Response to Reviewer 2

General comments

Yu et al present the ORCHIDEE-CROP model that incorporates a time-varying surface albedo that considers foliar yellowing and crop residue. The effect of crop residue on surface roughness, surface temperature, and surface energy partitioning was also analyzed. Overall, the work is solid and addresses effects not considered in current models, while it may benefit from some clarification on methods and interpretations. I suggest publication of the manuscript after minor revision.

[Response] Thank you so much for your time in reviewing our manuscript and for providing your constructive comments and suggestions. The valuable comments helped us improve the paper. Following the comments, our main revision is as below:

(1) Clarified the magnitude of impacts of foliar yellowing and residue covering on water and heat variables in the Abstract, and included the relative changes in targeted variables between the improved model and the initial version in the results sections; (2) Expanded the discussion of the uncertainty and spatiotemporal variability of residue impacts in sections 4.2 and 4.5; (3) Supplemented more details about the calibration of crop development and harvest timing in sections 2.2.5 and 2.3.

Please find our detailed responses to all of your comments below.

Major Comments

1. *In several places across the manuscript (e.g., L36), the manuscript claims a significant impact on surface energy balance. However, in most scenarios, the impact seems small (less than a few W/m2) to me, and the uncertainty is at similar magnitudes as the difference. I think the magnitude of the differences can be better addressed.*

[Response] We agree that the absolute changes in surface energy fluxes (i.e., LE and H) are generally modest (Fig. 4e and f) and at similar magnitudes as the uncertainty. However, these small values of the mean of differences across the sites mask substantial spatiotemporal variability, especially in residue effects. During the foliar yellowing period, the ~20-day increase in surface albedo (~0.02) only slightly perturbs the surface energy balance. At this stage, the balance between latent and sensible heat fluxes is primarily controlled by crop transpiration when the soil is invisible. Because the available surface energy remains nearly unchanged, total flux variations remain minor.

During the residue covering period, flux responses exhibit pronounced spatiotemporal heterogeneity with a relatively large standard deviation. Temporally, residue-induced albedo enhancement evolves with time. It peaks within the first 15 days and weakens as residues decompose (Figs. 3 and S4), producing short-lived yet locally significant perturbations in water and heat processes which lasts about 5-30 days after the peak and also persist for 1-2 months beyond residue removal through tillage or natural decomposition (Fig. S5 and S6). Spatially, variations in climate, soil properties and management practices amplify local differences in residue impacts. For example, we found that during the residue covering period, BE-Lon exhibits the largest mean relative decrease in LE in the improved model compared to the initial version (-27.69±11.62%), whereas the change at DE-Geb is minimal (-6.10±33.48%). This contrast arises because the higher soil moisture and sandy texture at BE-Lon support greater evaporative fluxes, whereas the limited soil water and clay-rich soil at DE-Geb favor energy dissipation as sensible rather than latent heat (Dumont et al., 2023; Buysse et al., 2023). Moreover, even with fixed 50% decrease of soil conductance and residue height parameters of 0.5 m (see sections 2.3.3 and 2.3.4), the model reproduces clear site-to-site variability in the magnitude and direction of residue effects on water and heat fluxes.

In addition, long-term simulations show the accumulated residue impact on soil moisture and soil temperature. The 10-year simulation under the drying climate scenario reveals a statistically significant cooling trend, despite a mean annual temperature decrease of only 0.3 °C (Fig. 5). This demonstrates that even modest instantaneous flux changes can produce meaningful long-term surface cooling effects.

Therefore, evaluating residue effects requires a context-specific approach that accounts for the interactions among climate, soil, and crop characteristics. Process-based land surface models provide an effective framework for such assessments at varying scales, as they explicitly represent the coupled biophysical and ecological mechanisms controlling surface energy and water exchanges. This approach provides an opportunity to guide residue management strategies under variable environmental settings, emphasizing the importance of this work.

We revised the manuscript to more accurately describe the strength of residue effects in the Abstract.

Lines 36-37: "This study underscores that crop pigmentation **has a minor influence on heat and water budgets, while residues moderately** modulate surface energy partitioning **with significant spatial heterogeneity**, and demonstrates the potential of its management for climate mitigation. "

We also expanded the discussions in sections 4.2 and 4.5 with the following sentences:

Lines 564-578: "I**t should be noted that the averaged difference in surface energy fluxes (i.e., LE and H) over all sites between the new and old models are generally modest (Fig. 4 (e) and (f)) and** at similar magnitudes as **model uncertainty, which masks the substantial spatiotemporal variability in residue effects during the residue covering period. Temporally, residue-induced albedo enhancement peaks within the first 15 days after harvest and weakens as residues decompose, causing short-lived but locally significant perturbations in water and heat fluxes (Fig. 3, Fig. S4-S5). The residue impact on the water-heat processes persists for an additional 1-2 months beyond residue removal through tillage or natural decomposition (Fig. S6). Spatial variations in climate, soil properties and management practices amplify local differences in residue impacts. For example, we found that during the residue covering period, BE-Lon exhibits the largest mean relative decrease in LE in the improved model compared to the initial version (-27.69±11.62%), whereas the change at DE-Geb is minimal (-6.10±33.48%). This contrast arises because the higher soil moisture and sandy texture at BE-Lon support greater evaporative fluxes, whereas the limited soil water and clay-rich soil at DE-Geb favor energy dissipation as sensible rather than latent heat (Dumont et al., 2023; Buysse et al., 2023). In addition, long-term simulations show the accumulated residue impact on heat budgets. The 10-year simulation under the drying climate scenario shows a low but statistically significant cooling trend, with a yearly average of -0.3 °C (Fig. 5). This demonstrates that even modest instantaneous flux changes can generate meaningful long-term surface cooling effects.**"

Lines 674-678: "[...], **evaluating residue effects requires a context-specific approach that accounts for the interactions among climate, soil, and crop characteristics. Process-based land surface models provide an effective framework for such assessments at varying scales, as they explicitly represent the coupled biophysical and ecological mechanisms controlling surface energy and water exchanges. This approach provides an opportunity to guide residue management strategies under variable environmental settings.** [...]."

2. *L231, L242: It would be good to explain how the calibrations were performed in the supplementary.*

[Response] We appreciate this suggestion for improving this analysis. For the calibration of crop development, it has been comprehensively described and published in Su et al. (2025, https://doi.org/10.1016/j.eja.2025.127723). To avoid unnecessary repetition, we did not reproduce all methodological details here. Instead, we now include a concise description of the calibration procedure in the revised manuscript with the reference of this paper:

Line 252-258: "The maturity and harvesting dates were decided by the growing degree days and grain water content in the crop development processes of the ORCHIDEE-CROP model. The threshold of meeting harvesting conditions was calibrated **following the procedure described by Su et al. (2025). Parameters governing the growing degree day requirements for key phenological stages were optimized using observed phenological records (planting, flowering, and harvest dates) from 2890 DWD climate stations across Germany (949 sites for maize and 1941 for wheat; https://opendata.dwd.de/climate_environment/). The optimal parameter sets for wheat and maize were identified by minimizing the root mean square error (RMSE) between simulated and observed harvest dates across all sites.**"

For the calibration of the duration between maturity and harvest, we run this model iteratively with a range of potential durations between maturity and harvest (from 5 to 40 days at 2-day increments). The duration that resulted in a simulated harvest date perfectly matching the observed harvest date was then selected for each site year. This approach ensures that the simulated phenology aligns closely with site-specific agricultural practices and environmental conditions.

We included this duration information in Supplementary Table 1, and supplemented the details in section 2.3 with the following sentences:

Line 265-270: "In addition, to align the total crop development period (from sowing to harvest) between simulations and observations at each site, the duration between maturity and harvesting in ORCHIDEE-CROP was calibrated using recorded harvesting dates at each site. **In each winter wheat year at each site, simulations were performed iteratively with potential maturity-harvest intervals ranging from 5 to 40 days at 2-day increments. The optimal duration for each case was identified when the simulated harvest date matched the recorded management date. The calibrated durations are summarized in Table S1.** "

3. *L312: The equation number seems incorrect*

[Response] We replaced the equation numbers from Eqs.15 and 19 to Eqs. 12 and 14 (Line 341).

4. *L355: How was the αsurf model trained? Random forest is mentioned here, but Section 2.4.2 describes a direct fitting of the parameters in Eqs. 13 and 14.*

[Response] Thank you for pointing us to this writing mistake. The α_{surf} training is based on polynomial regression rather than a random forest model based on data from 10 sites with 33 winter wheat site-years. We used a linear incremental function (Eq. 12) to fit α_{surf} increase during the foliar yellowing and the first 15-day residue covering periods, and an exponentially decreasing function (Eq. 14) to describe the α_{surf} decrease during the residue covering period (sections 2.3.1, 2.3.2 and 2.4). In addition, we corrected the text in section 3.1, where we referred to this procedure, by adding the following sentences:

Line 390-392: "The least squares regression in these two fitting models captures the mean tendency of the data but fails to reproduce extreme variations, as it minimizes average errors rather than explaining outliers."

5. *Figure 4: It would be good to show the relative difference in the main text or supplementary to provide more context.*

[Response] We added the relative difference of E_{soil}, T_{surf}, LE and H between the new and old models in section 3.2-3.4, Please see the revised manuscript.

Here we give a modified example (**Lines 420-426**): "ORC-AE simulates slightly lower soil evaporation (E_{soil}) during foliar yellowing and residue covering periods than the standard version of ORCHIDEE-CROP (ORC-D), with averaged decreases of -0.01±0.04 mm d^{-1} **(-3.07±13.00%)** and -0.11±0.14 mm d^{-1} **(-13.34±32.60%)**, respectively (Fig. 4a). The effects of soil conductance (β_4) and soil roughness(Z_0) reduced E_{soil} on average by -0.01±0.03 mm/d **(-2.86±9.91%)** and -0.09±0.12 mm d^{-1} **(-9.69±38.16%)** (ORC-E) during foliar yellowing and residue covering periods, respectively. Impacts on α_{surf} alone cause reductions of respectively -0.01±0.04 mm d^{-1} **(-2.30±15.50%)** and -0.06±0.10 mm d^{-1} **(-9.59±22.43%)** (ORC-A) for the same periods. The influence of crop residues on E_{soil} disappears within 40 days after residue coverage (Fig. S5a, Fig. S6a)."

Reference

Buysse, P., Depuydt, J., and Loubet, B.: ETC L2 ARCHIVE, Grignon, 2022-12-31–2023-09-30, ICOS RI, doi:10.18160/jU9ftXkRFqo-dc91cDfOYuA8, 2023.

Dumont, B., Bogaerts, G., Chopin, H., De Ligne, A., Demoulin, L., Faurès, A., Heinesch, B., Longdoz, B., Manise, T., and Orgun, A.: ETC L2 ARCHIVE, Lonzee, 2022-12-31-2023-09-30, ICOS RI, https://doi.org/10.18160/JmEjmkD1hSr4YIuo5Uu-L69a, 2023.

Su, Y., Lauerwald, R., Makowski, D., Viovy, N., Guilpart, N., Zhu, P., Gabrielle, B., & Ciais, P. Future warming increases the chance of success of maize-wheat double cropping in Europe. European Journal of Agronomy, 170, 127723. https://doi.org/10.1016/j.eja.2025.127723, 2025.