

Response to Reviewer 3

In black: Reviewer's comments.

In blue: Response to reviewer.

In red: Revised manuscript.

(As many questions are arisen in one paragraph, we broke up some paragraphs to make the comment-response clearer.)

This study examines how snowpack affects winter respiration across the Northern Hemisphere. The topic matters and the dataset is impressive, but the analytical framework has a fundamental problem: you're treating snowpack and soil temperature as competing independent drivers when snowpack actually works through soil temperature. This makes your results hard to interpret mechanistically.

We appreciate your constructive comments regarding the causal relation between snowpack and soil temperature. In our original framework, the primary objective was to quantitatively partition the statistical associations of multiple factors with winter ecosystem respiration. However, we recognize that treating factors in parallel could inadvertently obscure the underlying sequential physical process, where snowpack modulate respiration by regulating soil hydrothermal conditions. To eliminate any potential ambiguity and make this mechanistic sequence explicit, we have significantly upgraded our analytical framework. Rather than contrasting these interrelated drivers, we incorporated a partial least squares structural equation model and introduced a snowpack insulation indicator to explicitly decompose the total impact into direct and indirect mediation pathways. This refined structure crystallizes the multi-dimensional pathways of snowpack regulation.

With this clarified mechanistic foundation, your comments substantially improved the mechanistic clarity, causal coherence, and presentation thoroughness of our study. In response, we (1) reframed the study's claims to avoid cross-domain impact comparisons;

(2) added a partial least squares structural equation model (PLS-SEM) to decompose snowpack effects into direct, thermal, and moisture pathways; (3) introduced a snowpack insulation indicator to clarify the insulation mechanism; (4) clarified the baseline and enhanced model R^2 to contextualize the contribution of snowpack indicators; (5) reconciled the causal logic between partial correlation and PLSR by restructuring the Results section; and (6) validated ERA5-Land snow variables against multiple in situ networks across the Northern Hemisphere. The detailed responses and the corresponding revisions are listed below.

Major comments:

The causal logic is backwards. Your PLSR puts snowpack depth, soil temperature, and climate into one model and asks "which matters most?" But that's not how snowpack works. The real causal chain is: Snowpack \rightarrow changes soil temperature \rightarrow affects respiration. It's not reasonable to ask "is snowpack or soil temperature more important?" when snowpack operates through soil temperature. When your results show snowpack has higher VIP than soil temperature in 30% of the area, what does that actually mean? Either: (a) snowpack strongly affects soil temperature which drives respiration, or (b) snowpack has some direct effect independent of temperature (like blocking gas exchange). You did not distinguish these possibilities. Some mediation analysis could be added. Maybe use R packages like mediation or lavaan to partition snowpack's effect into: indirect (through soil temperature), indirect (through soil moisture), and direct (independent of soil conditions). You already have all the data. Without this, your claim that "snowpack impacts exceed climate impacts" is mechanistically empty.

To address the causal inference concern, we have incorporated a partial least squares structural equation model (PLS-SEM). PLS-SEM inherently embeds a mediation structure by simultaneously estimating direct and indirect pathways, thereby addressing the causal

partitioning concern raised. Compared to covariance-based SEM, PLS-SEM imposes no distributional assumptions and is more robust under small sample sizes of data, making it a more appropriate choice for this study. Your comment identified two possible mechanisms. Our PLS-SEM decomposed the impact of snowpack on $\text{Reco}_{\text{winter}}$ into three pathways: (1) direct effect, (2) thermal pathway (snowpack \rightarrow soil temperature \rightarrow $\text{Reco}_{\text{winter}}$), and (3) moisture pathway (snowpack \rightarrow soil water content \rightarrow $\text{Reco}_{\text{winter}}$).

PLS-SEM analyses were conducted across different hydrothermal regions (Table S5). We applied a latent variable “snowpack”, which considered three reflective indicators (snowpack depth, snowpack density, and snowpack duration) collectively.

Table S5. Hydrothermal classification rules for partial least squares structural equation models.

| Thermal condition Moisture condition | Annual mean air temperature $\leq 0^{\circ}\text{C}$ | Annual mean air temperature $> 0^{\circ}\text{C}$ |
|-----------------------------------------|------------------------------------------------------|---------------------------------------------------|
| Aridity Index (AI) < 0.2 | Cold and arid | Warm and arid |
| $0.2 \leq \text{AI} < 0.5$ | Cold and semi-arid | Warm and semi-arid |
| $0.5 \leq \text{AI} < 0.65$ | Cold and semi-humid | Warm and semi-humid |
| $\text{AI} \geq 0.65$ | Cold and humid | Warm and humid |

The PLS-SEM results revealed that the impact of snowpack on $\text{Reco}_{\text{winter}}$ is multi-dimensional and regionally distinct (Figure 6). Specifically, the thermal pathway consistently promoted $\text{Reco}_{\text{winter}}$ across all regions, whereas the moisture pathway generally exerted a weak negative effect. The direct effect shifted direction by climate zone, exhibiting a significant negative impact in cold regions, but turning positive in warm regions. These findings demonstrate that the spatial heterogeneity of the snowpack– $\text{Reco}_{\text{winter}}$ relation is rooted in the differential combinations of these competing mechanisms rather than a single dominant factor. These results have been incorporated into the Discussion section. This analysis explicitly elucidates the multi-dimensional complexity of how snowpack affects $\text{Reco}_{\text{winter}}$.

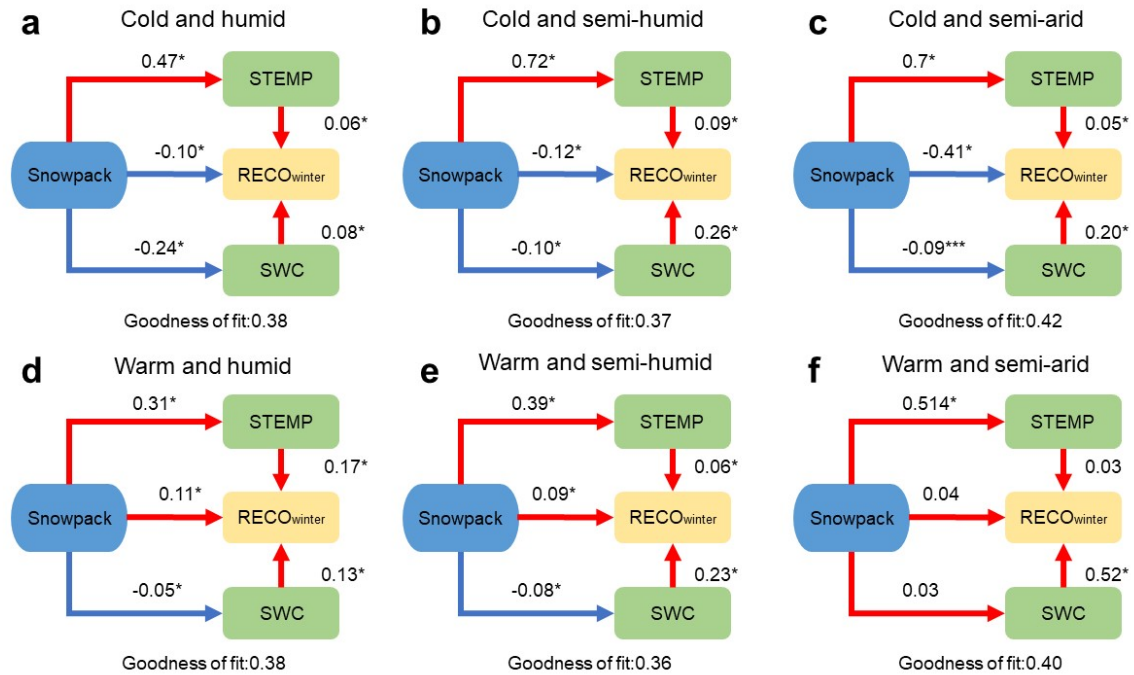


Figure 6. Path coefficient diagrams of snowpack on winter ecosystem respiration ($Reco_{winter}$) over different climatic zones. The values are standardized path coefficients (* represents $p < 0.05$). The blue and red lines indicate negative and positive effects, respectively. The latent variable snowpack is composed of snowpack depth, snowpack density, and snowpack duration days. STEMP: soil temperature, SWC: soil water content.

We agree that claiming "snowpack impacts exceed climate impacts" based solely on PLSR results without mechanistic decomposition is analytically insufficient. Accordingly, we have removed all such comparative statements from the manuscript. Rather than making magnitude comparisons, we now characterize snowpack as an indispensable factor in accurately representing winter ecosystem respiration. We believe this reframing is more appropriate for two reasons. First, the influence of snowpack on $Reco_{winter}$ operates through multiple concurrent pathways rather than a single dominant mechanism. Second, the relative contributions of these pathways vary substantially across hydrothermal regimes. Given this complexity, a detailed mechanistic characterization is more scientifically informative than a simple ranking of effect sizes. The mechanistic decomposition provided

by the PLS-SEM analysis now forms the evidential basis for this revised conclusion.

We added the PLS-SEM methods as follows:

Lines 130–143: We incorporated a partial least squares structural equation model (PLS-SEM) to explain the mechanism of the impact of snowpack on $\text{Reco}_{\text{winter}}$ (Figure 6, Table 1). PLS-SEM inherently embeds a mediation structure by simultaneously estimating direct and indirect pathways, and imposes no distributional assumptions and is more robust under small sample sizes of data. We explicitly decomposes the impact of snowpack on $\text{Reco}_{\text{winter}}$ into three pathways: 1) direct effect, 2) thermal pathway (snowpack \rightarrow soil temperature \rightarrow $\text{Reco}_{\text{winter}}$), and 3) moisture pathway (snowpack \rightarrow soil water content \rightarrow $\text{Reco}_{\text{winter}}$). To account for climatic context, analyses were conducted across regions defined by hydrothermal conditions. Thermal regime was determined by annual mean air temperature, with regions classified as cold (annual mean air temperature $\leq 0^{\circ}\text{C}$) or warm (annual mean air temperature $> 0^{\circ}\text{C}$). Moisture regime was determined using the aridity index (AI) from the Global Aridity Index and Potential Evapotranspiration Database (Version 3), with regions classified as arid ($\text{AI} < 0.2$), semi-arid ($0.2 \leq \text{AI} < 0.5$), semi-humid ($0.5 \leq \text{AI} < 0.65$), or humid ($\text{AI} \geq 0.65$) (Jiao et al., 2021; Zomer et al., 2022). Specifically, one latent variable (snowpack) and three observed variables (soil temperature, soil water content, and $\text{Reco}_{\text{winter}}$) were included in PLS-SEM. For the latent variable “snowpack”, three reflective indicators (snowpack depth, snowpack density, and snowpack duration) were considered. The goodness-of-fit index (GOFI) is used to determine whether the constructed model is effective. A GOFI value higher than 0.36 indicates that the results obtained from the model are reliable (Wetzels et al., 2009).

And the PLS-SEM results are added in Discussion section as follows:

Lines 285–318: To explain the mechanism of the impact of snowpack on $\text{Reco}_{\text{winter}}$ across different thermal conditions, we applied PLS-SEM analysis. PLS-SEM results revealed that snowpack affects $\text{Reco}_{\text{winter}}$ through three pathways, with the direction and

relative contribution of each pathway showing significant regional differences. The GoFI of the models for each region ranged from 0.36 to 0.42, indicating that the models have acceptable interpretability.

The thermal pathway was significant across all climate zones, with snowpack enhancing soil temperature through its insulating effect (standardized path coefficients: 0.31–0.72) and thereby positively promoting ecosystem respiration. This finding is consistent with previous findings that snowpack affects $\text{Reco}_{\text{winter}}$ through snowpack insulation (Christiansen et al., 2018; Slater et al., 2017; Zhang et al., 2018). In ecosystems characterized by low air temperatures, snowpack functions as an insulation layer, thereby significantly affecting the heat exchange between the soil and the atmosphere (Christiansen et al., 2018; Slater et al., 2017; Yi et al., 2020). This results in higher ground surface temperatures than snowpack-free scenes (Zhang, 2005), which favors the maintenance of respiration.

The moisture pathway also exhibited regional differentiation. Across most climate zones, standardized path coefficients ranged from -0.025 to -0.006 , indicating that winter snowpack reduces soil liquid water availability through freezing and thereby suppresses respiration. In the warm and semi-arid zone, the moisture pathway coefficient shifted to positive (0.018), though this did not reach statistical significance. The replenishment of soil moisture by snowpack contributes to microbial activities beneath snowpack (Brooks et al., 1996), but snowmelt signals were not observed in most Arctic regions because of low soil temperatures, and the partial correlation between snowmelt and $\text{Reco}_{\text{winter}}$ is weak (Figure 1c, g). However, site studies have revealed that snowmelt is increasing during the winter in the North America and is sensitive to climate warming (Musselman et al., 2021). This implies that future studies should pay attention to the impacts of snowpack on the winter soil water content.

The direct effect of snowpack varied in direction across climate zones, exhibiting significant negative values in cold regions ranging from -0.415 to -0.102 , reflecting the

physical suppression of soil–atmosphere gas exchange by the snowpack. In warm regions, the direct effect shifted to positive values (0.044–0.109). It should be noted that this direct effect represents the residual impact of snowpack on $\text{Reco}_{\text{winter}}$ after statistically controlling for both the thermal and moisture pathways. Therefore, it indicates that snowpack exerts an additional effect on respiration that is independent of soil temperature and soil moisture regulation. This may be explained by changes in the dominant microbial communities and the total microbial population (Li et al., 2016; Schimel et al., 2004; Wang et al., 2020). In regions with warmer climates, higher baseline respiration rates reduce the relative contribution of snowpack to ecosystem respiration, thereby limiting the overall impact of snowpack on respiration.

Integrating all three pathways, the mechanism by which snowpack influences winter ecosystem respiration is not uni-dimensional. In cold regions, the positive promotion via the thermal pathway co-exists with the negative suppression of the direct effect, while in warm regions, the three pathways all showed positive impact of snowpack on respiration. These results demonstrate that the spatial heterogeneity of the snowpack– $\text{Reco}_{\text{winter}}$ relation is rooted in the differential combination of multiple impact mechanisms under varying hydrothermal conditions, rather than the dominance of any single pathway.

Table 1. Comparison of the direct and indirect effects of snowpack on winter ecosystem respiration ($\text{Reco}_{\text{winter}}$) over different climatic zones.

| | Cold and humid | Cold and semi-humid | Cold and semi-arid | Warm and humid | Warm and semi-humid | Warm and semi-arid |
|----------------------|----------------|---------------------|--------------------|----------------|---------------------|--------------------|
| Direct path effect | −0.1022 | −0.1213 | −0.4148 | 0.1088 | 0.0856 | 0.0442 |
| Thermal path effect | 0.0283 | 0.0613 | 0.0335 | 0.0541 | 0.0238 | 0.0168 |
| Moisture path effect | −0.0204 | −0.0252 | −0.0175 | −0.0058 | −0.0185 | 0.0180 |

The method part includes some content about comparing snowpack, climate, and soil factors. But Figure 2 only shows detailed spatial patterns for the three snowpack variables. Climate and soil just appear as colored categories in panel 2a. A basic questions: In the 11% where climate dominates, which climate variable specifically? What do soil temperature VIP patterns look like? You ran the analysis but didn't report it?

Climate indicators include temperature, precipitation, radiation, and wind speed. Temperature has a dominant range of 4.18%, precipitation 2.41%, radiation 2.36%, and wind speed 2.31%. Because their impact is relatively small and their distribution is scattered, displaying nine variables on the same graph could easily lead to confusion. Therefore, the four climate indicators are shown collectively in gray in Figure 2a. Regarding soil temperature, elevated VIP values are concentrated primarily in central Siberia. We have placed the VIP distribution patterns of climate and soil factors in the responses and supplements, as we are more focused on the characteristics of snowpack's impact and therefore have not provided a detailed analysis for other factors in the manuscript.

Furthermore, we have adjusted some of the analysis in Section 3.2, focusing on the magnitude and extent of the impact of different snowpack indicators on $\text{Reco}_{\text{winter}}$. As you mentioned, directly using the PLSR model to compare the impacts of snowpack, climate, and soil indicators may confuse readers regarding the understanding of the impact mechanisms.

Line 184: Distinct and complementary roles of multiple snowpack indicators in affecting $\text{Reco}_{\text{winter}}$

Lines 185–188: The most dominant factor for $\text{Reco}_{\text{winter}}$ was identified for each pixel using VIP values, and the impacts of different snowpack indicators were compared. The three snowpack indicators (snowpack depth, snowpack density, and snowpack duration) were the dominant factors influencing $\text{Reco}_{\text{winter}}$ changes in 30.43% of the region (Figure

2a).

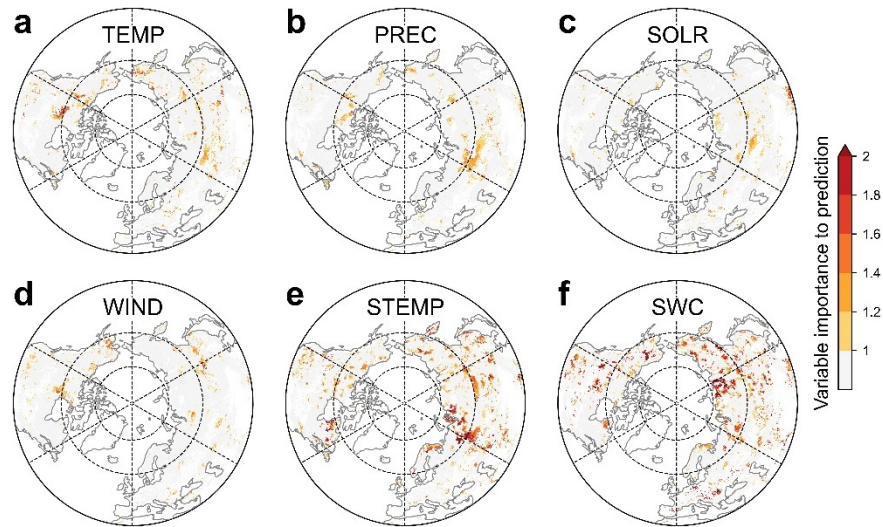


Figure S6. Spatial pattern of the VIP values of climate and soil indicators in partial least squares regression (PLSR) analysis. TEMP: air temperature, PREC: precipitation, SOLR: solar radiation, WIND: wind speed, STEMP: soil temperature, SWC: soil water content.

Same with Figure 3, you show adding snowpack improves R^2 by 0.23 on average, but never tell us what the baseline R^2 was. If it goes from 0.1 to 0.33, which means the whole model is weak. If it goes from 0.6 to 0.83, snowpack is a nice addition. We need that context.

Regarding Figure 3, we modified the presentation, adding a baseline model R^2 without snowpack and model R^2 with progressively adding snowpack depth, snowpack density, and snowpack duration to models. It can be observed that after adding the snowpack indicators, the R^2 in many areas shifted from poor to better accuracy, demonstrating that investigating these diverse aspects of snowpack serves as a valuable supplement for a thorough understanding of the variations in $Reco_{winter}$.

Lines 201–207: The baseline model without snowpack indicators showed an average R^2 of 0.56, established as an acceptable and usable predictive baseline (Figure 3a). Concurrently, it should be noted that R^2 fell below 0.5 in 36.91% of the study area, which leaves space for further improvement. The integration of snowpack depth into the models, in contrast to baseline model, resulted in an enhancement of R^2 by 0.19–0.21 across 18.85%

of the study area (Figure 3b). Additionally, the addition of snowpack density increased R^2 by an average of 0.22 over 32.96% of NH ecosystems, compared with baseline model (Figure 3c). By utilizing all three snowpack indicators in the PLSR analysis, R^2 improved by an average of 0.24 over 50.18% of the study area (Figure 3d).

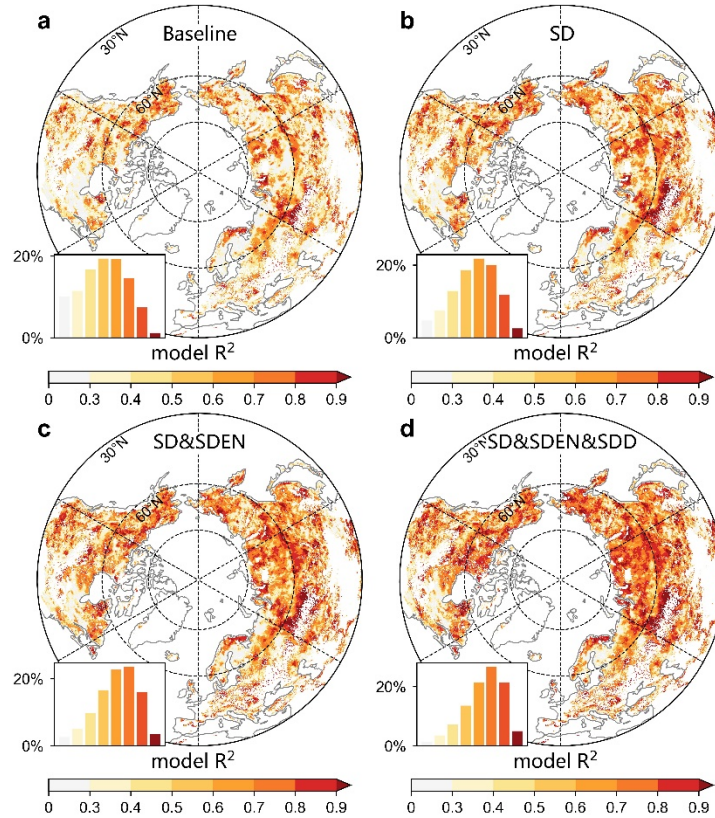


Figure 3. Determination coefficients (R^2) in the partial least squares regression analysis. (a) baseline model with no snowpack indicator, (b–d) models with one to three snowpack indicators. The inset barplots indicate the proportion of R^2 improvement in different intervals. SD, snowpack depth; SDEN, snowpack density; SDD, snowpack duration days.

Also, Figure 2a only shows pixels where $VIP > 1$ and $R^2 > 0.8$. About half of your study area is grayed out. What's different about those regions where the model fails?

Thank you for this insightful comment. Figure 2a applies two criteria. First, only pixels with $R^2 > 0.8$ are retained. Pixels failing this threshold (23.64%) are considered to have unstable or unreliable predictor–response relations and are therefore masked. Second,

Figure 2a depicts the indicator with the highest VIP score in each pixel, which we interpret as the dominant driver of ecosystem respiration at that location. VIP quantifies the contribution of each predictor to the model. Retaining only pixels where the maximum VIP exceeds 1 ensures that a clearly dominant factor can be identified; in 4.50% of the study area, no single predictor achieves sufficient prominence to be designated as dominant.

We also acknowledge a mistake in Figure 2: the basemap (pixels in light gray) used to delineate the study area was inconsistent with that in Figure 1. Specifically, we inadvertently used a map of the snowpack rather than the stable snowpack region (which requires this place to have a snowpack duration of more than 30 days), which inflated the apparent proportion of masked area. This error has been corrected in the revised manuscript.

We recognize that the PLSR applied here is a relatively simple statistical framework, and some degree of spatial heterogeneity in model performance is unavoidable. To maintain transparency and avoid introducing subjective filtering that could mislead readers, we present the complete spatial results with the masking criteria explicitly defined, rather than restricting the display to only high-confidence pixels.

This is revised Figure 2 with subplot a displaying the original VIP classification results:

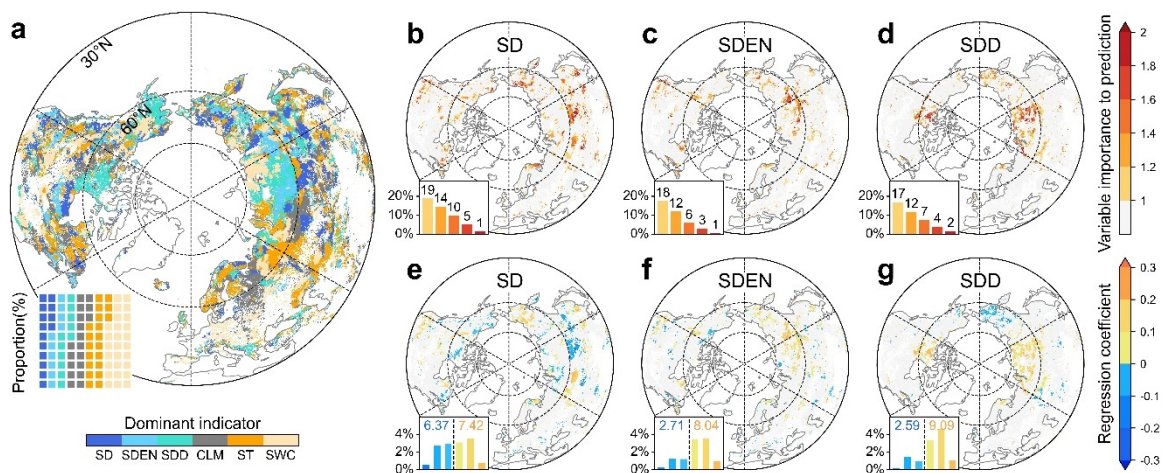


Figure 2. (a) Spatial pattern of the dominant indicators for winter ecosystem respiration in partial least squares regression (PLSR) analysis. The inset waffle plot indicates the proportion of the dominant indicator, with each pixel corresponding to 1%. (b–d) Spatial pattern of the VIP values

of snowpack indicators. The inset barplots indicate the proportions of VIPs in different intervals. (e–g) Spatial pattern of the regression coefficients of snowpack indicators. The inset barplots indicate the proportions of negative and positive regression coefficients in different intervals. SD, snowpack depth; SDEN, snowpack density; SDD, snowpack duration days; CLM, climate indicators; ST, soil temperature; SWC, soil water content.

Section 3.1: partial correlation controlling for climate (treating climate as a confounder); Section 3.2: PLSR with climate as predictor (treating climate as competitor). These assume different causal structures. You don't explain why you need both or how to reconcile them. Path analysis would handle both issues in one coherent framework.

We appreciate your insightful observation regarding the potentially inconsistent causal assumptions underlying Sections 3.1 and 3.2. We acknowledge that the original manuscript did not adequately articulate the logical relation between these two analytical components, and we have restructured and clarified the revised manuscript accordingly.

In the revised manuscript, Section 3.1 "Dominant snowpack indicators affecting $\text{Reco}_{\text{winter}}$ " employs partial correlation analysis with climate variables treated as covariates. The purpose of this section is to identify which snowpack indicators exhibit robust associations with $\text{Reco}_{\text{winter}}$ independent of shared climatic variance, rather than to directly quantify the magnitude of snowpack effects on respiration. By screening out indicators that show weak independent associations with $\text{Reco}_{\text{winter}}$, this step establishes the indicator framework upon which subsequent quantitative analyses are built.

Section 3.2 "Spatial heterogeneity in the impacts of snowpack indicators on $\text{Reco}_{\text{winter}}$ " then quantifies the magnitude and spatial pattern of snowpack impacts through two complementary perspectives: the spatial distribution of individual snowpack indicator effects, and the increment in explained variance (ΔR^2) when snowpack indicators are incorporated into the model. We note that the portion of Section 3.2 that framed climate as a competitor to snowpack has been removed from the revised manuscript, as this framing

introduced the causal ambiguity you have identified. The remaining content of Section 3.2 focuses specifically on quantifying snowpack contributions rather than making comparative causal claims between snowpack and climate.

Taken together, Sections 3.1 and 3.2 follow a coherent "which snowpack indicators have impact on $\text{Reco}_{\text{winter}} \rightarrow$ quantifying the impact of snowpack on $\text{Reco}_{\text{winter}}$ " progression, with Section 3.3 providing mechanistic interpretation through hydrothermal gradient analysis and the snowpack insulation indicator (SII) framework. Furthermore, in response to your suggestion regarding path analysis, we have incorporated a structural equation model into the Discussion section, which provides a comprehensive causal decomposition of the snowpack– $\text{Reco}_{\text{winter}}$ pathways.

The modification we added to Section 3.1 is as follows:

Lines 146–147: We screened and identified the key snowpack indicators that exhibited impact on $\text{Reco}_{\text{winter}}$ by conducting partial correlation analyses between six snowpack indicators and $\text{Reco}_{\text{winter}}$ (Figure 1).

The modification we added to Section 3.2 is as follows:

Line 184: Distinct and complementary roles of multiple snowpack indicators in affecting $\text{Reco}_{\text{winter}}$

Lines 185–188: The most dominant factor for $\text{Reco}_{\text{winter}}$ was identified for each pixel using VIP values, and the impacts of different snowpack indicators were compared. The three snowpack indicators (snowpack depth, snowpack density, and snowpack duration) were the dominant factors influencing $\text{Reco}_{\text{winter}}$ changes in 30.43% of the region (Figure 2a).

The SII framework we added to Section 3.3 is as follows:

Lines 237–257: We further introduced a snowpack insulation indicator (SII), defined as the difference between soil surface temperature and overlying air temperature, to explicitly quantify the thermal insulation effect of snowpack. Partial correlation analysis was then applied to examine two sequential linkages: 1) snowpack \rightarrow SII, and 2) SII \rightarrow

Reco_{winter}. When analyzing the relation between each snowpack indicator and SII, the impacts of other two snowpack indicators and air temperature were controlled. The impact of soil moisture and air temperature are also controlled when analyzing the relation between SII and Reco_{winter}.

Snowpack depth and snowpack duration exhibited comparable positive relations with SII, exhibited comparable positive relations with SII, with significant positive correlations observed across 20.96% and 23.79% of the study area, respectively, while significant negative correlations were limited to 5.66% and 5.59%. The positive correlations were predominantly observed in Siberia and high-latitude North America, where characterized by deep and stable seasonal snowpack. It is consistent with the physical principle that greater snowpack depth and prolonged snowpack amplify the soil–atmosphere temperature differential, thereby enhancing thermal insulation. In contrast, snowpack density, displayed a predominantly negative partial correlation with SII, with significant negative correlations covering 11.00% of the study area. This inverse relation is physically coherent, as elevated snowpack density increases thermal conductivity of the snowpack, which diminishes its insulating capacity and consequently reduces SII.

SII exhibited the highest proportion of significant positive partial correlations with Reco_{winter} among all variables examined (26.81%), while negative correlations were confined to only 2.30%, indicating a highly directionally consistent relation. The spatial distribution of significant SII–Reco_{winter} correlations showed substantial overlap with that of snowpack depth–SII correlations, suggesting a coherent mechanistic chain in which deep and persistent snowpack enhances thermal insulation, sustains elevated soil temperatures throughout winter, and consequently promotes respiration. Moreover, the SII–Reco_{winter} relation was both stronger and more spatially consistent than the direct partial correlations between individual snowpack indicators and Reco_{winter}, providing evidence that SII functions as an effective mediating indicator that bridges snowpack and winter ecosystem respiration.

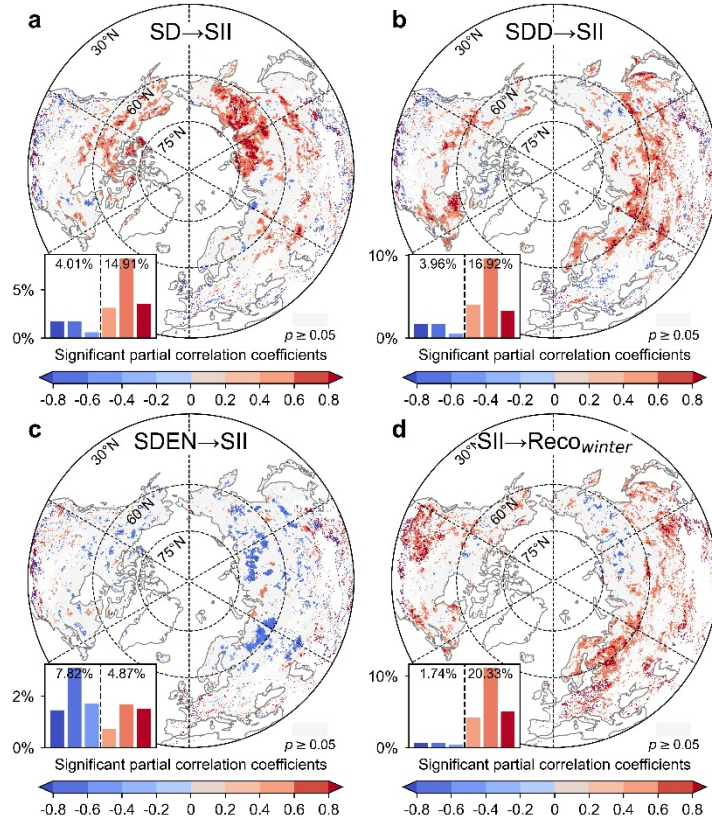


Figure 5. Spatial patterns of partial correlation coefficients between snowpack insulation and winter ecosystem respiration ($Reco_{winter}$). The region shaded in gray denotes areas of non-significance ($p \geq 0.05$). (a–c) The partial correlation coefficients between snowpack indicators and snowpack insulation indicator. (d) The partial correlation coefficients between snowpack insulation indicator and $Reco_{winter}$. SD, snowpack depth; SDEN, snowpack density; SDD, snowpack duration days. SII, snowpack insulation indicator.

You keep saying "snowpack insulation" but never demonstrate it. If that's really the mechanism, show that in regions where snowpack has high VIP: (a) snowpack correlates strongly with soil temperature, AND (b) soil temperature correlates strongly with respiration. You have the data but never test this chain. lines 295-302 say snowpack matters more in cold regions because "respiration is more temperature-sensitive below $0^{\circ}C$ ". but do you actually see that in your data? Consider to calculate Q10 values for different temperature zones. The negative correlations in coastal Canada get one vague paragraph

(lines 268-275) about "too thick snowpack limits gas exchange." At what threshold? Could it be something else, like unstable snowpack in maritime climates?

The comparative discussion of snowpack, soil, and climate effects (original Line 263–271) has been removed from the revised manuscript. The atmosphere–soil temperature difference has been introduced as an intermediate indicator in the manuscript to provide causal support for the snowpack thermal insulation chain. Section 4.2 has been restructured around the PLS-SEM framework, which offers a more comprehensive mechanistic account of the multiple pathways through which snowpack influences ecosystem respiration. Regarding the physical suppression of soil–atmosphere gas exchange by thick snowpack, this pathway has been explicitly incorporated into PLS-SEM, providing direct quantification of its effect. We did not quantify Q10 values in this study. The cited references published findings (Arndt et al., 2023; Segura et al., 2019; Zheng et al., 2025) to qualitatively support the notion that soil respiration is more temperature-sensitive below 0°C, which is a well-established pattern in the literature. This statement was intended as contextual support rather than a mechanistic claim. To avoid potential misinterpretation, we have removed this sentence from the revised manuscript, as the mechanistic discussion has been restructured around the PLS-SEM framework.

The revised Section 4.2 is detailed in the first response, thus we do not repeat it here.

Everything depends on ERA5-Land snowpack (which is modeled, not observed). You mention it overestimates mountain snow depth in one sentence (line 308) but provide no actual validation. Compare to SNOTEL, Russian network, or Scandinavian station data. Show bias by region. Your "insulation" interpretation depends on whether ERA5 gets snow density and thermal conductivity right.

We thank you for this important concern. We have conducted systematic validation of ERA5-Land snow variables against station observations across the Northern Hemisphere, using data from multiple networks spanning North America and Eurasia.

For snowpack depth, ERA5-Land shows good agreement with station observations across the Northern Hemisphere ($R=0.756$, $MAE=0.237\text{m}$, $RMSE=0.371\text{m}$). Performance is consistent between North America ($R=0.754$, $MAE=0.282\text{m}$, $RMSE=0.419\text{m}$) and Eurasia ($R=0.777$, $MAE=0.108\text{m}$, $RMSE=0.184\text{m}$). Furthermore, pixels with maximum snowpack depth exceeding 2.5 m were excluded from all analyses. Such extreme snowpack depths are unlikely to support measurable soil respiration, as the soil surface is effectively decoupled from the atmosphere. This threshold effectively removes the majority of high-relief mountainous regions where ERA5-Land's overestimation bias is most pronounced, thereby reducing the influence of this known limitation on our results.

For snowpack density, ERA5-Land also performs reasonably well at the hemispheric scale ($R=0.641$, $MAE=0.049\text{g/cm}^3$, $RMSE=0.066\text{g/cm}^3$). Regarding your concern about thermal conductivity and the insulation interpretation, snowpack density is directly related to snow thermal conductivity, and the validation results indicate that ERA5-Land captures the observed density range (approximately $0.1\text{--}0.4\text{ g/cm}^3$) with acceptable bias. Taken together, these validation results support the reliability of ERA5-Land snowpack representation for the purposes of this study, and provide a physical basis for the insulation interpretation central to our findings. These validation figures and the station dataset description have been added to the supplementary materials.

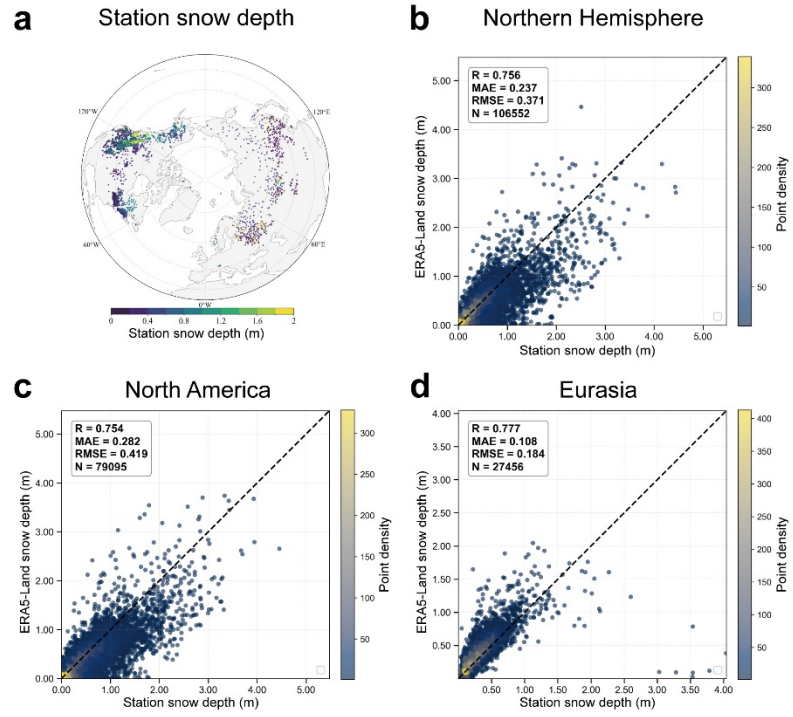


Figure S7. Comparison of ERA5-Land snowpack depth with station observations.

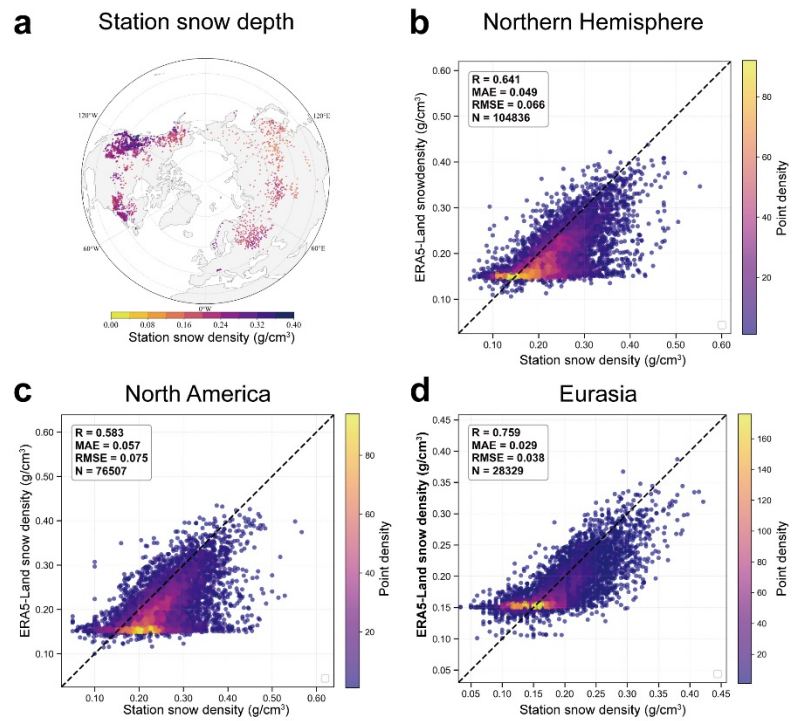


Figure S8. Comparison of ERA5-Land snowpack density with station observations.

Table S3. Description of snow station observation datasets.

| Country | Data source |
|---------------|------------------------------------------------------------------------------|
| Canada | CanSWE v6 (Environment and Climate Change Canada) |
| United states | USDA NRCS Snow Survey & SNOTEL |
| | Maine Geological Survey |
| | Northeast Regional Climate Center (NRCC) |
| | U.S. National Snow & Ice Center |
| | New Hampshire DES Dams |
| Finland | Finnish Environmental Institute (SYKE) |
| Russia | All-Russia Research Institute of Hydrometeorological Information (RIHMI-WDC) |
| | FSU Snow Survey (Hydromet Service of USSR) |
| Norway | Norwegian Water Resources and Energy Directorate (NVE) |
| Switzerland | WSL / SLF (Institute for Snow and Avalanche Research) |
| France | FMA Weather Station & Col de Porte Observatory (CENACLAM Project) |
| Austria | Weisssee AWS (Kaunertal Research Site) |
| China | China Meteorological Administration, National Climate Center |

Section 3.2 is confused. Title says "Impacts of snowpack dynamics" but content is multi-factor comparison. You mix two different analyses: VIP (who's dominant?) and R^2 improvement (how much does adding snowpack help?). These answer different questions. Your results show this tension: snowpack dominates in 30% of areas but improves R^2 in 50%. That 20% gap means snowpack helps without being #1. Why not discuss this?

Thank you for this constructive comment. We agree that the original Section 3.2 lacked structural clarity, and we have revised it accordingly.

We have updated the section title to “Spatial heterogeneity in the impacts of multiple snowpack indicators on $Reco_{winter}$ ”, which more accurately reflects the content. The section is now reorganized into two parts with a clear logical progression: (1) the spatial distribution and magnitude of the impact of individual snowpack indicators; and (2) the change in model R^2 before and after incorporating snowpack indicators. Both parts address

“how much does snowpack matter”, but from complementary perspectives.

Regarding the 20% gap you identified, we agree this is an important finding that deserves explicit discussion. We have added a statement in the revised manuscript to explicitly acknowledge and interpret this gap, as we agree that leaving it unaddressed could appear as an oversight.

Line 184: Distinct and complementary roles of multiple snowpack indicators in affecting $\text{Reco}_{\text{winter}}$.

Lines 185-188: The most dominant factor for $\text{Reco}_{\text{winter}}$ was identified for each pixel using VIP values, and the impacts of different snowpack indicators were compared. The three snowpack indicators (snowpack depth, snowpack density, and snowpack duration) were the dominant factors influencing $\text{Reco}_{\text{winter}}$ changes in 30.43% of the region (Figure 2a).

Lines 207-209: This spatial extent (50.18%) exceeds that in which snowpack indicators were identified as the dominant factor (30.43%). In the additional approximately 20% of the study area, snowpack indicators were not the dominant indicator, yet still exhibited non-negligible impact.

Minor comments:

Line 73: What is the total snowmelt? Is that SWE? How did you calculate it?

Total snowmelt is the portion of land surface snow that melts into water during winter, used to characterize the moisture supply that snowpack can provide to the soil during winter. This study directly uses the snowmelt amount from the snow module in ERA5-land, which is theoretically equivalent to the total of the previous day's SWE minus the current day's SWE when the current day's SWE is lower than the previous day's SWE. The information of datasets used are described in Table S2.

Table S2. Dataset details.

| Type | Variable | Source |
|---------------|-------------------------|----------------------------------------------------------------------------|
| Snowpack | Snowpack depth | ERA5-Land |
| | Snowpack density | ERA5-Land |
| | Snowmelt | ERA5-Land |
| Respiration | Ecosystem respiration | FLUXCOM |
| | Ecosystem respiration | BEPS |
| | Ecosystem respiration | LGS |
| Climate | Air temperature | ERA5-Land |
| | Precipitation | ERA5-Land |
| | Solar radiation | ERA5-Land |
| | Wind speed | ERA5-Land |
| Soil | Soil water content | ERA5-Land |
| | Soil temperature | ERA5-Land |
| Land cover | Underlying surface type | CCI-LC |
| Aridity index | | Global Aridity Index and Potential Evapotranspiration Database - Version 3 |

Line86: Regarding the soil data, what are the specific soil depths? How did you calculate the mean value using depth weighting? Use one or two sentences to describe them.

The soil depth weighting formula and weighting are as follows:

$$T_{\text{weighted}} = \frac{\sum_{i=1}^4 w_i \cdot T_i}{\sum_{i=1}^4 w_i}$$

where T_{weighted} represents the average soil state, T_i represents the value corresponding to the current soil layer, and w_i represents the weight of the current soil layer.

Table S1. Information of soil layering and weight allocation.

| Soil layer | Depth range | Thickness | Weight |
|------------|-------------|-----------|--------|
| 1 | 0–7 cm | 7 cm | 0.0242 |
| 2 | 7–28 cm | 21 cm | 0.0727 |
| 3 | 28–100 cm | 72 cm | 0.2491 |
| 4 | 100–289 cm | 189 cm | 0.6540 |

Line 135-138: It may be better to move these sentences to the method part.

Actually, we did explain these sentences in methods part, but emphasized it again in results before displaying results. Line 93–97: “This study examined the impacts of different snowpack indicators on $\text{Reco}_{\text{winter}}$ by conducting a partial correlation analysis on a per-pixel basis. This methodology was employed to mitigate the confounding effects of other climate variables, including air temperature, precipitation, solar radiation, and wind speed during the corresponding period. Notably, our analysis was confined to pixels with significant correlations ($p < 0.05$) and the magnitude of the significant correlations. Therefore, we identified the key snowpack indicators in the relation between snowpack and $\text{Reco}_{\text{winter}}$.” We removed the repeated description in Line 135–138.

Lines 188-205: Figure 3 shows every possible combination of snowpack indicators. Just show the progression: baseline → add depth → add density → add duration. Much clearer.

Regarding the graph of R^2 improvement (Figure 3), we replaced it with the baseline R^2 without snowpack and the R^2 with snowpack. The figure and analysis have been detailed in previous responses.

Lines 212-222: Good finding on temperature gradient, but your explanation (line 303) that warm regions are "less constrained by temperature" is unclear. Higher baseline respiration making snow effects relatively smaller would be a better mechanism.

Thanks for your advice! This interpretation INDEED make the logic clearer. We modified the corresponding sentence to Lines 312–314: In regions with warmer climates, higher baseline respiration rates reduce the relative contribution of snowpack to ecosystem respiration, thereby limiting the overall impact of snowpack on respiration.

Figure 4d,e: This is actually your clearest result.

The core problem is you're using a prediction model (PLSR) to make causal claims about mechanisms. That doesn't work without proper causal analysis. Fix the logic, complete the reporting, and this could contribute meaningfully to understanding winter carbon dynamics.

We sincerely appreciate your critical comments, which have substantially strengthened the logical coherence of our study. We have restructured the manuscript to clarify the distinct roles of each analytical component: partial correlation analysis serves to identify snowpack indicators with robust independent associations with $\text{Reco}_{\text{winter}}$, while PLSR is used to quantify the magnitude and spatial patterns of snowpack impacts. To address the causal inference concern directly, we have incorporated a structural equation model that decomposes the snowpack–insulation–respiration pathway and validates the proposed mechanism. We believe these revisions strengthen the study's contribution to understanding winter carbon dynamics, and we thank you again for the constructive guidance.

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