

Response to Reviewer 1

We thank Reviewer 1 for the constructive and insightful comments. All revisions in the manuscript are highlighted in red. In this response, the reviewer's comments are first presented in full (*in dark blue*), followed by a summary of the corresponding revisions with updated line numbers in the revised manuscript. Detailed explanations were provided in the initial response. The abstract and parts of the conclusions have also been revised to reflect the changes made in the manuscript.

Comment 1 – *Line 13 and 149: Although UAV technology offers extremely high-resolution data, it is important to recognize that the TSEB model, like most resistance-based energy balance models, must be applied over an appropriate spatial domain to satisfy its physical assumptions and underlying formulations. Consequently, TSEB cannot be applied at the leaf level; the radiative transfer and turbulent exchange processes on which it depends require the model to be run at spatial resolutions of the order of meters. The 15 cm resolution of multispectral and thermal imagery used for running TSEB may need stronger justification for its selection. Evapotranspiration maps are helpful for irrigation management; however, 15 cm resolution may not be feasible for practical irrigation applications.*

Response: The manuscript has been revised to clarify the physical scale of TSEB application and the role of high-resolution UAV data in improving input characterization rather than altering the model's effective scale.

Revisions in manuscript:

- Lines 70–75: Added discussion on TSEB physical assumptions and appropriate spatial scale. Added supporting references (Jaafar and Sujud, 2025; Hoffmann et al., 2016; Nassar et al., 2020; Burchard-Levine et al., 2021)
- Lines 813 – 822: Clarified the relevance of high-resolution ET outputs for irrigation management by discussing a multi-scale framework, where high-resolution inputs reduce pixel mixing and uncertainty, and outputs are aggregated into management zones for practical application. Added supporting references (von Hebel et al., 2021; Serrano et al., 2020; Flint et al., 2023)

Comment 2 – *Line 162-163: The radiometric sensor calibration and imagery correction are important for reliable LST data. Cited a reference and explained how the calibration parameters were used in the calibration?*

Response: The manuscript has been revised to clarify how radiometric calibration parameters were applied and to support this with appropriate references.

Revisions in manuscript:

- Lines 199–205: Expanded description of radiometric calibration parameters and implementation and added references supporting sensitivity of UAV thermal data to environmental conditions

Comment 3 – *Line 174-181: Was a thermal infrared sensor or similar used to measure LST from the ground-based reference targets? Later, it stated that a multiple regression model was developed, but it is unclear how the ground temperature was measured and how the environmental variables were used to generate the model.*

Response: The description of ground reference targets and the regression-based correction approach has been clarified.

Revisions in manuscript:

- Lines 216–228: Added description of reference targets and temperature measurements
- Lines 199–205: Clarified radiometric workflow and correction strategy
- Appendix reference corrected

Comment 4 – *Line 193: There is a lack of understanding of the terms: 1) fractional vegetation cover, 2) vegetation fractional from the viewing angle, and 3) fraction of green LAI. Also, there is an error in naming the terms throughout the paper; for example, at line 193, fractional vegetation cover was labeled FVC, and equation B1 shows the calculation of the green area index. Similar for line 221.*

Response: Terminology has been standardized and the distinction between structural and functional variables clarified. Sections 2.4.2–2.4.4 rewritten for clarity.

Revisions in manuscript:

- Lines 232–249: Clarified FVC to GAI derivation
- Lines 258–262: Clarified f_g and f_c implementation
- Lines 264–273: Clarified the f_c derived by model.
- Line 299: notes that f_c is internally derived in the model
- Table 1 and Figure 4 updated for consistency

Comment 4b – *Table 1 shows the model input; however, the fractional cover listed in equation (A10) is based on vegetation fractional cover viewed from an angle, which differs from the fractional cover calculated from multispectral data using soil and canopy pixel classification. Revise the original paper of TSEB formulation. Figure 4 shows equation A10, which is not related to the PT equation*

Response: Equation numbering and cross-referencing have been corrected throughout the manuscript.

Revisions in manuscript:

- Table 1 updated with correct equation references
- Figure 4 updated to align with Appendix equations

Comment 5 – Line 362: *TSEB model compute the surface energy fluxes R_n , H , G and LE or ET is calculated as a residual from the energy balance, in order to evaluate the outputs from TSEB model it is also necessary to compare the modeled and measured R_n , H and G . Additionally, TSEB model output are based on closed energy balance and EC data are non-closed energy balance it is recommended to compare for both scenarios: energy balance closed and non-closed.*

Response: The manuscript now includes full flux comparisons and evaluation under both open and closed EC energy balance conditions.

Revisions in manuscript:

- Lines 335–342: Added energy balance closure methodology Added supporting references (Twine et al., 2000; Mokhtari et al., 2021)
- Lines 387–453: Added flux comparison results
- Figures 8 and 10 added for flux comparisons
- Figures 9 and 11 added closed EC energy balance comparison metrics
- Appendix tables updated with RMSE and R^2 metrics

Comment 5b – *The crop water stress can be derived from TSEB outputs. The paper does not present a method for assessing crop water stress. The following paper explains a method to get CWSI from TSEB: <https://doi.org/10.1016/j.jag.2025.104737>. Assessment of different remote sensing techniques to estimate the CWSI of almond trees using canopy temperature.*

Response: We have revised the manuscript to include an explicit crop water stress assessment derived from TSEB outputs. In addition to evaluating relative ET patterns, a daily crop water stress proxy ($K_s = ET/ET_0$) was implemented to assess crop water status relative to atmospheric demand, where values below unity indicate reduced evapotranspiration likely associated with water limitation (Allen et al., 1998). The manuscript has also been expanded to discuss how TSEB-derived variables and energy balance approaches can be integrated into crop water stress assessment frameworks and irrigation applications, including reference to alternative approaches such as CWSI.

Revisions in manuscript:

- Lines 192–195: Introduced crop water stress proxy ($K_s = ET/ET_o$)
- Lines 543–567: Added results and analysis of K_s across crops and time
- Lines 795–801: Expanded discussion of water stress detection using ET-based metrics. Added supporting references (Giardina et al., 2019)
- Lines 802–813: Added discussion of TSEB and energy balance approaches for crop water stress assessment and irrigation applications. Added supporting references (Sánchez-Virosta et al., 2025; Wanniarachchi and Sarukkalgige, 2022; Elfarkh et al., 2023; Ankela et al., 2026).
- Figure 3: Updated workflow to include crop water stress proxy (K_s)
- Figure 16: Added temporal analysis of K_s using EC (open/closed) and TSEB results, including multi-scale comparisons (field, footprint, stress zones)

Comment 6 – *Line 545: A Daily ET map is needed for irrigation scheduling, and an extrapolation technique using weather data can be used to upscale from hourly to daily ET. However, soil moisture and rainfall data are required for irrigation scheduling. In the literature, extrapolation techniques were assessed for ET derived from UAV data.*

Response: The initial focus of the study was on instantaneous ET estimation using UAV-derived inputs (LST, LAI, f_g) and relative within-field variability. In response to the reviewer's comment, daily ET was derived by upscaling instantaneous estimates using a reference ET fraction approach, enabling evaluation of practical applicability for water balance and irrigation contexts, as well as comparison with existing studies.

Revisions in manuscript:

- Line 192: Added daily ET upscaling methodology and validation against EC measurements
- Lines 537–587: Added new section presenting daily ET results and performance metrics. Added supporting reference (Cammalleri et al., 2014)
- Figure 3: Updated workflow to include upscaling to daily ET using reference ET fraction
- Figure 17: Added daily ET performance metrics (RMSE, R^2 , bias) for open and closed EC energy balance conditions

Comment 7 – *Using high-resolution UAV imagery allows for canopy and soil temperature pixel separation. TSEB-2T, using canopy and soil temperatures, reported better results than TSEB-PT. TSEB-2 T does not consider Priestley-Taylor formulation initialization. Why was the criterion to use TSEB-PT having high-resolution imagery?*

Response: The manuscript has been revised to clarify the rationale for selecting TSEB-PT over TSEB-2T. Additional discussion has been included to outline conditions where TSEB-2T may be beneficial and to justify its exclusion in this study.

Revisions in manuscript:

- Lines 84-90: Added explanation in the Introduction for selecting TSEB-PT over TSEB-2T. Added supporting reference (Kool et al., 2021)
- Line 769 – 778: Expanded discussion on the potential benefits and limitations of TSEB-2T, including its suitability under sparse vegetation conditions. Added supporting references (Li et al., 2019; Lun et al., 2026)

Comment 8 – *How was the shadow managed in the multispectral and thermal imagery, and how was the impact on TSEB results?*

Response: The manuscript has been revised to address the influence of shadowing on multispectral and thermal data and its impact on TSEB results. A discussion has been added describing potential biases, mitigation strategies, and why shadow effects were limited in this study due to acquisition timing and canopy conditions.

Revisions in manuscript:

- Lines 747 – 767: Added discussion on shadow effects, their influence on ET estimation, mitigation approaches, and the advantage of LiDAR-based inputs being largely independent of illumination conditions. Added supporting references (Mokhtari et al., 2021; Lu et al., 2022; Gao et al., 2023; Duran-Gomez et al., 2026; Aboutalebi et al., 2019)

Minor Comments

- *Line 42: The citation is missing a parenthesis*
 - The missing parenthesis has been added.
- *Line 115: Adding the flux footprint of the EC tower may explain the predominant winds on the study site*
 - *Flux footprints* are in the appendix and referenced on line 335-336 in the section 2.4.7 discussing the flux footprint used for validation
- *Line 236: Net radiation (Rn) is not the same as incoming solar radiation; line 147 shows incoming solar radiation as Rn*
 - Fixed variable definition on line 170

- *Line 293: there is no plot b) correlation of weather conditions with the difference (delta) between the thermal sensor and actual temperature of ground thermal targets for each date.*
 - Lines 354-356, Updated text to correctly reference the relocated Appendix figure.

Response to Reviewer 2

We thank Reviewer 2 for the thoughtful and constructive comments, including helpful suggestions and ideas. All revisions in the manuscript are highlighted in red. In this response, the reviewer's comments are presented in full (*in dark blue*), followed by a summary of the corresponding revisions with updated line numbers in the revised manuscript. The abstract and conclusions have also been revised to reflect the changes made in the manuscript.

Comment 1 – *It is unclear what resolution is used in the application of the TSEB model. The 15 cm resolution is very high and it is not clear how it can be used to define the inputs to TSEB. This needs to be clearly discussed.*

Response: Clarified the high-resolution rationale in the Introduction

Revisions in manuscript:

- Lines 70–75: Added that TSEB is originally used at coarser resolutions and to why we chose to use high resolution. Added supporting references (Jaafar and Sujud, 2025; Hoffmann et al., 2016; Nassar et al., 2020; Burchard-Levine et al., 2021)

Comment 2 – *Only compare ET and not the other energy balance components nor do they mention how they dealt with energy balance closure. Comparison with closed or unclosed H and LE should be discussed. Furthermore, an X-Y scatter plot comparing all 4 components for each crop type would be very helpful to the reader.*

Response: The manuscript has been revised to include evaluation of all surface energy balance components (R_n , H , G , and LE) and to address EC energy balance closure. Comparisons are now provided using both open and Bowen ratio closed EC fluxes. Following the reviewer's suggestion, X–Y scatter plots for all flux components have been added, replacing the original bubble plots.

Revisions in manuscript:

- Lines 335–342: Added energy balance closure methodology Added supporting references (Twine et al., 2000; Mokhtari et al., 2021)
- Lines 387–453: Added flux comparison results
- Figures 8 and 10 Added X–Y scatter plots for flux comparisons across crops
- Figures 9 and 11 Added RMSE and R^2 comparisons for ET under open and closed EC energy balance conditions
- Appendix tables updated with RMSE and R^2 metrics
- Added RMSE and R^2 comparisons for ET under open and closed EC energy balance conditions

Comment 3 – *There are also several fractional cover terms discussed but is confusing to the reader which ones are applied under the different crop conditions (e.g., pre and post senescence).*

Response: The manuscript has been revised to clearly distinguish between the different fractional cover terms and to clarify their use under varying crop conditions, including pre- and post-senescence.

Revisions in manuscript:

- Lines 232–249: Clarified FVC to GAI derivation
- Lines 258–262: Clarified f_g and f_c implementation
- Lines 264–273: Clarified the f_c derived by model.
- Line 299: notes that f_c is internally derived in the model
- Table 1 and Figure 4 Updated for consistency in terminology and usage

Comment 4 – *With such high resolution thermal and multispectral imagery, could the authors have also used the TSEB-2T version? If not, they should provide rationale in going with TSEB-PT.*

Response: The manuscript has been revised to clarify the rationale for selecting TSEB-PT over TSEB-2T. While TSEB-2T may offer advantages under sparse canopy conditions, TSEB-PT was selected for its more robust performance across crop types and phenological stages in this study.

Revisions in manuscript:

- Lines 84-90: Added explanation in the Introduction for selecting TSEB-PT over TSEB-2T. Added supporting reference (Kool et al., 2021)
- Line 769 – 778: Expanded discussion on the potential benefits and limitations of TSEB-2T, including its suitability under sparse vegetation conditions. Added supporting references (Li et al., 2019; Lun et al., 2026)

Comment 5 – *Some of the figures should be modified for better clarity. For example, in Figure 5 the authors should consider adding a 2nd y-axis to show the difference in LST_{OG} and LST_{TC} as the temperature range from 10 to 40 C significantly suppresses differences in the plots. The figures 8 and 10 would be more useful to the reader if they were shown as scatter plots (2 x 3 separating the two LST inputs versus EC observations and for LAI a 3x3 for the three LAI/f_g estimates) and distinguishing with symbols pre and post senescence. Also for both current figures 8 and 10 the symbols for $LST=LST_{OG}$ and $LAI=GAI, f_g=1$ are very faint and hard to see. Plus, the vertical dashed lines I believe indicate pre and post crop senescence but are not mentioned in the figure captions and should be a darker color (black?) so is easily visible to the reader. Finally, there are unexplained dashed light blue lines for the potato plots which are not described. However, I believe scatter plots would be much more useful to the reader and easier to evaluate differences with the EC data as scatter plots. On the other hand, I like the way the authors show the difference statistics for the different model output in figures 9 and 11. In Figure 13, the figures have an insert with a blue circle...seems out of place and not explained.*

Response: The figures have been revised to improve clarity, readability, and interpretability. Following the reviewer's suggestions, key figures have been updated, including the addition of ΔLST visualization and the use of scatter plots for flux comparisons. Figure annotations and captions have also been improved to clearly describe all elements.

Revisions in manuscript:

- Figure 5: Added a second y-axis showing ΔLST ($LST_{TC} - LST_{OG}$) to highlight thermal correction differences
- Figures 8 and 10: Replaced original bubble plots with X-Y scatter plots comparing fluxes under both open and closed EC energy balance conditions; senescence periods are indicated using lighter shading
- Figure 6 and 7: Updated vertical dashed lines to black for improved visibility and clarified their meaning in the captions
- Figure 13: Added figure index and caption clarification to describe the inset (zoomed area) and its location within the field

Comment 6– *Under section 4.5 Practical impacts and considerations for farming practices, the authors should go the extra mile and compute daily ET using the simple approach evaluated by Cammalleri et al (2014). This approach is used and tested in many applications even with UAV data (e.g., Nassar et al. 2021). I recommend the authors make a final calculation using this approach and compare with daily ET from the EC data using their best inputs. The daily ET is more relevant to farmers and for stress perhaps they can show these daily ET maps relative to reference crop or potential ET from FAO56 to highlight the stress area.*

Response: Following the reviewer's recommendation, the manuscript has been revised to include daily ET estimation by upscaling instantaneous UAV-based TSEB outputs using a reference ET fraction approach (Cammalleri et al., 2014). Daily ET estimates are now compared with EC-derived daily ET under both open and closed conditions. Additionally, a daily-scale stress proxy ($K_s = ET/ET_o$) is included to assess water limitation relative to atmospheric demand.

Revisions in manuscript:

- - Line 192: Added daily ET upscaling methodology and validation against EC measurements
- -Lines 537 -587: Added new section presenting daily ET results and performance metrics. Added supporting reference (Cammalleri et al., 2014)
- Figure 3: Updated workflow to include upscaling to daily ET using reference ET fraction
- Figure 17: Added daily ET performance metrics (RMSE, R^2 , bias) for open and closed EC energy balance conditions
- Lines 192–195: Introduced crop water stress proxy ($K_s = ET/ET_o$)
- Lines 543–567: Added results and analysis of K_s across crops and time
- Lines 795–801: Expanded discussion of water stress detection using ET-based metrics. Added supporting references (Giardina et al., 2019)
- Lines 802–813: Added discussion of TSEB and energy balance approaches for crop water stress assessment and irrigation applications. Added supporting references (Sánchez-Virosta et al., 2025; Wanniarachchi and Sarukkalige, 2022; Elfarkh et al., 2023; Ankela et al., 2026).
- Figure 3: Updated workflow to include crop water stress proxy (K_s)
- Figure 16: Added temporal analysis of K_s using EC (open/closed) and TSEB results, including multi-scale comparisons (field, footprint, stress zones)

Additional improvements beyond reviewer comments

In addition to the revisions requested by the reviewer, the manuscript has been further improved through:

- Title changed to be shorter and less specific. Also to include multi-sensor use.
- Abstract changed to include new additions to methods and results
- Lines 609–616: Expanded future work on emissivity correction, sensor integration, and satellite fusion
- Lines 632–644: Expanded discussion on structural (PAI) vs functional (GAI) LAI
- Lines 742 – 748: Additional future improvements from UAV with hyperspectral and SIF measurements
- Lines 772 -781: Expanded discussion on possible improvements with alternative resistance formulations.

- Lines 854 – 873: Additions to conclusion from new results (daily ET and stress proxy). Additional contribution with LiDAR as LAI input and added new future prospects section at end of conclusion.
- Lines 962 – 983: Added a new section of the appendix for formulations for energy balance closure, potential ET, upscaling to daily ET, water stress proxy.

New references added

The following references were added to strengthen the revised manuscript:

- Aboutaleb, M., Torres-Rua, A. F., McKee, M., Nieto, H., Kustas, W., & Coopmans, C. (2019). The impact of shadows on partitioning of radiometric temperature to canopy and soil temperature based on the contextual two-source energy balance model (TSEB-2T). *Proceedings of SPIE--the International Society for Optical Engineering*, 11008. <https://doi.org/10.1117/12.2519685>
- Acharya, B., & Sharma, V. (2021). Comparison of Satellite Driven Surface Energy Balance Models in Estimating Crop Evapotranspiration in Semi-Arid to Arid Inter-Mountain Region. *Remote Sensing*, 13(9). <https://doi.org/10.3390/rs13091822>
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- Brenner, C., Thiem, C. E., Wizemann, H.-D., Bernhardt, M., & Schulz, K. (2017). Estimating spatially distributed turbulent heat fluxes from high-resolution thermal imagery acquired with a UAV system. *International Journal of Remote Sensing*, 38(8–10), 3003–3026. <https://doi.org/10.1080/01431161.2017.1280202>.
- Burchard-Levine, V., Nieto, H., Riaño, D., et al. (2021). The effect of pixel heterogeneity for remote sensing-based retrievals of evapotranspiration in a semi-arid tree-grass ecosystem. *Remote Sensing of Environment*, 260, 112440.
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- El Hazdour, I., Le Page, M., Hanich, L., Chakir, A., Lopez, O., & Jarlan, L. (2025). A GEE TSEB workflow for daily high-resolution fully remote sensing evapotranspiration: Validation over four crops in semi-arid conditions and comparison with the SSEBop experimental product. *Environmental Modelling & Software*, 187, 106365. <https://doi.org/10.1016/j.envsoft.2025.106365>
- Flint, E. A., Hopkins, B. G., Svedin, J. D., Kerry, R., Heaton, M. J., Jensen, R. R., Campbell, C. S., Yost, M. A., & Hansen, N. C. (2023). Irrigation Zone Delineation and Management with a Field-Scale Variable Rate Irrigation System in Winter Wheat. *Agronomy*, 13(4). <https://doi.org/10.3390/agronomy13041125>
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- Jonard F., De Cannière S., Brüggemann N., Gentine P., Short Gianotti D. J., Lobet G., Miralles D. J., Montzka C., Pagán B. R., Rascher U., and Vereecken H. (2020). Value of chlorophyll fluorescence for quantifying hydrological states and fluxes: Current status and challenges. *Agricultural and Forest Meteorology*, 291: 108088.
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