Reply to Anonymous Referee #2

Review of" Drivers of soil organic carbon from temperate to alpine forests: a model-based analysis of the Swiss forest soil inventory with Yasso20".

Authors analyzed significance of soil properties especially missing organo-mineral (OM) interactions on mismatch between the soil organic C (SOC) stocks measured in Alps and their modeled counterparts estimated with Yasso20 model. The study itself is interesting and relevant.

The conclusion is in line with the expectations of the theoretical set up of the analysis. Authors conclude that the model failed to estimate SOCs in regions where OM is relevant mechanism of total SOC accumulation and where dependency of decomposition on precipitation could not capture its reduction related to higher soil moisture levels. Authors thus demonstrate that the model indeed fails to estimate precisely the SOC variability and conclude that if the model is applied in Alps, then it needs further development. This is known in literature and not new.

What is new is nicely demonstrating where the model **(applied as in this study)** fails in Alps and how much it fails. Simplified, these are the soils with ph <5 showing Fe correlation to SOC and ph > 5 showing Ca correlation to SOC, and soils with MAP > 1400 mm.

Author's response

We thank the Anonymous Referee 2 for the constructive comments and suggestions, which helped to improve the quality and clarity of our manuscript. We have considered each of your remarks and modified the manuscript accordingly. You can find below our responses to all your comments.

Reviewer comment

However, authors also demonstrate that the SOC discrepancies between measurements and Yasso20 could be estimated more precisely with statistical models (explaining about 50% of variance). Although, how much of total variance is explained in combination of Yasso + statistical models is not known. The final conclusions revolve about findings expected from the analysis setup. The motivation why SOC needs to be evaluated in combination of statistical and process models is not clear.

Author's response

Thank you very much for your suggestion. In this study, we make use of the deviations between Yasso20-simulated SOC stocks and measured SOC stocks to more clearly disentangle the main drivers of SOC stocks across an extensive Swiss forest soils dataset. Since Yasso is a simple soil C model driven by litter inputs and climate, deviations between simulated and measured SOC stocks can be mostly related to drivers of SOC stocks not accounted in the models, such as mineral soil properties, which are not explicitly implemented in Yasso. For this reason, we have sequentially analyzed the Yasso deviations by statistical model, which allows us to evaluate the effects of different predictors on Yasso deviations.

Although a combined approach – directly coupling Yasso with a statistical model - would be very promising since it will allow to incorporate predictors that are not explicitly included in the Yasso model (e.g. mineral soil properties), this would be beyond the focus of this manuscript. As a first step in this direction, we here demonstrate what are the: (1) main drivers of SOC stocks, and (2) main drivers of Yasso20 deviations for the Swiss forest soils. This could contribute to further improve Yasso in future works.

We have now clarified the rationale for using Yasso followed by statistical analysis at line 69-72 in the introduction:

"Here, we aimed to identify the main factors controlling SOC stocks in Swiss forest soils across a large gradient of climate, soil biogeochemistry and forest types. To disentangle the main drivers of SOC stocks, our main approach was to (1) simulate SOC stocks in forest soils by Yasso20, driven only by litter input and climate, and (2) statistically analyze the deviations between Yasso20-simulated and measured SOC stocks. This allows to evaluate the importance of mineral-driven SOC stabilization, since mineral soil properties are not explicitly implemented in Yasso."

We have added at line 426 in the discussion the suggestion of a combined approach of Yasso and statistical model:

"*A combined approach – directly coupling Yasso with a statistical model - would allow to account for additional parameters (as mineral soil properties) that are currently not included as model drivers but are known to be important factors controlling SOC stabilization."*

Reviewer comment

All mismatch between Yasso and measurements of SOC is blamed on Yasso missing relevant processes in the model structure of decomposition, though the litter C input itself which is the most essential driver of Yasso modeled SOC was estimated using rather simple imprecise approach with high level of uncertainty. **Given that the C inputs were estimated with low precision (litter inputs C quantity represented average for all species, litter input C quality differing only between conifers and broadleaves, and C input representing rather large spatial unit of 0.25 km2 derived from last 20 years compared to soil samples representing much smaller unknown unit cc 10 m2 representing SOC development changes of 1000+ years?) this should be taken into consideration when interpreting the modeled SOC data. At present state, the study is biased by ignoring impact of imprecise estimates of C input data used to run Yasso.**

Author's response

Thank you very much for your remark. We are aware that NPP represents an approximation of the productivity at each site and a proxy of long-term C input to the soil. Unfortunately, no stand inventory or litter input measurements were available at the sampled sites. Nonetheless, our approach to use NPP (here derived from Terra and Aqua MODIS satellite 500-m resolution) as input of the soil C model Yasso (see line 150) is consistent with the approach of published SOC model applications (Abramoff et al., 2022; Pierson et al., 2022), and with the current Yasso20 calibration (Viskari et al., 2022), where NPP is used as model input.

Considering that NPP represents an approximation of long-term litter C input to the soil, we address the limitations of this satellite approach in the updated manuscript. In addition, we discuss that terrestrial-based methods may also lead to biased estimates of litter inputs, e.g. due to the application of country-specific allometric equations or due to underestimates of C inputs from rhizosphere or understory vegetation. Both satellite- and terrestrial-based approaches to estimate litter inputs are normally obtained from the last few decades of measurements, while SOC turns over on decadal to millennia timescales.

Despite the difficulties with any approach in estimating C inputs, we are certain that the large-scale pattern in C inputs across Swiss forests with MATs ranging between 2 and 12°C and MAPs ranging between 400 and 2200 mm is robust. Therefore, also the magnitude of the differences between regions explored here appears robust.

We have now expanded and clarified the limitations of litter input estimates at line 413 in the discussion, and added Figure S1a to the supplement:

"*Satellite-derived NPP is here used as input for Yasso simulations of SOC stocks at steady state. Since direct measurements of forest stands and detailed information of soil C inputs are often lacking at larger scales - as in this study - the use of NPP as a proxy of long-term litter C input to the soil is consistent with SOC model applications at the regional and global scales (Abramoff et al., 2022; Pierson et al., 2022), as well as in the calibration of Yasso20 (Viskari et al., 2022). We are aware that litter input derived from satellites can be uncertain, thus potentially contributing to the observed discrepancies between simulated and measured SOC stocks at the site level. In fact, the fine scale variability in litter inputs cannot be captured by satellite-derived NPP estimates given (1) the larger pixel size of MODIS (500 m x 500 m) compared to the site scale of the soil sampling, and (2) the partitioning into tree components using average allocation factors, due to the lack of data at the site level. Satellite-derived NPP may have resulted in an overestimation of the litter input in regions with intensive forest management as in the Plateau, since small-scale disturbances such as thinning are not well detected by satellite estimates (Neumann et al., 2015; Park et al., 2021). Lastly, forests allocate a portion of NPP not only to fast-cycling components that are annually returned to the soil (i.e. fine roots and foliage) but also to components with slower turnover time such as stems and branches. Nevertheless, the satellite NPP approach proves to be a reasonable proxy of the large range of forest productivity across Swiss forests, i.e. ranging from 0.3 kg C m^{-2} yr^{-1} in the Alps to 0.8 kg C m^{-2} yr^{-1} at the warmest sites (see **Fig. S1a**), which is consistent with the gross volume increment shown across different regions in the Swiss NFI (Brändli et al., 2020). Moreover, at the 18 sites of the long-term forest monitoring program LWF, the mean NPP over the period 2001-2010 based on the satellite approach amounted to 0.49±0.04 kg C m^{-2} yr^{-1} as compared to 0.46±0.05 kg C m^{-2} yr^{-1} estimated by the terrestrial approach for the same period (Etzold et al., 2014).*

Similarly, terrestrial methods based on forest inventories may lead to uncertain estimates of litter inputs. These uncertainties mostly relate to (1) country-specific allometries and expansion factors used to estimate tree biomass, (2) turnover times applied to obtain the litter inputs, and (3) failing to appropriately estimate inputs from fine roots and understory vegetation, which remain severely unconstrained despite their major contribution to forest soil C inputs (Didion, 2020; Neumann et al., 2020)."

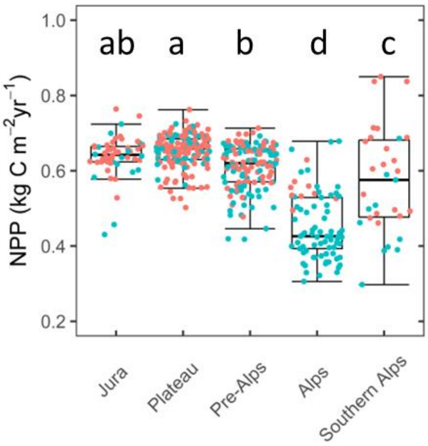

***Fig. S1a**. Net primary production (NPP) across Swiss forest regions, excluding waterlogged soils. Total n sites = 468. Letters indicate significantly different across regions, based on ANOVA followed by Tukey's test with P < 0.05.*

Reviewer comment

From the study it is difficult to understand whether it makes sense at all to use Yasso model. Although, if Yasso's decomposing of fraction of NPP explains anything than it is somewhat hinted that the model combination would yield better results than statistical models only. The main strength of combination of Yasso and statistical models over only statistical models is, however, the potential for modelling not only SOC stocks but also their changes over time (needed for estimating of ecosystem C fluxes in warming climates).

Author's response

To evaluate the effects of the main drivers of SOC stocks, our approach was to analyze Yasso deviations from measured SOC stocks using a statistical model. An improvement of Yasso may represent the next step. Despite the regional differences, Yasso20 captured the average SOC stocks for Switzerland. Please also refer to our *Author's response* above. As reported in the manuscript at line 432-433, we do not simulate here SOC stock changes, since no repeated SOC stock measurements were available at the sites.

In addition to the clarification in the introduction regarding the rationale for using Yasso followed by statistical analysis (at line 69-72, see above), we also added a sentence to facilitate result interpretation at line 176:

"Yasso20 deviations (simulated minus measured values of total SOC stocks) were tested using linear mixed-effect models with the nlme package, version 3.1–160 (Pinheiro et al., 2022) to assess effects of the main drivers of SOC stocks on model discrepancies".

Reviewer comment

In theory in ideal application of Yasso, the litter input C quantity and quality should reflect implicitly the site environmental conditions including the soil properties. However, from the analysis here it could be expected that litter inputs represented only the average for the region and thus the SOC estimates also only represent the average and could not be expected to show the small-scale variability. For example, it can be expected that if you plot derived C inputs on 2^{nd} axis in Fig.3 these would be only similar averages for different regions with not much variation as modeled SOCs, unlike variation seen in measured SOCs.

Author's response

While we agree with the reviewer that Yasso ideally captures litter inputs driven by environmental variables, it cannot capture all effects of soil properties on SOC stocks that lead to SOC stabilization in the soil (mineralogy) or suppress decomposition (anaerobic conditions) as they are not explicitly included in the model.

We are also aware that the fine scale variability in litter input cannot be fully detected by satellite-derived NPP estimates given the larger pixel size of MODIS (500 m x 500 m) (see *Author's response* above, and the changes in the manuscript already reported above). However, the satellite NPP approach still provides a proxy of forest productivity across Swiss forests, being able to show a large productivity range across Switzerland and statistical differences across Swiss regions (see added **Fig. S1a**), which is consistent with the productivity trend across Swiss forest regions (Brändli et al., 2020). Given the low temperatures occurring in the least productive region (i.e. the Alps) – leading to slower SOC decomposition – and the high temperature at the most productive regions – leading to faster SOC decomposition – differences in simulated SOC stocks across regions were rather limited (see added **Fig. S1b**).

We have added a supplemental figure which show the differences in NPP across regions (see new Fig. S1a, b below):

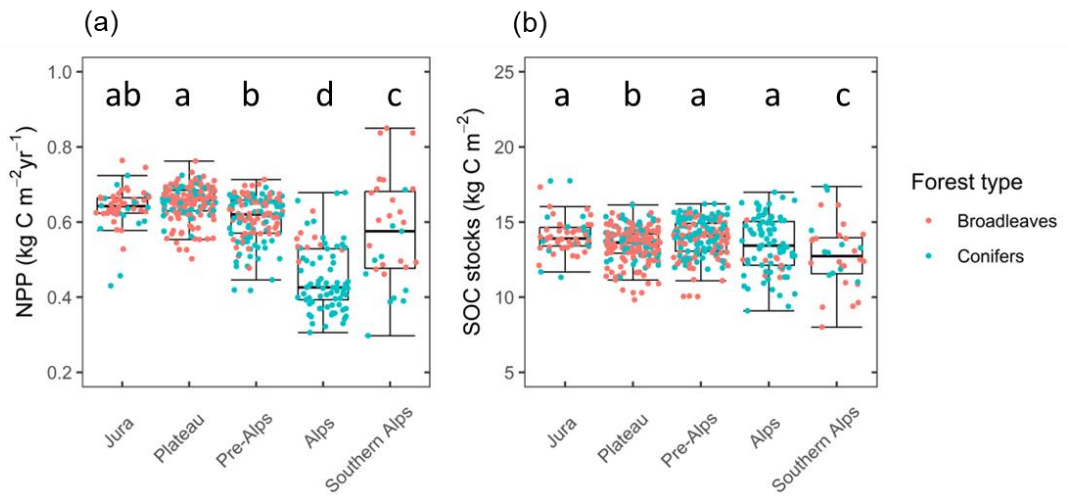

***Fig. S1**. Net primary production (NPP) (a), and Yasso20-simulated SOC stocks (b) across Swiss forest regions, excluding waterlogged soils. Total n sites = 468. Letters indicate significantly different across regions, based on ANOVA followed by Tukey's test with P < 0.05.*

Reviewer comment

However, the main message is correct, as it demonstrates that Yasso model structure needs development for application in Alp and thus should account for interaction with minerals and limitation of decomposition with excessive moisture. Discussion claims that Yasso20 also fails due to missing moisture limitation (which is known) but does not notice that dependency on moisture was evaluated with Yasso07 (Tupek et al., 2024) and could have been already applied here instead of precipitation.

Author's response

Thank you very much for your suggestion of this promising approach to include soil moisture as model driver in Yasso, which can be especially useful for peatland forest C modelling (Ťupek et al., 2024). Given that the moisture modifier of Yasso07 was developed specifically for nine sites in a boreal forest–mire ecotone in Finland, the applicability of this approach would require more tests in a larger number of experimental study sites covering Swiss forests, before being applied to this large Swiss forest soil dataset. This would go beyond the aim of this paper.

We have taken your remark into account in the manuscript at line 376-378:

"*this could be resolved in the future by including soil moisture at monthly time steps as model driver, or by applying a moisture modifier as shown in a boreal forest–mire ecotone in Finland for Yasso07 (Ťupek et al., 2024), or by coupling Yasso to a soil water model (Guenet et al., 2024).*"

Reviewer comment

My main concern is that the relation of modeled SOCs on poor litter input estimates should be elaborated in the paper to separate the mismatch in measured and modeled SOCs due to Yasso model structure (misrepresented decomposition rates) and due to misrepresented C inputs. Showing that NPP did not correlate with SOCs (Tabe 2, and Fig. 3) does not help with confidence in estimated C inputs (which were not shown). Although, I recognize enormous work done and appreciate that the data used in the analysis was made openly available, the lack of confidence in litter input is the main weakness that requires clarifying in major revision before the paper can be accepted.

Author's response

Thank you very much for your comment. We have now elaborated in the manuscript that the discrepancies in the model residuals (simulated – measured SOC stocks) can also be related to uncertain litter input estimates (see *Author's response above*), in addition to the lack of implementation of soil properties and waterlogging processes in the current model formulation. Currently, we cannot fully disentangle the two components of uncertainties e.g. from litter input estimates and lack of soil processes representation in the model, but we have considered the uncertainty derived from litter input estimation by adding an additional paragraph to the manuscript.

We have now expanded and clarified the limitations of litter input estimates at line 413 in the discussion, and added Figure S1a to the supplement:

"*Satellite-derived NPP is here used as input for Yasso simulations of SOC stocks at steady state. Since direct measurements of forest stands and detailed information of soil C inputs are often lacking at larger scales - as in this study - the use of NPP as a proxy of long-term litter C input to the soil is consistent with SOC model applications at the regional and global scales (Abramoff et al., 2022; Pierson et al., 2022), as well as in the calibration of Yasso20 (Viskari et al., 2022). We are aware that litter input derived from satellites can be uncertain, thus potentially contributing to the observed discrepancies between simulated and measured SOC stocks at the site level. In fact, the fine scale variability in litter inputs cannot be captured by satellite-derived NPP estimates given (1) the larger pixel size of MODIS (500 m x 500 m) compared to the site scale of the soil sampling, and (2) the partitioning into tree components using average allocation factors, due to the lack of data at the site level. Satellite-derived NPP may have resulted in an overestimation of the litter input in regions with intensive forest management as in the Plateau, since small-scale disturbances such as thinning are not well detected by satellite estimates (Neumann et al., 2015; Park et al., 2021). Lastly, forests allocate a portion of NPP not only to fast-cycling components that are annually returned to the soil (i.e. fine roots and foliage) but also to components with slower turnover time such as stems and branches. Nevertheless, the satellite NPP approach proves to be a reasonable proxy of the large range of forest productivity across Swiss forests, i.e. ranging from 0.3 kg C m^{-2} yr^{-1} in the Alps to 0.8 kg C m^{-2} yr^{-1} at the warmest sites (see* ***Fig. S1****), which is consistent with the gross volume increment shown across different regions in the Swiss NFI (Brändli et al., 2020). Moreover, at the 18 sites of the long-term forest monitoring program LWF, the mean NPP over the period 2001-2010 based on the satellite approach amounted to 0.49±0.04 kg C m^{-2} yr^{-1} as compared to 0.46±0.05 kg C m^{-2} yr^{-1} estimated by the terrestrial approach for the same period (Etzold et al., 2014).*

Similarly, terrestrial methods based on forest inventories may lead to uncertain estimates of litter inputs. These uncertainties mostly relate to (1) country-specific allometries and expansion factors used to estimate tree biomass, (2) turnover times applied to obtain the litter inputs, and (3) failing to appropriately estimate inputs from fine roots and understory vegetation, which remain severely unconstrained despite their major contribution to forest soil C inputs (Didion, 2020; Neumann et al., 2020).”

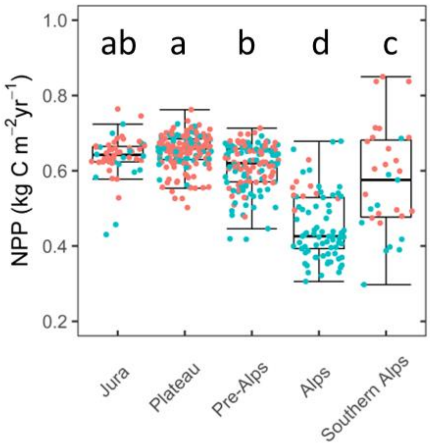

Fig. S1a*. Net primary production (NPP) across Swiss forest regions, excluding waterlogged soils. Total n sites = 468. Letters indicate significantly different across regions, based on ANOVA followed by Tukey's test with P < 0.05.*

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