Response to Reviewer 1

I have read this manuscript with interest. The study is well written, clearly illustrated, and easy to follow. It convincingly highlights the importance of incorporating daily bare soil albedo information into land surface and agroecosystem models in order to improve the simulation of short-term thermal and moisture dynamics. This is particularly relevant, as static or climatological representations of bare soil albedo may limit the ability of models to capture rapid transitions associated with soil wetting-drying cycles.
Overall, I the manuscript is of very good quality and can be accepted after some minor revisions.

[Response] We thank the reviewer for their positive assessment and are grateful for their encouraging comments on the quality, clarity, and relevance of our study. Please find our point-by-point responses to reviewer's comments below.

General comments

1. I feel that the manuscript would benefit from a clearer and more explicit illustration of the relationships between soil moisture, soil texture, and albedo, which are mentioned in the abstract, objectives, and discussion (see also L391, L429, L455 and following).

[Response] Following the reviewer's suggestion, we have revised Introduction and section 4.2 to clarify the relationship between soil moisture, soil texture, and albedo.
Lines 42-49: "Bare soil albedo is controlled by a combination of intrinsic soil properties **and varying environmental conditions (He et al., 2019). Soil properties,** including texture, mineral composition, roughness, organic matter content, and bulk density **determine the optical characteristics of soil surface (Matthias et al., 2000, Cierniewski et al., 2018) and soil hydrological properties (Han et al., 2023). As a result, they affect soil albedo directly and indirectly (via modulating the relationship between albedo and water availability). Soil moisture and solar radiation geometry further modulate the short-term temporal variability of soil albedo by altering the amount and direction of the observed reflected solar radiation** (Hapke, 1981; **Gascoin et al., 2009, Badía et al., 2016**)."
Lines 397-402: "**The decomposition of bare soil albedo into spatial and temporal components provides a framework for interpreting its physical controls. Intrinsic soil properties affect bare soil albedo by establishing the optical characteristics of the soil surface and regulating soil-water interaction**, while soil moisture dynamics **and radiative geometry control the temporal fluctuations of the observed bare soil albedo.**"
Lines 416-418: "**The magnitude and duration of these responses depend on the soil water retention capacity (Post et al., 2000), resulting in different α_{bs} responses to the same soil moisture change for different soil textures**".
Lines 424-432: "Soil properties explain much of the stable spatial structure onto which moisture and geometry act (Rizzo et al., 2023). **For example, soil texture influences bare soil albedo through both direct and indirect pathways. Particle size, mineral composition directly influence soil optical properties (e.g., surface color and scattering characteristics), thereby establishing the inherent bare soil albedo. In addition, these properties related with texture regulate the soil hydraulic behaviour (Sadeghi et al 2018)**"
Lines 448-451: "**Overall, these controls are interacting components governing bare soil albedo rather than independent drivers. Among the intrinsic soil properties, soil texture plays an important role because it establishes the background optical characteristics of the soil surface and regulates soil-**

water interactions, while soil moisture and solar geometry determine the short-term variability of the observed α_{bs}."

2. As a 1st step I suggest moving Supplementary Figure 7 (linear relationship between site-level bare soil albedo and soil moisture) into the main text, as it directly supports some of the key arguments of the study.
Along the same lines, it would be useful to provide some basic contextual information for the validation sites, such as pedoclimatic conditions, crop rotations, and fallow periods. This would help the reader better understand the representativeness and variability of the dataset.

[Response] Following the reviewer's suggestion, we moved Fig S7 into section 3.3. We also added a summary table (Table S1) describing the validation sites, including their climatic conditions, dominant crop rotations, and typical length of fallow periods. Regarding fallow periods, we note that quantifying a fixed period for each site is difficult, as it varies among years depending on crop rotation and management practices (e.g., cover crops and tillage operations). Therefore, we provide the average fallow period duration in 2018-2020 estimated from the crop calendars reported for each site.

Table S1. Basic contextual information for the validation sites

Site	Latitude (°)	Longitude (°)	Mean annual air temperature (°C)	Mean annual incoming shortwave solar radiation (seasonal maximum and minimum range) (W m^{-2})	Mean annual rainfall (mm)	Mean annual soil water content (seasonal maximum and minimum range) (%)	Mean annual cloud cover (%)	Soil type	Silt, clay and sand contents (%)	Crop rotations	Averaged length of fallow periods
BE-Lon	50.55	4.75	10.2	110.2 (22.8-267.9)	742.6	29.5 (13.4-40.3) (3-layer soil with depth of 25 cm)	63.2	Luvisol	78.1, 14.7, 7.2	4-year rotation: sugar beet-winter wheat-potato-winter wheat	60-90 days
FR-Lam	43.50	1.24	13.4	157.0 (43.8-283.4)	677.0	32.8 (11.1-51.1) (3-layer soil with depth of 30 cm)	55.1	Calcaric Fluvisol	31.8, 52.9, 15.3	2-year rotation: winter wheat-irrigated maize	90-180 days
FR-Aur	43.55	1.11	13.1	161.3 (40.3-280.6)	652.1	27.4 (13.0-39.1) (3-layer soil	55.1	Calcaric Cambisol	42.5, 39.4, 18.1	4-year rotation: winter wheat-	60-120 days

						with depth of 30 cm)				rapeseed - barley- sunflower	
FR-EM 2	49.87	3.02	11.2	137.3 (24.1-269.5)	616.7	26.6 (18.6-33.3) (3-layer soil with depth of 75 cm)	60.0	Luvisol	74.4, 18.7, 6.9	6-year rotation: spring pea-rapeseed-winter wheat-spring barley-maize (or sugar beet)-winter wheat	60-90 days
DE-RuS	50.87	6.45	11.2	130.0 (25.0-276.8)	548.9	20.6 (8.2-36.7) (1-layer soil with depth of 5 cm)	60.1	Luvisol	32.0, 53.0, 15.0	5-year rotation: sugar beet-winter wheat-winter barley-rapeseed-potatoes	60-120 days
DE-Geb	51.10	10.91	9.2	126.0 (20.7-275.3)	521.2	20.1 (8.4-31.0) (3-layer soil with depth of 10 cm)	60.9	Chernozem / Phaeozem	32.0, 53.0, 15.0	8-year crop rotation: winter wheat-potatoes-rape-winter barley-sugar beet-peppermint-durum-spring wheat	30-90 days
DE-Kli	50.89	13.52	8.1	130.6 (17.2-290.2)	782.5	25.3 (8.7-36.4) (1-layer soil with depth of 5 cm)	59.4	Cambisol	26.6, 46.9, 26.5	5-year crop rotation: rapeseed-winter wheat-forage maize-	30-60 days

										spring barley-winter barley-occasional catch crop	
CZ-KrP	49.57	15.08	7.1	133.5 (26.4-291.0)	620.0	17.4 (8.2-24.2) (3-layer soil with depth of 20 cm)	57.7	Cambisol	44.0, 18.0, 38.0	winter wheat-spring barley-rapeseed-temporary leys	60-90 days
Ultuna in Uppsala in Sweden	59.82	17.65	8.4	119.0 (6.1-290.2)	519.0	-	62.6	Eutric Cambisol	40.0, 42.0, 18.0	winter barley-spring wheat-oats-rye	117 days (the year of 2019); 145 days (the year of 2020)

'-' means no data

Specific comments

3. L238 and following:
Could you add a notion of a gradient in your evaluation dataset? The dataset includes only eight sites, and it would strengthen the manuscript to better demonstrate that these sites cover a meaningful pedoclimatic gradient. I recommend to better describ how the selected sites represent variability in:
soil types (e.g. texture, possibly linked to soil color), climatic conditions (e.g. radiation, cloud cover), management practices (e.g. crop rotations, fallow periods), seasonal dynamics (as proxies for variations in radiation intensity, cloud cover, and soil moisture throughout the year; see also L271).

[Response] Following the reviewer's suggestion, we summarized the climatic, soil, and management characteristics of each validation site in Table S1 (see above) and described the broad pedoclimatic gradient represented by these sites in Section 2.3:
Lines 253-260: "**The selected eight sites encompass a broad pedoclimatic and management gradient across European croplands (Table S1). They represent contrasting soil conditions, including Luvisol, Fluvisol, Cambisol, and Chernozem/Phaeozem, with the ranges of silt, clay and sand contents from 26.6 to 78.1 %, from 14.7 to 53.0 %, and from 7.2 to 38.0 %, respectively. These sites also cover diverse climatic conditions in air temperature, incoming shortwave solar radiation, precipitation and cloud cover at annual scale. Seasonal variability in solar radiation and soil moisture (characterized by the seasonal minimum and maximum values in Table S1) captures the range of environmental conditions experienced across seasons. In addition, these sites implement different agricultural management practices, including crop rotations of 2-8 years and bare soil periods occurring mainly in spring, autumn and winter (approximately 30-180 days, Fig. S2).** "

4. L238 please cite Figure 3

[Response] Following the reviewer's suggestion, we cited Fig 3 in section 2.3:
Line 242-245: "Five types of α_{bs} datasets were utilized to evaluate the performance of the final spatiotemporal albedo predictions ($\alpha_{bs,\,RF}$) at seven ICOS European cropland sites (BE-Lon, FR-Lam, FR-

Aur, FR-EM2, DE-RuS, DE-Geb, DE-Kli), one European Fluxes Database Cluster (EFDC) European cropland site (CZ-KrP), and one Swedish cropland site in Uppsala, and the overall European cropland regions during bare soil periods (**Fig. 3**, Table 3)."

5. Figure 5 as non of the values is over 0.4 may be adjust the Figure to y axis 0-0.3. Figure 6 as non of the values is over 0.4 may be adjust the Figure to y axis 0-0.3

[Response] Following the reviewer's suggestion, we adjusted the range of y-axis to 0-0.3 in Figures 5-6.

Response to Reviewer 2

The authors of this manuscript present a novel method to determine the spatiotemporal albedo variation for European cropland without vegetation cover or litter at field-scale. This method requires significant skill in processing satellite data and combining it with other cartographic data. The authors argue that albedo of bare arable fields, due to the large total area of cropland worldwide, can significantly influence the radiation flux between the atmosphere and the Earth's surface. First, the authors identified periods when cropland is bare and their albedo (abs) values were extracted from the 10-meter, 5-day Sentinel-2 reflectance products obtained from 2018-2020 after filtering clouds and snow cover using four spectral indices: NDVI, NBR2, GI, and NBR. The thresholds for these indices for extracting bare soils were established based on the reflectance spectra of over 8,000 soil samples from around the world. The Lucas 2018 Copernicus land dataset and 10-meter ESA WorldCover map were also used in this stage. Next, two random forest regression models were trained to determine during bare soil periods spacial distribution and temporal anomalies abs at the European cropland scale. This first model predicted the spatial distribution of the temporal average of abs, using the following input features: temporal-averaged local solar zenith angle (LSZA), soil organic carbon, sand and clay contents, bulk density, pH, temporally averaged soil moisture (SM) and elevation. However, this second model predicted the temporal variation of abs using as input features: LSZA, time of day, days of year, relative SM anomaly and the predicted values of spatial abs provided by the first model. A dataset containing almost 76,000 values of the temporal average of abs was used to train and test the first model, and a dataset containing almost 57,000 values of the temporal anomaly of abs was used to train and test the second model. Finally, the abs values predicted by these models were compared with existing datasets at local and European scales. Five types of abs datasets at seven European cropland sites from Belgium, France, Germany and the Czech Republic were used to evaluate the performance of the final spatiotemporal abs predictions for all European cropping regions during bare soil periods.

These models successfully reproduced both spatial patterns and temporal variability of abs across European arable lands, allowing the identification of bare soil factors that most strongly influence the variability of their abs values. It was found, as in previously published papers, that the spatial distribution of abs of bare soils depends primarily on LSZA, averaged SM and elevation, while their temporal variation depends on instantaneous SZA, and SM anomalies. My research also demonstrates that the short-term variability of bare soils abs depends on the soil surface roughness shaped by agricultural tools and its modification by heavy rainfall. The spatiotemporal average of abs, 0.15 ± 0.01 for European arable land in 2018–2020, is similar to its previously determined value of 0.15 to 0.22 obtained from over 7,500 topsoil samples across Europe in 2022. The multi-year spatial pattern established in this manuscript shows broad west-to-east and north-to-south gradients, corresponding to the main soil zones, with darker surfaces where organic matter content is higher and lighter surfaces where carbonates predominate. The Iberian Peninsula, southwestern and southern France, and the coastal regions of the Mediterranean are characterized by light soils with abs of 0.18-0.20. In contrast, soils in north-central and eastern Europe (e.g., Germany and Poland) are dark, with abs of 0.12-0.15. The authors of this manuscript have found that the prediction of daily abs values of bare soils also depends on the type of units classifying them. They report that the errors in prediction abs were smaller for bright Alfisols in Belgium and France than for dark Mollisols in Germany and Inceptisols in the Czech Republic. Therefore, in similar studies, the influence of soil classification should also be taken into account.

[Response] We thank the reviewer for their thorough and accurate summary of our methodology and findings. We also appreciate the reviewer highlighting the role of soil surface roughness and its modification by heavy rainfall as a contributor to short-term albedo variability, and the consistency of our derived European-scale average (0.15 ± 0.01) with previously published values. Regarding the influence of

soil taxonomic class on prediction accuracy (better performance for bright Alfisols versus dark Mollisols/Inceptisols), we agree this is an important point and have ensured it is appropriately emphasized as a consideration for similar future studies (see response 1) .

MAJOR COMMENT

1. In my opinion, the daily abs prediction for bare soils would be more accurate if the authors of this manuscript also included the roughness of the bare soils among their analyzed soil properties, resulting from the use of specific agricultural tools, modification of this roughness after heavy rainfall, and the formation of a thin crust, primarily on heavy soils. The omission of soil roughness in this study seems strange to me, especially since the authors mentioned this property as significantly affecting the albedo of bare soils in the "Introduction" (line 43).

[Response] We agree that soil roughness, influenced by agriculture practices, rainfall events and crust formation, is an important determinant of bare soil albedo (Matthias et al., 2000; Cierniewski et al., 2023), however there is a lack of gridded soil roughness reconstructions required for the upscaling. We discussed the implication of the omission changes in soil roughness but admit it was rather limited (See section 4.3). Following the reviewer's suggestion, we now extended the discussions. In addition, we note that some selected predictors included in our RF framework, such as soil texture (sand and clay content) and bulk density, could partly capture the variability of soil roughness (Herodowicz-Mleczak et al., 2022; Rizzo et al., 2023), but the quick change of roughness induced by agriculture practices, rainfall events and crust formation cannot be resolved. We have clarified the missed soil roughness in section 4.3.

Line 483-489: "**One important example is varying soil surface roughness which varies according to agriculture practices, rainfall events and crust formation. Its impact on α_{bs} was not explicitly represented as the required spatiotemporal datasets of soil roughness are currently unavailable at the European scale. In addition, assessing the impact of temporal variation of soil roughness on predicted α_{bs} at site scale remains challenging as no soil roughness measurements are available at the evaluation sites. Our RF framework relies on intrinsic soil properties that may partially capture roughness-related variability (Herodowicz-Mleczak et al., 2022; Rizzo et al., 2023) but cannot explicitly resolve the effects of agricultural practices, rainfall-induced smoothing, or soil crust formation.**"

MINOR COMMENTS

I have found a certain disagreement between references in the list of "References" and references inside of the manuscript text. The following items in the "References" list, Carrer et al. 2010, Jr et al. 2007, and Liu et al. 2002, are not referenced in the text. Also, several items mentioned in the text, Carrier et al. 2018, Charles et al. 2007, Liu et al. 2023, and Liu et al. 2002, are not referenced in the "References" list.

[Response] We apologise for the misleading information in the citations and reference list. We have carefully checked all references and made the following corrections:

- The unreferenced entries 'Carrer et al. 2010, Jr et al. 2007, and Liu et al. 2002' have been removed from the reference list.
- 'Carrier et al. 2018' has been added to the reference list.
- The citation 'Charles et al. 2007' in the manuscript was a typographical error and has been corrected to Garten et al., 2007, which has also been included in the reference list.
- The citation "Liu et al. (2023)" referred to Lin et al. (2022) in Section 2.1.1. This has been corrected accordingly.

What the authors have presented in this manuscript significantly complements the existing numerical data on the spatiotemporal variation of daily albedo in European bare soils. Therefore, I recommend publication of this manuscript in the journal "Biogeosciences," taking into account only these minor comments. I believe that incorporating this major comment of mine into the revised manuscript will not be possible.

Reference

Herodowicz-Mleczak, K., Piekarczyk, J., Kaźmierowski, C., Nowosad, J., & Mleczak, M. (2022). Estimating soil surface roughness with models based on the information about tillage practises and soil parameters. Journal of Advances in Modeling Earth Systems, 14, e2021MS002578. https://doi.org/10.1029/2021MS002578