, 2(2), e1500323.

Mekonnen, M. M., & Hoekstra, A. Y. (2020). Blue water footprint linked to national consumption and international trade is unsustainable. Nature Food, 1(12), 792-800.

Rosa, L., & Sangiorgio, M. (2025). Global water gaps under future warming levels. Nature Communications, 16(1), 1192.

Thank you very much for the suggested literature, which we were partly not yet aware of (2025 publications). We will situate our method within the existing studies and discuss similarities and differences in the approaches and results in the restructured discussion section. We also add the baseline (2001-2010) result of Citrini et al. (2025) / Rosa and Sangiorgio (2025) to Table 1 as a comparative reference for validation.

****Figure2**:** The figure is excellent. One suggestion would be to revisit the colorbar and its tick labels. Because the text consistently refers to thresholds at 0.2–0.4–0.6–0.8–1.0, harmonizing the colorbar bins/ticks with those intervals (similar to the style used in Fig. S11) would improve readability and make cross-references more immediate. If a full reclassification is not desired, introducing color breakpoints at those thresholds would still create a clear visual link to the classes cited in the text. Please take this as an optional refinement to consider.

It would also help to state explicitly in the caption that the colorbar applies to all panels in the figure (as you did in the caption of Figure 4).

Thank you very much for this comment, we will adapt the proposed changes in order to improve the readability of Figure 2.

****lines 181-184**:** Another enhancement to consider is splitting Figure 2 into five panels (2a–e) instead of two, so the manuscript can reference each component explicitly. For example: "*The green water stress patterns show a high seasonal variability over the year due to changing weather conditions but also season-specific growing seasons (**Fig. 2b-e**). Europe and North America do experience less (or even no) GWS during the winter months since the water demand of the crops grown during that time is very low (**Fig. 2b**). During the summer months (**Fig. 2d**), however, especially southern regions in Europe and the western US are highly green water stressed (GWS >0.4). Large regions in Brazil change into GWS hotspots from June to November where pulses, rapeseed and sugarcane are especially green water stressed (**Fig. 2d-e**). India, by contrast, does not experience high GWS from June to November (**Fig. 2d-e**), when most crops are grown.*"

We agree with the proposed splitting of Figure 2 and will adjust the figure accordingly.

Figure 5: The figure appears very similar to the patterns reported by Citrini et al. (2020) for the 2001–2010 baseline (see their Supplementary Fig. 2a). It would strengthen the paper to briefly position your map against those results - highlighting key consistencies or divergences and the likely reasons in the Discussion section. This seems especially pertinent if your overuse metric is restricted to surface-water resources, whereas Citrini et al. used a source-agnostic approach (i.e., not distinguishing whether scarcity arises from groundwater or surface water).

Citrini, A., Sangiorgio, M., & Rosa, L. (2025). Global multi-model trends of unsustainable irrigation under climate change scenarios. Environmental Research Letters, 20(10), 104011.

Thank you very much for this suggestion, we will include the study of Citrini et al. (2025) in our paper and discuss the similarities and differences accordingly in the revised Discussion section.

****Discussion section**:** The Discussion would benefit from engaging with the most recent literature published this year, e.g., Rosa & He (2025) for GWS, and Rosa & Sangiorgio (2025) together with Citrini et al. (2025) for blue-water overuse. Situating your findings alongside these studies (noting agreements, differences, and methodological nuances) would further strengthen the contribution. Could you clarify what drives the difference between the estimates (585 km^3yr^{-1} vs ~460 km^3yr^{-1})? Is the difference mainly due to (i) restricting blue-water availability to surface sources, (ii) using withdrawals rather than consumptive use, or (iii) other methodological choices (e.g., treatment of return flows, reservoirs, EFRs, routing, baseline years)?

In addition, the sentence at lines 302–304 should be supported with appropriate references.

Citrini, A., Sangiorgio, M., & Rosa, L. (2025). Global multi-model trends of unsustainable irrigation under climate change scenarios. Environmental Research Letters, 20(10), 104011.

Rosa, L., & He, L. (2025). Global multi-model projections of green water scarcity risks in rainfed agriculture under 1.5° C and 3° C warming. Agricultural Water Management, 314, 109519.

Rosa, L., & Sangiorgio, M. (2025). Global water gaps under future warming levels. Nature Communications, 16(1), 1192.

We will improve our discussion by incorporating this very recent literature on blue water consumption and overuse. We anticipate that our estimate of 585 km^3 yr^{-1} of blue water from non-sustainable surface water resources will likely decrease following the recalculation of irrigation water consumption, and we will elaborate on this accordingly in the revised manuscript.

****lines 314-315**:** It would be helpful to briefly outline how such these new case studies would be implemented. For example, would higher spatial and/or temporal resolution be required? If so, please indicate the additional data needs (e.g., finer-resolution water use, irrigation, hydrologic, and management datasets) and whether the availability of such data currently constrains feasibility.

Thank you for this comment. Indeed, additional datasets with higher spatial and temporal resolution—particularly for irrigation and management—would be highly valuable. The case studies mentioned in this section, however, were intended to take a more qualitative approach, relying on interviews and bottom-up analyses together with actors affected by water scarcity to better understand local impacts and potential solutions. Since global modeling studies like ours depend on large gridded datasets, such qualitative insights would help validate whether the changes and effects in water use and stress that we identify are also observed by local actors. A more interdisciplinary approach would therefore be highly beneficial, and we will shortly elaborate on this in the discussion section.

****Reference list**:** Just a minor formatting note, likely governed by the journal's template rather than the authors: applying a hanging indent to the paragraph/list would make the items much easier to scan and review.

Thank you for this suggestion, we will apply a hanging indent to the reference list in the revised manuscript.

Thank you for the opportunity to revise the study. Again, this is great work (congratulations!) and minor clarificatory revisions are requested.

Lorenzo Rosa

References

Citrini, A., Sangiorgio, M. and Rosa, L.: Global Multi-Model Trends of Unsustainable Irrigation under Climate Change Scenarios, ERL, 20, 10, 104011, https://doi.org/10.1088/1748-9326/adfcee, 2025.

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