

S1 Supplementary Methods

S1.1 Calculation of Snowpack Phenology

The duration spanning from 1 August of the present year to 31 July of the following year is termed a snowpack year, in accordance with the seasonal variations in snowpack in the NH[3, 6]. To reduce the effect of ephemeral snow on snowpack duration, the consecutive 5-day method is applied to extract SOD and SED by using daily snowpack depth data [2, 8]. The snowpack onset date was defined as the first day of the first five consecutive days of snowpack presence within each snowpack year (Equation S1), the snowpack end date was defined as the final day of the last five consecutive days of snowpack presence within each snowpack year (Equation S2), and the snowpack duration was defined as the number of days between the snowpack onset date and the snowpack end date.

$$\text{Snowpack onset date} = \min\{t\} \mid \left\{ t \in [0, m - 4] \text{ and } \sum_{k=0}^4 S_{t+k} = 5 \right\} \quad (\text{S1})$$

$$\text{Snowpack end date} = \max\{t\} + 4 \mid \left\{ t \in [0, m - 4] \text{ and } \sum_{k=0}^4 S_{t+k} = 5 \right\} \quad (\text{S2})$$

where t represents a date, m is the number of dates in a hydrological year, and S_t represents the value of a pixel, with 0 meaning non-snowpack and 1 meaning snowpack.

S1.2 Partial correlation analysis

Partial correlation analysis controls the effects of other correlated variables and measures the linear relationship between two variables, while the magnitude of the correlation is usually expressed as a partial correlation coefficient, which ranges from -1 to 1. The formula is as follows:

$$r_{xy,z} = \frac{r_{xy} - r_{xz} \cdot r_{yz}}{\sqrt{(1 - r_{xz}^2)(1 - r_{yz}^2)}} \quad (\text{S3})$$

where r_{xy}, r_{xz} , and r_{yz} stand for the simple correlation coefficient (the zeroth-order partial correlation) between x , y , and z variables. $r_{xy,z}$ is the 1st-order partial correlation coefficient between variable x and variable y , in controlling the impact of variable z . The nth-order partial correlation can be easily computed from (n - 1)th-order partial correlations. The t-test is usually used to test the significance of the partial correlation coefficients as follows:

$$t = \frac{\sqrt{(n - k - 2)} \cdot r}{\sqrt{(1 - r^2)}} \quad (\text{S4})$$

where r is the partial correlation coefficient, n is the size of samples, k is the number of variables upon which we are conditioning, $n - k - c$ is the numerator of the radical. We would reject the hypothesis and conclude that there is a significant partial correlation between these two variables if the absolute value of the test statistic exceeded the critical value from the t-table evaluated at $\alpha = 0.05$ over 2:

$$|t| > t_{n-2-c, \alpha/2} \quad (\text{S5})$$

S1.3 Calculation of Variable importance to prediction (VIP)

For a Partial linear regression model with m latent components where one seeks to predict y ($n \times 1$) from X ($n \times p$), the VIP value for the j^{th} is defined as follows:

$$\text{VIP}_j = \sqrt{\frac{p}{\sum_{h=1}^m R_{(y,t_h)}^2} \sum_{h=1}^m R_{(y,t_h)}^2 w_{kj}^2} \quad (\text{S6})$$

29 where $R^2_{(y,t_h)}$ is the proportion of the y variance explained by t_h .

30 S2 Supplementary Tables

Table S1: Dataset and pre-processing details

Type	Variable	Source	Resolution	Citation
snowpack	Snowpack depth	ERA5-Land	10km	[7]
	Snowpack density	ERA5-Land	10km	[7]
	Snowmelt	ERA5-Land	10km	[7]
respiration	Ecosystem respiration	FluxCom	0.0833°	[5]
	Ecosystem respiration	BEPS	0.07°	[4]
	Ecosystem respiration	LGS	500m°	[9]
climate	Air temperature	ERA5-Land	10km	[7]
	Precipitation	ERA5-Land	10km	[7]
	Solar radiation	ERA5-Land	10km	[7]
	Wind speed	ERA5-Land	10km	[7]
soil	Soil water content	ERA5-Land	10km	[7]
	Soil temperature	ERA5-Land	10km	[7]
land cover	Underlying surface type	CCI-LC	300m	[1]

31 S3 Supplementary Figures

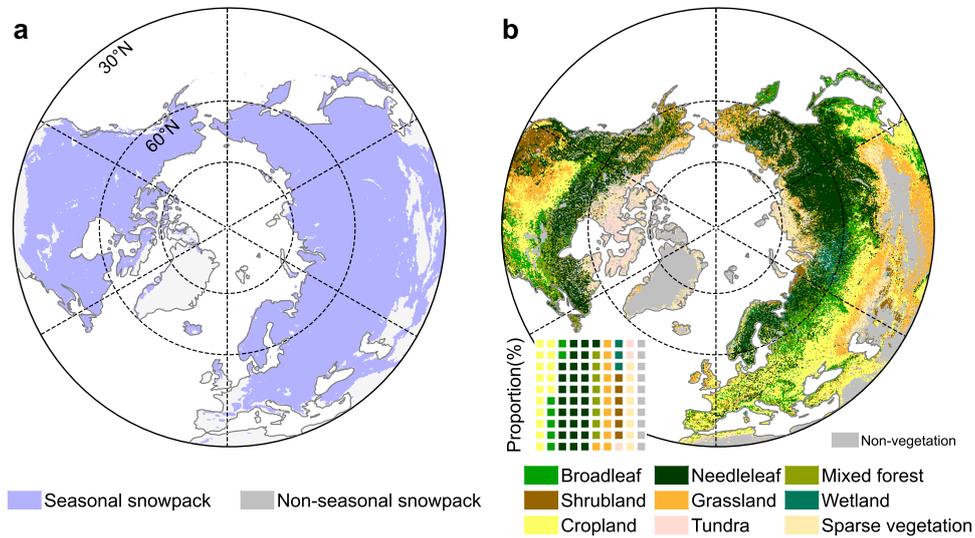


Figure S1: Spatial distribution of seasonal snowpack and vegetation types in the study area. The inset waffle in (b) indicates the proportion of the vegetation type in the Northern Hemisphere ($>30^\circ\text{N}$). Each pixel corresponds to 1%.

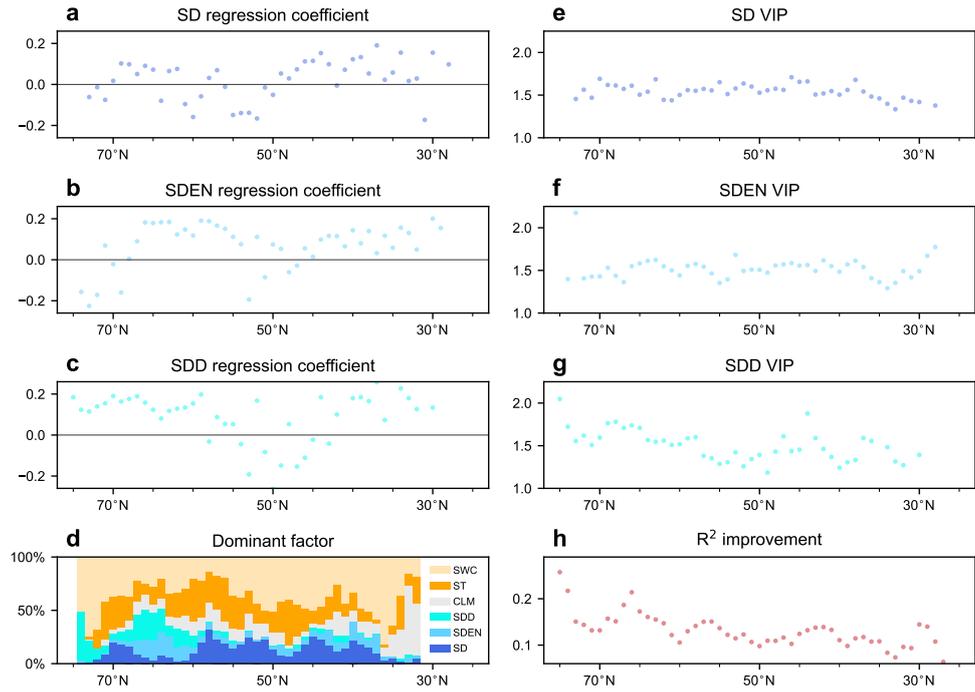


Figure S2: The impacts of snowpack on winter ecosystem respiration in relation to latitude. (a-c) Latitudinal distribution of regression coefficients of snowpack indicators in partial least squares regression (PLSR) analysis. Each dot represents the mean value of the regression coefficients between the snowpack indicators and $Reco_{winter}$ in a specific interval of latitude. (d) Latitudinal distribution of the proportions of dominant indicators to $Reco_{winter}$. Only intervals with more than 30 observations are remained. (e-g) Latitudinal distribution of variable importance on projection (VIP) of snowpack indicators in PLSR analysis. (h) Improvements in determination coefficients (R^2) employing three snowpack indicators in the PLSR analysis across different latitudes. The latitude gradient is binned every 1 degree. SD, snowpack depth; SDEN, snowpack density; SDD, snowpack duration days; CLM, climate indicators; ST, soil temperature; SWC, soil water content.

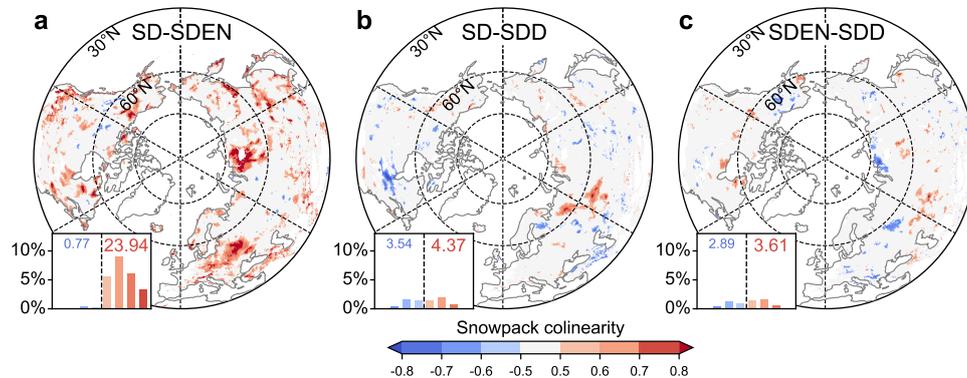


Figure S3: Partial correlations between different snowpack indicators. The inset bar plot indicates the proportion of negative and positive partial correlation coefficients. The regions shaded in gray denote area of weak correlations. SD, snowpack depth; SDEN, snowpack density; SDD, snowpack duration days.

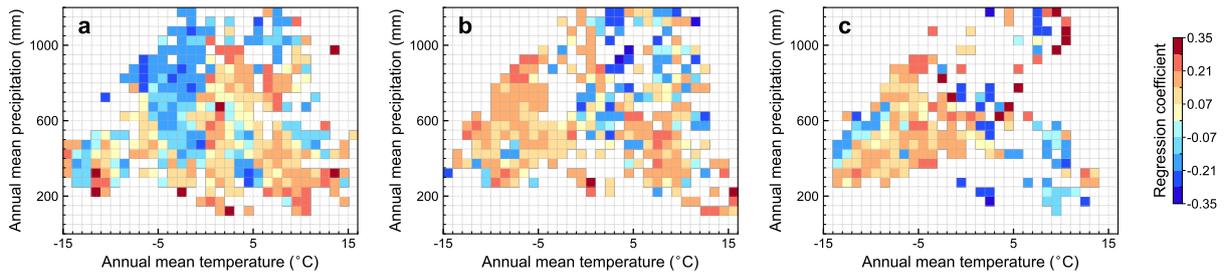


Figure S4: Variations in the regression coefficients between snowpack indicators and winter ecosystem respiration ($Reco_{winter}$) along temperature and precipitation gradients. Each zone represents the mean value of the regression coefficients of the snowpack indicators in partial linear regression analysis in a specific interval of annual mean air temperature and precipitation. Only zones over 30 observations are remained. The mean annual air temperature and precipitation gradients are binned every 1°C and 50mm, respectively. SD, snowpack depth; SDEN, snowpack density; SDD, snowpack duration days.

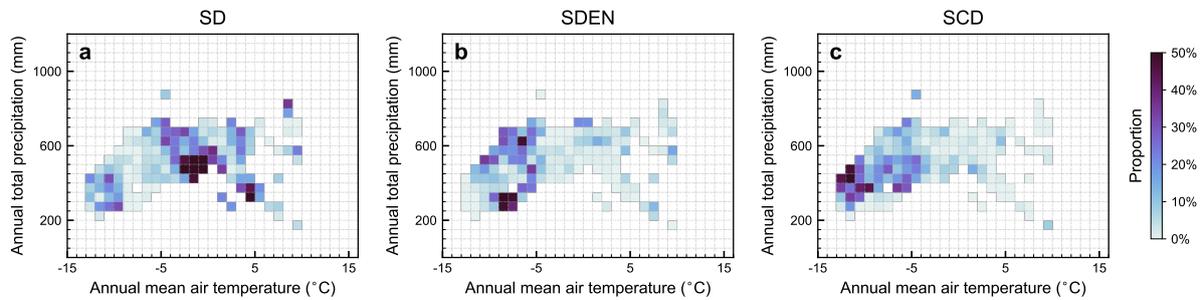


Figure S5: The proportions of snowpack indicators as dominant indicators for winter ecosystem respiration ($Reco_{winter}$) along temperature and precipitation gradients. Only zones over 30 observations are remained. The mean annual air temperature and precipitation gradients are binned every 1°C and 50mm, respectively. SD, snowpack depth; SDEN, snowpack density; SDD, snowpack duration days.

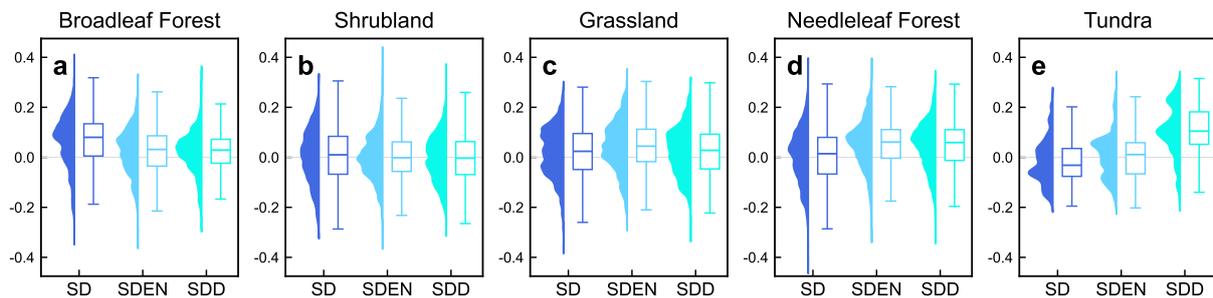


Figure S6: Variations in the relation between snowpack and winter ecosystem respiration ($Reco_{winter}$) among five main vegetation types (a. broadleaf forest, b. shrubland, c. grassland, d. needleleaf forest, and e. tundra). The left violin plots show the distributions of the regression coefficients of snowpack indicators in the per-pixel partial least squares regression analysis. The centerlines in the box plots indicate the median values, and the whiskers indicate the 1/99th values. The upper bars present the proportions of the dominant indicators in different vegetation types. SD, snowpack depth; SDEN, snowpack density; SDD, snowpack duration days.

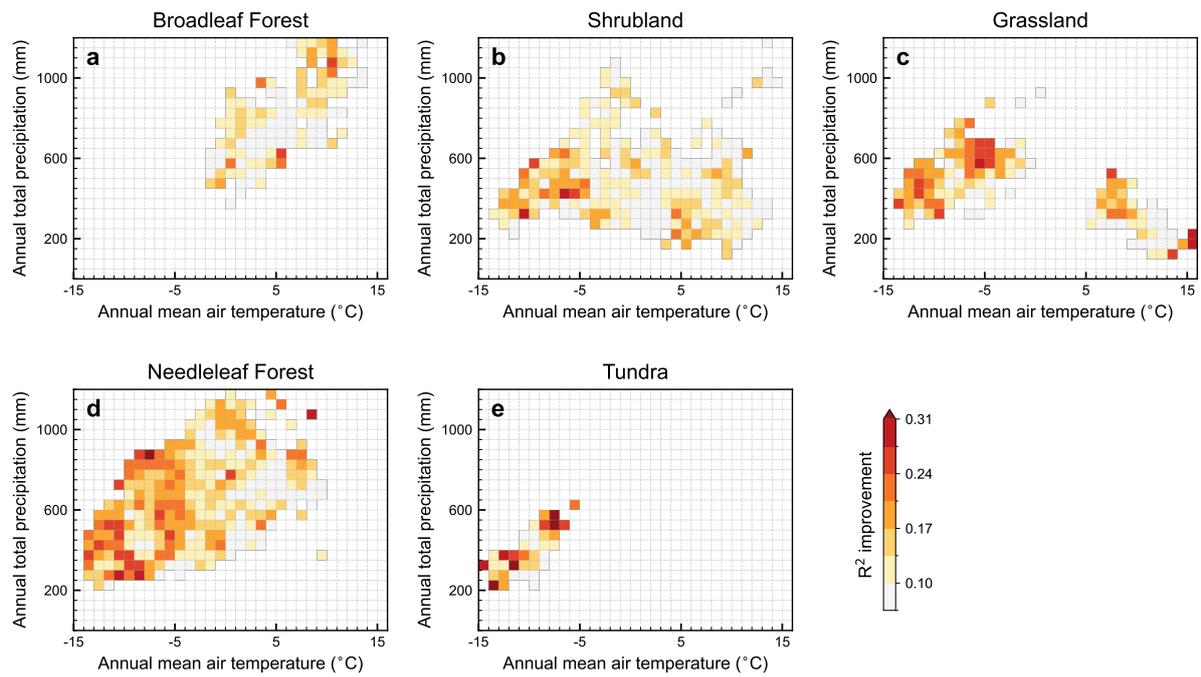


Figure S7: Variations in the significance of snowpack to winter ecosystem respiration ($\text{Reco}_{\text{winter}}$) along temperature and precipitation gradients among five main vegetation types (a. broadleaf forest, b. shrubland, c. grassland, d. needleleaf forest, and e. tundra). Each zone represents the mean value of improvements in the model determination coefficients (R^2) when multiple snowpack indicators are considered in a specific interval of temperature and precipitation gradients. Only intervals with more than 30 observations are remained. The temperature and precipitation gradients are binned every 1°C and 50 mm, respectively.

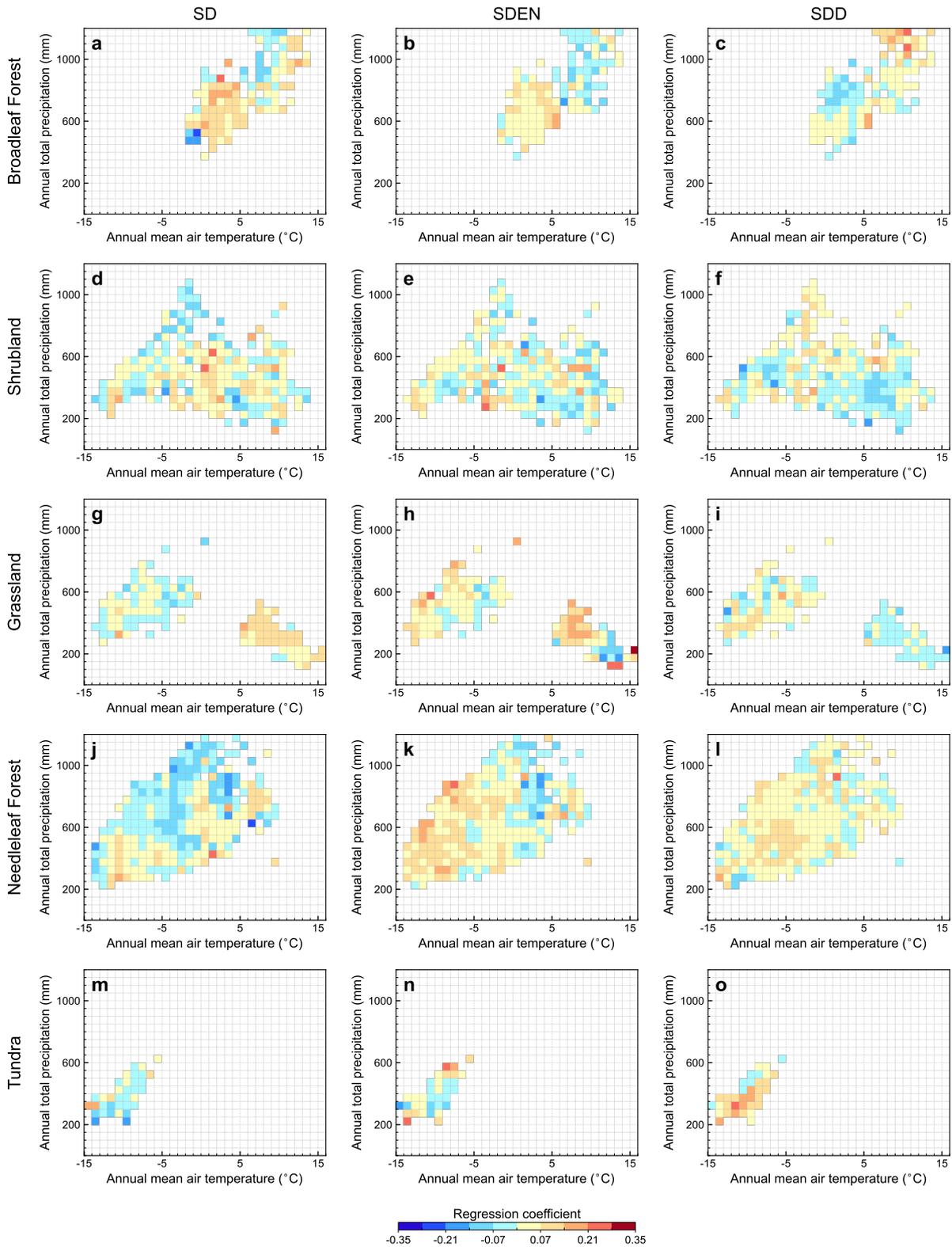


Figure S8: Variations in the regression coefficients between snowpack indicators and winter ecosystem respiration ($Reco_{winter}$) along temperature and precipitation gradients among five main vegetation types. Each zone represents the mean value of the regression coefficients between the snowpack indicators and $Reco_{winter}$ in a specific interval of annual mean air temperature and precipitation. Only intervals with more than 30 observations are remained. The mean annual air temperature and precipitation gradients are binned every 1°C and 50mm, respectively. SD, snowpack depth; SDEN, snowpack density; SDD, snowpack duration days.

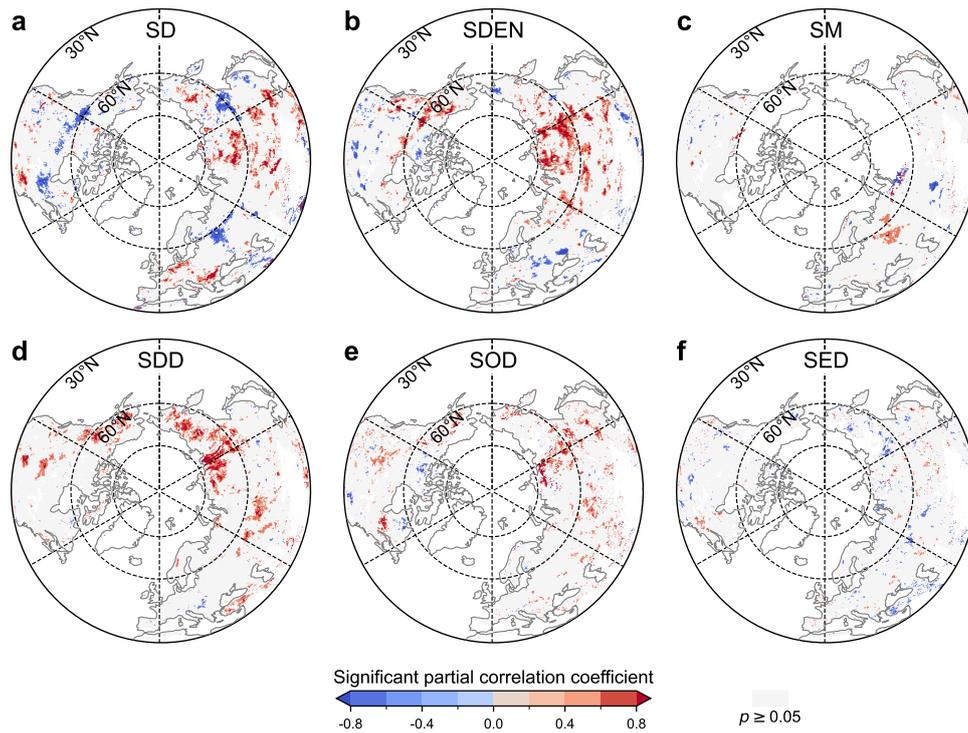


Figure S9: Spatial patterns of the significant partial correlation coefficients between the snowpack indicators and winter ecosystem respiration ($Reco_{winter}$) based on the BEPS dataset. The region shaded in gray denotes areas of non-significance ($p \geq 0.05$). SD, snowpack depth; SDEN, snowpack density; SM, total snowmelt; SDD, snowpack duration days; SOD, snowpack onset date; SED, snowpack end date.

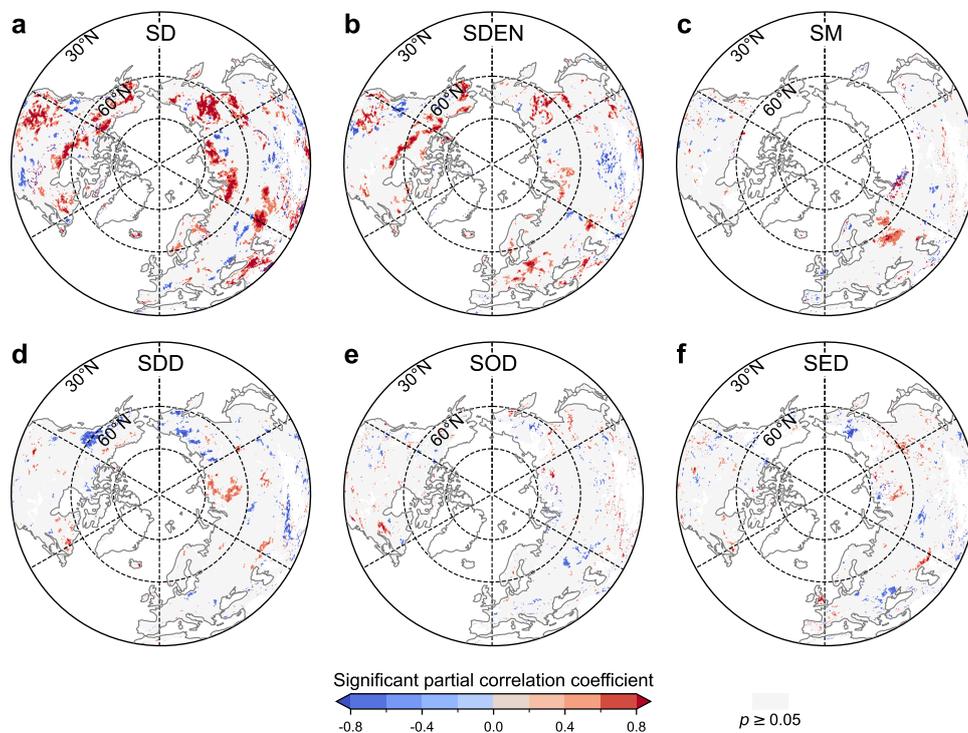


Figure S10: Spatial patterns of the significant partial correlation coefficients between the snowpack indicators and winter ecosystem respiration ($Reco_{winter}$) based on the LGS dataset. The region shaded in gray denotes areas of non-significance ($p \geq 0.05$). SD, snowpack depth; SDEN, snowpack density; SM, total snowmelt; SDD, snowpack duration days; SOD, snowpack onset date; SED, snowpack end date.

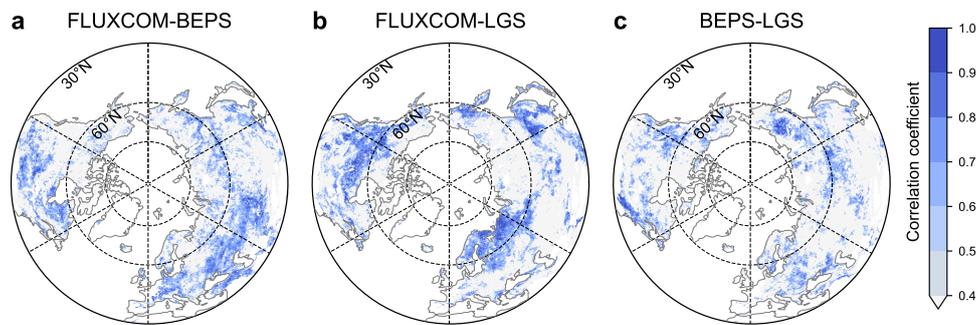


Figure S11: Comparison of the consistency between different ecosystem respiration datasets in the study area. a, b, and c indicate the correlation coefficient between FLUXCOM and BEPS, FLUXCOM and LGS, and BEPS and LGS, respectively. The correlation coefficient of all results are at a significance level of $P < 0.05$.

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