Reply on Comment (Anonymous Referee #1)

We are grateful to the anonymous referee for their careful reading of our manuscript and the constructive suggestions.

Below, each comment from the referee is *in italicized font*, and our responses in red normal font. Any new or added text in the manuscript is underlined in red, deleted text is with ~~a strikethrough~~ in red, and these changes will be incorporated into the next revision.

All the line numbers in this reply refer to the original version of EGUsphere Manuscript ID: **egusphere-2025-2004**

Here is my review for "Detecting irrigation signals from SMAP L3 and L4 soil moisture: A case study in California's Central Valley" submitted to Hydrology and Earth System Sciences. The paper aims to detect irrigation signals by comparing SMAP Level 3 and Level 4 soil moisture products, which is demonstrated in California's Central Valley. The results highlight the potential of satellite-based observations to identify irrigation effects. However, several aspects of the methodology, data usage, and interpretation require clarification and improvement to strengthen the study's scientific rigor and clarity. My recommendation is major revision to address the concerns outlined below.

Below, I provide general comments on the manuscript's overall contribution, followed by specific comments to guide the authors in revising their work.

Reply: We appreciate your time and efforts devoted to reviewing our work. We have carefully considered your comments and will revise the manuscript accordingly as outlined in the following.

General Comments:

The authors note that SMAP L4 assimilation is based on brightness temperature anomalies, thereby excluding persistent irrigation effects embedded in the *climatological mean. However, in practice, irrigation is not always applied consistently during soil moisture deficits; its timing can be irregular and largely influences soil moisture anomalies rather than the climatology. Moreover, this assumption neglects potential non-stationary changes in irrigation practices driven by agricultural policies. I recommend that the authors assess whether the identified irrigation dates are realistic and consider conducting a synthetic experiment to demonstrate that SMAP L4 indeed lacks any irrigation-related signal.*

Reply: Thank you very much for your helpful comments and suggestions.

We agree that irrigation is not always applied consistently during periods of soil moisture deficit. The irregular irrigation application can influence soil moisture anomalies rather than long-term climatology, meaning that in some scenarios the SMAP L4 may indeed still contain irrigation-related signals or effects. **As noted in our discussion (Section 5.1), when there is a non-negligible amount of precipitation during the irrigation season, our approach does not perform well**. This description is consistent with your concerns regarding the anomalies versus climatology. It is challenging to draw a clear line between irrigation signals that appear more random (randomly timed from year to year) and those that behave more like a climatology (the similar irrigation patterns every year).

In contrast, in areas where there is little to no rainfall during the irrigation season (as in the California Central Valley and the Snake River Basin), during the cropping season there is only negligible rain and irrigation is required every year to maintain soil moisture for crop growth. In these regions, irrigation is applied in a consistent pattern year after year. As a result, the added water becomes **part of the expected climatology rather than an anomaly**, **meaning it is not assimilated in the SMAP L4 product**. Under these conditions, **our approach works well, since the irrigation signal remains distinct and detectable**.

We also appreciate the suggestion to conduct a synthetic experiment that examines irrigation-related effects on the SMAP L4 product. However, at our current capacity, it is very challenging to isolate an independent synthetic experiment from the SMAP production workflow to directly demonstrate the absence of irrigation signals in the SMAP L4 soil moisture. While the SMAP L4 Handbook and User Guide[2] provide detailed descriptions of the data assimilation process, very little insight is offered into how irrigation effects are handled. Nonetheless, we believe it is crucial to show that **assimilating anomalies does not cause SMAP L4 to carry irrigation effects**. To address your concern, we plan to **include a synthetic experiment** in the next version of the manuscript, as outlined below:

Step #1: Baseline synthetic experiment setup. The synthetic experiment will be based on the surface soil water mass balance equation, as Eq. (R1) shows:

$$\Delta z \frac{d\theta(t)}{dt} = P(t) - ET(t) - Q(t) = P(t) - L(t) \quad \text{(R1)}$$

where Δz is the depth of soil control volume, θ is the volumetric soil moisture, P is precipitation, ET is evapotranspiration, Q is drainage and runoff, and $L = ET + Q$ is the "loss function". On the grid cells where irrigation is needed, surface runoff is negligible, and runoff term can be omitted, simplifying the loss function as $L = ET$. Following McColl et al. (2019), the precipitation will be generated using Eq. (R2) [2].

$$\bar{P}(t) = \overline{P_0} + A_{\bar{P}} \sin\left(\frac{2\pi t}{365}\right) \quad \text{(R2)}$$

where t is the day, $\bar{P}(t)$ is the annually mean daily precipitation, and $A_{\bar{P}}$ is the amplitude of the seasonal cycle.

The loss function L will be generated by Eq. (R3) as follows:

$$L = \begin{cases} E_{max}, s \geq s_* \\ \frac{s-s_w}{s_*-s_w} E_{max}, s_w \leq s \leq s_* \\ \frac{K_s\left[e^{\beta\left(s-s_{fc}\right)}-1\right]}{e^{\beta\left(1-s_{fc}\right)}-1}, s \leq s_* \end{cases} \quad \text{(R3)}$$

where $s = \theta/n$ is soil saturation, n is the soil porosity, s_w is wilting point, s_* is a critical saturation at which the transition from stage-I to stage-II ET occurs, s_{fc} is field capacity, K_s is the saturated hydraulic conductivity, and β is an empirical parameter controlling the shape of the drainage curve.

Eq. (R1) above indicates the baseline experiment where no irrigation will be incorporated into soil moisture.

Step #2: Irrigation synthetic experiment setup. For irrigated grid cells, irrigation is introduced as an additional water input term alongside precipitation as shown in Eq. (R4):

$$\Delta z \frac{d\theta(t)}{dt} = P(t) + I(t) - L(t) \tag{R4}$$

where $I(t)$ is irrigation water input.

We will then introduce two kinds of irrigation scenarios:

Scenario (1): a continuous irrigation water input (e.g., fixed irrigation interval for each year) during the typical irrigation season. This yields a consistent soil moisture time series with irrigation. Detailed information on the settings of irrigation will be provided in the next version of the manuscript.

Scenario (2): a scenario where the irrigation water input is highly variable across years (e.g., highly variable irrigation interval). This scenario helps us understand how anomaly will be in such regions with variable or intermittent irrigation practices.

Step #3: Anomaly Comparison: We will run these simulations over multiple years and compute the soil moisture anomalies (e.g., deviations from the long-term mean seasonal cycle) for both the non-irrigation and irrigation scenarios. We will then compare the anomaly time series between the two scenarios. If the anomalies from the irrigation scenario closely resemble those from the control scenario, it indicates that the presence of irrigation does not significantly alter the anomaly patterns. In other words, assimilating anomaly data (as is done in SMAP L4) would not introduce irrigation signals into the soil moisture product.

We hope that this synthetic experiment will address your concern. We will include the supplementary information of this synthetic experiment in our revised manuscript, and we will also this clarification in the revised version:

Line 148: Based on the above explanation, in regions where irrigation is irregular or subject to significant changes (for example, due to evolving agricultural policies), these non-stationary irrigation practices can alter the SMAP L4 climatology baseline, introducing irrigation-related anomalies into the assimilated data. In other words, under highly irregular irrigation regimes, irrigation effects could indeed be present in the

SMAP L4 product, which would limit the effectiveness of the proposed approach.

We thank you once again for these insightful comments and suggestions. They have helped us improve the rigor of our work, and we hope that the revisions will address the concerns raised.

[1] *U.S. Department of Agriculture, National Agricultural Statistics Service, 2024. Irrigation and Water Management Survey. https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Farm_and_Ranch_Irrigation/*

[2] *K. A. McColl, Q. He, H. Lu, and D. Entekhabi, 2019. Short-Term and Long-Term Surface Soil Moisture Memory Time Scales Are Spatially Anticorrelated at Global Scales. J. Hydrometeor., 20, 1165–1182, doi: 10.1175/JHM-D-18-0141.1.*

[3] *R.H. Reichle, G. De Lannoy, R. Koster, W. Crow, J. Kimball, Q. Liu, M. Bechtold, 2022. SMAP L4 global 3-hourly 9 km EASE-Grid surface and root zone soil moisture geophysical data, Version 7. doi:10.5067/EVKPQZ4AFC4D*

Specific Comments #1: *Line 145: Limitation of SMAP L4 Assumptions*

The manuscript states that SMAP L4 excludes irrigation signals in croplands with continuous irrigation. This assumption significantly limits the method's applicability, as it may not account for regions with variable or intermittent irrigation practices. The authors should clarify the conditions under which this assumption holds and discuss its implications for the method's generalizability.

Reply: Thanks for your helpful comments and we think this comment expressing the same thing as the General Comments.

Please refer to the Reply to the General Comments above.

Specific Comments #2: *Section 2.1.3: Outdated Irrigated Area Map*

The manuscript relies on a 2005 Global Map of Irrigated Areas (GMIA) dataset, despite using SMAP data from 2016–2022. Given potential changes in irrigation extent over this 15-year period due to agricultural expansion, urbanization, or policy shifts, the use of an outdated map introduces uncertainty. The authors should justify this choice or consider incorporating a time-series irrigated area dataset to align with the SMAP data *period. A discussion of how changes in irrigation patterns might affect the results is also warranted.*

Reply: Thanks for your valuable suggestions.

We applied the Global Map of Irrigated Area (GMIA) Version 5 as it remains **the latest publicly available and extensively validated global irrigated-area dataset**. GMIA Version 5 has undergone extensive validation by Siebert et al.[1] and is recognized as one of the most reliable global irrigation-related datasets currently available[2]. It still serves as **a foundational dataset input for irrigation representations in the global hydrological models**, including PCR-GLOBWB, WaterGAP, and H08. On the other hand, GMIA's native 5 arcmin resolution closely matches the EASEv2.0 M09 grid used by SMAP (≈9 km at the equator), which minimizes uncertainties associated with resampling and interpolation.

However, we acknowledge that newer irrigated area maps have since been developed (e.g., MIRCA-OS [3], MapSPAM [4], and Nagaraj et al. 2021's global irrigation dataset for 2001–2015 [5]). We are currently reviewing these alternative datasets and intend to include an expanded discussion in our supplementary materials regarding the potential implications that the temporal mismatch between the GMIA dataset (2005) and the SMAP data period (2016–2022) may have on our results.

Accordingly, we propose to include the following text in the next version of the manuscript:

Line 158: The GMIA is a static dataset that represents the percentage of irrigated land relative to the total grid cell area around 2005 (Siebert et al., 2013). <u>It is still recognized as one of the most reliable global irrigation-related datasets currently available</u>.

Line 378: since the GMIA was estimated based on the global irrigated land data in 2005 (Siebert et al., 2013), any subsequent changes are not captured in the GMIA. <u>The temporal mismatch between the GMIA dataset and the SMAP data period is further discussed in the Supplementary Information Section S10.</u>

Supplementary Information Section S10 (new): We will add a discussion of the newer irrigated area datasets and how changes in irrigated area maps may affect our findings.

[1] *S. Siebert, V. Henrich, K. Frenken, J. Burke, 2013. Global map of irrigation areas version 5.*

[2] *S. McDermid, M. Nocco, P. Lawston et al., 2023. Irrigation in the Earth system. Nature Review earth &environment. (4): 435-453*

[3] *E.A. Kebede, K.O. Oluoch, S. Siebert et al., 2025. A global open-source dataset of monthly irrigated and rainfed cropped areas (MIRCA-OS) for the 21st century. Scientific Data 12, 208*

[4] *Q. Yu, L. You, U. Wood-Sichra et al., 2020. A cultivated planet in 2010 – Part 2: The global gridded agricultural-production maps, Earth Syst. Sci. Data, 12, 3545–3572*

[5] *D. Nagaraj, E. Proust, A. Todeschini, M.C. Rulli et al., 2021. A new dataset of global irrigation areas from 2001 to 2015. Advances in Water Resources. (152): 103910*

Specific Comments #3: *Equation (2): Handling Precipitation Bias and Crop Rotation Equation (2) defines the irrigation signal as the difference in mean soil moisture difference (MD) between cropping and non-cropping seasons, based on SMAP L3_E and L4 data in irrigated grid cells. However, line 270 notes that high MD values in the non-cropping season may result from precipitation, which could confound irrigation signals. The authors should address how precipitation biases and rain/no-rain errors are considered during the cropping season. Additionally, the method assumes distinct cropping and non-cropping seasons, which may not apply to regions with year-round crop rotation. The authors should discuss the method's applicability to such regions and propose potential adaptations.*

Reply: Thank you for your helpful comments and suggestions.

Our study defines the irrigation signal (*IS*) as the difference between the *MD* values for the cropping and non-cropping seasons, where for each season the *MD* is defined as the inter-product difference (i.e., *MD* = SMAP L3_E minus L4 soil moisture). By design, this approach **allows for systematic biases (differences in rainfall responses) between SMAP L3_E and L4 products, while only requiring that outside irrigated areas such systematic biases remain consistent across the cropping and non-cropping seasons**. Therefore, before detecting irrigation signals within irrigated grid cells, our method requires validating whether this assumption (the consistency of

SMAP L3_E and L4 systematic biases between cropping and non-cropping seasons) holds true in non-irrigated grid cells of the study area. If most non-irrigated grid cells show inconsistent biases between cropping and non-cropping seasons, any detected *IS*, no matter how substantial, would not be reliable. Conversely, if the consistency assumption holds, we can expect that a high *MD* during the non-cropping season would correspond to a similarly high (in non-irrigated grid cells, reflecting the baseline systematic bias) or higher (in irrigated grid cells, baseline bias combined with irrigation effects) *MD* during the cropping season. Under such circumstances, irrigation signals can still be detected. In summary, the proposed definition method of *IS* effectively minimizes potential confounding from precipitation when detecting irrigation signals using SMAP L3_E and L4 products.

Our method implicitly assumes distinct cropping and non-cropping seasons, which could be identified based on local cropping calendars. At present, the proposed method is generally not applicable to regions with multiple cropping seasons or year-round irrigation because the baseline *MD* between SMAP L3_E and L4 in a non-cropping season is essential for calculating the irrigation signals. Figure R1 provides two representative grid cells in the Lower Mississippi flood basin (a region typically having two cropping seasons, with winter-spring irrigation) as a demonstration. It can be observed that, although SMAP L3 soil moisture is significantly higher than L4 during June to November (the summer-autumn cropping season), it approaches saturation during December to May (winter-spring cropping season), while SMAP L4 remains relatively lower due to the potential removal of irrigation effects. Although this observation partially supports our assumption that SMAP L3 captures irrigation signals while SMAP L4 largely excludes them (SMAP L4 in generally lower than L3 throughout the whole year), our current method does not enable a reliable estimation of irrigation signals in Lower Mississippi flood basin, since it is a typical region with two cropping seasons, where our method is not applicable yet.

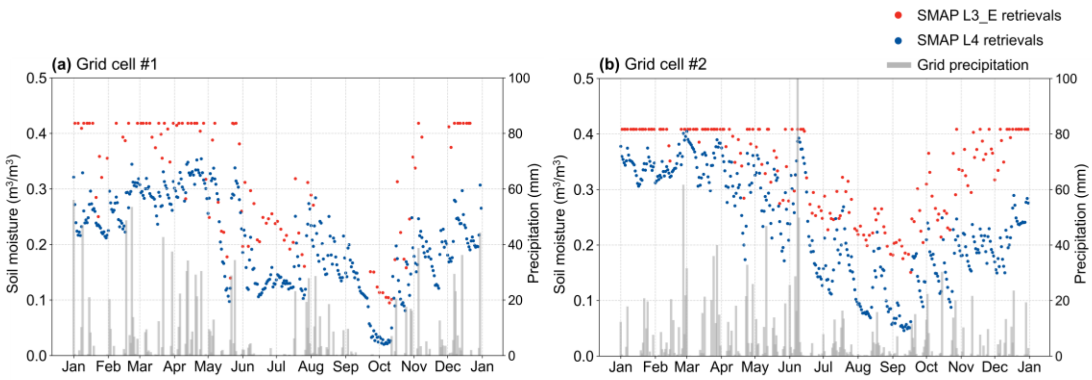

Figure R1: SMAP surface soil moisture from (red dots) L3_E and (blue dots) L4 for two representative grid cells in the Lower Mississippi flood basin.

Note that the manuscript already includes discussion of this limitation. E.g., in Line 410 we caution that our method can effectively capture irrigation signals only in regions with limited cropping-season precipitation (e.g., (semi-)arid, (semi-)Mediterranean climatic regions), which usually feature single-season cropping or rain-fed crops in the winter. In these regions, we can reliably identify a baseline *MD* in the non-cropping season unaffected by irrigation, thereby detecting irrigation signals during the cropping season. In the revised version, we will strengthen the discussion of the applicability of our method. In future research, we would like to explore alternative approaches to determine baseline *MD* without irrigation. For instance, using *MD* values from adjacent non-irrigated grid cells as a baseline reference, and reassess irrigation signals accordingly.

We appreciate your constructive comments, which significantly enhance the scientific rigor of our manuscript. In the next version, we will revise the relevant text as follows:
Line 244: Note that *IS* represents irrigation intensity rather than the absolute irrigation water use amount; this distinction is further elaborated in Section 5. Additionally, due to the requirement to differentiate between cropping and non-cropping seasons, our method is currently not applicable to regions with multiple cropping cycles or year-round irrigation.

Specific Comments #4: *Line 255 and Table 1: Inconsistent Threshold for Non-Irrigated Grid Cells*

Line 255 states that non-irrigated grid cells have an irrigated area fraction below 0.1%, but Table 1 reports a threshold of 0.11% (non-irrigated grid cell b).

Reply: Thanks for your careful revision and comments.

We re-checked the irrigated area fraction of grid cell (b), which is 0.011% (and not 0.11%). We apologize for the typo and will correct it in the next version as follows:

Table 1, Irrigated area fraction of Grid cell (b): ~~0.11%~~ 0.01%

Specific Comments #5: *Figures 2(d) and 3(c): Bias in Soil Moisture Differences*

Figures 2(d) and 3(c) show a higher mean difference between SMAP L3 and L4 in non-irrigated grid cell E (0.0471 m^3/m^3) compared to irrigated grid cell C (0.0354 m^3/m^3). This bias may stem from using the outdated 2005 GMIA dataset, as irrigation patterns may have changed. The authors should investigate whether this discrepancy reflects changes in irrigation extent or other factors (e.g., soil properties, land cover) and discuss their findings.

Reply: Thank you for your valuable comments and suggestions.

We would like to firstly clarify that **the comparison of *MD* between cropping and non-cropping seasons should only be conducted independently within each grid cell individually**, as defined in Eq. (2) of the original manuscript (i.e., *MD* for the cropping season compared to *MD* for the non-cropping season of a specific grid cell). This is because different grid cells have distinct soil characteristics, land cover, and other factors, the systematic bias baselines of *MD* vary among grid cells. Therefore, careful caution and test are needed when directly comparing *MD* values between different grid cells. This is also the reason why, as discussed in our reply to Specific Comment #**3**, we are still trying to test the potential use of *MD* from neighboring non-irrigated grid cells as a uniform baseline to quantify multi-seasonal irrigation effects. Specifically, in the example you mentioned, the non-irrigated grid cell e in Figure 2(d) indeed shows a higher *MD* than the irrigated grid cell C in Figure 3(c). However, the baseline *MD* of cell e is much higher than that of cell C (0.0717 m^3/m^3 vs. -0.0105 m^3/m^3), indicating substantial differences in systematic bias between SMAP L3 and L4 at two grid cells. Hence, from a methodological perspective, these two *MD* values should not be directly compared.

Additionally, we understand that the use of GMIA dataset based on year 2005 may introduce uncertainties into the validation process, as you have pointed out in Specific Comment **#2**. As mentioned in our response to Specific Comment #2, we will examine a newer irrigated area map to explore the potential impacts of the GMIA dataset and provide additional analysis in the supplementary information of the next version of manuscript.

To clarify the applicability of the proposed approach, we will add the following revised text in the next manuscript version:

Line 234: Note that the above analyses should be conducted independently for each grid cell; *MD* values from different grid cells cannot be cross compared.

Specific Comments #6: *Line 320: Error in Supplementary Figure Reference*

The reference to "Supplementary Information Figure S5-3" appears incorrect. Please verify and correct the figure number.

Reply: Thank you very much for your careful revision.

We have checked the figure number for this reference, and the correct figure number should be "Figure S5-4" here. We apologize for the typo error here and all figure numbers have been re-checked again.

The figure number will be revised in the next version:

Line 320: Supplementary Information Figure ~~S5-3~~ S5-4

Specific Comments #7: *Figures 5 and S-4: Interpretation of R_{non} Performance*

The manuscript reports that 72.7% of R_{non} values fall below the consistency threshold, suggesting limitations in the method's performance for SMAP L4. The authors attribute this to the absence of saturated soil moisture values in L4 compared to L3_E during the non-cropping season. However, SMAP L3_E's sensitivity to surface wetting (e.g., post-rainfall or standing water) may lead to unrealistic retrievals. The authors should clarify whether these values reflect true soil saturation or retrieval error.

Reply: Thanks for your insightful comments, and we appreciate the opportunity to clarify this point in the next version.

Our analysis indicates that these saturated SMAP L3_E soil moisture values are likely retrieval artifacts caused by standing water after heavy rainfall, rather than true soil saturation. Specifically, we observed that the saturation points in SMAP L3_E occur during the non-cropping season (winter-spring) in SV, following periods of intense precipitation. This timing suggests that the SMAP L3_E retrieval is responding to temporary surface wetting or ponding. Previous studies[1] have reported that even if a small fraction of a radiometer pixel (5% or more) is covered by standing water, SMAP L3_E algorithm can overestimate the soil moisture, sometimes by ~0.2 m^3/m^3, leading to unrealistically high retrievals. In our study case, SV experienced consecutive heavy rain events in winter-spring, which likely created standing water that the L3_E interpreted as saturated soil. In contrast, the SMAP L4 product uses a land surface model and assimilates brightness temperature anomalies (rather than directly using the radiometer's absolute soil moisture retrievals). This approach makes L4 less sensitive to transient standing water effects, so it shows high soil moisture but does not reach the saturation that L3_E does.

It should be noted that these potentially saturated points in SMAP L3_E limit the area where our method can be applied, they do not compromise our irrigation analysis results in areas where our method can be applied. We conducted a climatological consistency test between SMAP L3_E and L4, and the SV grid cells with low R_{non} (inconsistent wet-season behavior) failed that test. Consequently, even though those grid cells might contain irrigated areas, they were excluded from subsequent analyses. In other words, they were flagged as having inconsistent climatology and were not used when mapping irrigation signals.

We will revise the following description to clarify this issue in the next version:

Line 323: These saturated L3_E values are likely to be retrieval errors caused by surface wetting (e.g., standing water following heavy rainfalls) (Ye et al., 2015). SMAP L4's assimilation approach avoids these spurious saturation signals.

[1] *N. Ye, J.P. Walker, J. Guerschman et al., 2015. Standing water effect on soil moisture retrieval from L-band passive microwave observations. Remote Sensing of Environment. 169 (2015): 232-242*

Specific Comments #8: *Figure 7: Interpretation of Irrigation Signal (IS)*

The statement in line 245 that "a larger IS value indicates higher irrigation intensity" implies that any positive IS value signals irrigation activity. However, Figure 7 shows biases in some regions (e.g., region (i)), which may undermine this interpretation. The authors should clarify whether positive IS values consistently indicate irrigation or if biases (e.g., from precipitation or land cover changes) could lead to false positives. A sensitivity analysis of IS values would help address this concern.

Reply: Thanks for your professional comments.

We understand that our original statement in Line 245 ("A larger *IS* value indicates higher irrigation intensity") may appear overly definitive, particularly given that Figure 7 reveals some biases in certain regions, and some could result from the confounding factors.

In response, we will revise the description accordingly in the next manuscript version as follows:

Line 245: ~~A larger *IS* value indicates a higher irrigation intensity for the grid cell.~~ Ideally, a larger *IS* value would be associated with higher irrigation intensity; however, uncertainties caused by other factors (e.g., precipitation events, land cover changes) could introduce biases.

Additionally, we will add a sensitivity analysis of *IS* values (spatial map) in the supplementary information to explicitly address this concern.

Specific Comments #9: *Figure 8:*

The validation of the estimated irrigation signal, which relies on comparisons with the GMIA and irrigation water use datasets, is inadequate. Using GMIA as both an input to the method and a validation dataset introduces circularity, undermining the independence of the validation process. Additionally, the manuscript reports a spatial correlation of 0.5 with the ZL21 map, which is relatively low and raises questions about the method's accuracy. The authors should clarify the significance of this correlation value and consider incorporating independent validation datasets (e.g., in-situ irrigation records) to strengthen the evaluation of the irrigation signal estimates.

Reply: Thanks for your valuable comments.

We would like to clarify that our method uses the GMIA dataset in two independent steps. First (Section 3.1), GMIA is used solely to sample irrigated and non-irrigated grid cells to evaluate whether SMAP L3_E and L4 products are climatologically consistent within the study region; beyond this sampling, GMIA does not inform any further analysis. Second (Section 3.2), GMIA is applied to validate our estimated *IS* map. These two steps employ different procedures, and the first step does not provide any information related to GMIA to the second step, we believe the risk of circular validation is minimized.

The relatively low correlation coefficient is primarily attributed to two possible factors: (1) Different soil-moisture depths: ZL21 is based on rootzone soil moisture, whereas our *IS* method relies solely on surface soil moisture from SMAP L3_E and L4. In Central Valley, subsurface irrigation practices cannot be fully captured by surface-only observations. (2) Resolution mismatch: ZL21's native resolution is 1 km, which we resampled to 9 km for direct comparison with the *IS* map, potentially diluting finer-scale irrigation patterns. Accordingly, we will add the following text to the next version of the manuscript:

Line 365: <u>The relatively lower correlation with the ZL21 dataset likely arises since ZL21 utilizes rootzone soil moisture to estimate irrigation, which the proposed IS map cannot capture by the surface retrievals from SMAP products.</u>

Regarding in-situ irrigation observations, we must acknowledge that obtaining large-scale, continuous, reliable, publicly available in-situ irrigation records is very challenging. This limitation motivated our inclusion of the ZL21 map alongside GMIA for validation. On the other hand, even if farm-level irrigation withdrawal data were accessible, the mismatch between small-scale irrigation practices and SMAP's 9 km spatial resolution would likely introduce validation errors.

Once again, we greatly appreciate your helpful comments, which have significantly enhanced the scientific rigor of our manuscript.