Vegetation type is an important predictor of the arctic summer land surface energy budget

Despite the importance of high-latitude surface energy budgets (SEBs) for land-climate interactions in the rapidly changing Arctic, uncertainties in their prediction persist. Here, we harmonize SEB observations across a network of vegetated and glaciated sites at circumpolar scale (1994–2021). Our variance-partitioning analysis identifies vegetation type as an important predictor for SEB-components during Arctic summer (June-August), compared to other SEB-drivers including climate, latitude and permafrost characteristics. Differences among vegetation types can be of similar magnitude as between vegetation and glacier surfaces and are especially high for summer sensible and latent heat fluxes. The timing of SEB-flux summer-regimes (when daily mean values exceed 0 W m$^{-2}$) relative to snow-free and -onset dates varies substantially depending on vegetation type, implying vegetation controls on snow-cover and SEB-flux seasonality. Our results indicate complex shifts in surface energy fluxes with land-cover transitions and a lengthening summer season, and highlight the potential for improving future Earth system models via a refined representation of Arctic vegetation types.

As the Arctic warms at a fast pace above the global average$^{1,2}$, changes to a broad range of biogeophysical variables are being reported and projected$^{3,4}$. These changes include increases in rainfall, permafrost temperatures and permafrost thaw$^{5,6}$, declines in ice mass, snow thickness and -spatial extent$^{7,8}$, as well as complex changes in the composition, structure and function of Arctic vegetation, including shrub abundance, plant height and vegetation productivity$^{9,10}$. These changes impact climate dynamics at local to global scales, through various land-atmosphere feedbacks$^{11,12}$ that are mediated by the land surface energy budget$^{12,13}$ (SEB). Simply, the SEB is defined with the most relevant SEB-components:

$$\text{R}_{\text{net}} = \text{SW}_{\text{net}} + \text{LW}_{\text{net}} = H + LE + G + M$$

where $R_{\text{net}}$ is the net radiative energy absorbed (or lost) by the surface and $SW_{\text{net}}$ and $LW_{\text{net}}$ are surface net shortwave and longwave irradiances. $H$ is the sensible heat flux, $LE$ is the latent heat flux (excluding latent heat of fusion, which is separately denoted by ‘$M$’) and $G$ is the ground heat flux through snow, ice or soil (all units in W m$^{-2}$, Supplementary Table 1$^{14,15}$).

Despite their importance, uncertainties in SEB-components persist in high-latitude climate projections, specifically in the case of sensible and latent heat fluxes$^{16}$. These turbulent fluxes can directly feed back to Arctic biophysical variables by affecting near-surface atmospheric temperature and humidity$^{17}$. The magnitude and seasonality of SEB-components depend on a complex interplay of drivers, such as vegetation type, snow cover, soil and permafrost characteristics, topography, and meteorological conditions including cloud cover$^{18,19}$. However, to date, a quantitative understanding of the importance of vegetation type compared to other drivers of the Arctic SEB is missing$^{19,20}$. Land surface components in current Earth system models often represent Arctic vegetation by only a single or few plant functional types (PFTs)$^{20,21}$. Land surface components in current Earth system models often represent Arctic vegetation by only a single or few plant functional types (PFTs)$^{20,21}$. Previous observational studies demonstrate that Arctic vegetation types can influence SEB-components, including latent and sensible heat fluxes$^{22,23,24}$. However, these studies...
either focus on qualitative descriptions of conditions at different sites, or only cover limited geographic extents.

Therefore, here, we provide a quantitative, circumpolar assessment of the observed SEB of treeless land >60°N in the time period 1994–2021 and compare the predictive skill of vegetation type with other important SEB-drivers related to climate, topography, snow cover, permafrost characteristics and cloud cover (see Supplementary Table 1 for a full list of SEB-drivers identified in this study through a systematic literature review). Specifically, we harmonize in situ observations from regional and global monitoring networks (number of sites: 64, number of site-years: 652; Supplementary Tables 2, 3). Using literature-based site descriptions, we classify the vegetation type at each site according to the categories of the Circumpolar Arctic Vegetation map (CAVM), the most thematically detailed classification currently available at the circumpolar scale. These CAVM classes describe barren complexes (<40% horizontal plant cover), graminoid tundra, prostrate dwarf-shrub tundra, erect-shrub tundra and wetland complexes. Additionally, our data contained sites classified as glacier and boreal peat bogs, the latter of which occur south of the Arctic tree line but largely lack tree cover (Supplementary Fig. 1–3). For each site, we derived additional climatic and biophysical SEB-drivers using spatial data products (Supplementary Fig. 4). With these data, we quantify the magnitude and seasonality of surface energy fluxes and compare the relative importance of vegetation type and other SEB-drivers for explaining variations in SEB-patterns. We especially focus on the summer season (June–August), which is when local controls by the land surface are expected to be more important compared to the winter season.

Results

Importance of vegetation types for the terrestrial Arctic SEB

We use a variance partitioning analysis to compare the ability of 15 selected SEB-drivers (Supplementary Table 1) to predict summer mean magnitudes of the surface energy fluxes \( R_{\text{net}}, H, LE \) and \( G \) (Fig. 1; vegetation subset of data excluding glacier). This variance partitioning method allows us to account for the statistical confounding of predictors by discerning variance in surface energy fluxes explained jointly or independently by different drivers (see Methods).

We show that vegetation type is an important predictor of summer surface energy flux magnitudes. This importance is specifically pronounced for \( H \) and \( LE \) (Fig. 1b, c) for which vegetation type explains on average 56.3% (range: 53.8–58.8%) and 71.7% (range: 61.4–81.9%) of variance, respectively.

For \( G \) (Fig. 1d), vegetation type is ranked among the top three predictors (average explained variance 31.7%); after landscape-scale dominant vegetation (CAVM type; 40.6%) and bioclimatic subzone (CAVM subzone; 39.1%). These CAVM-derived variables are based on satellite-observed reflectance (including the normalized difference vegetation index, NDVI) and Arctic phytogeographic zones in combination with summer land surface temperatures, respectively (Methods).

For \( R_{\text{net}} \) (Fig. 1a), latitude and snow cover duration are the most important predictors, whereas vegetation type shows intermediate importance. However, results from a supplementary analysis with normalized fluxes (i.e., daily mean fluxes divided by daily maximum potential incoming shortwave radiation; Methods) show that vegetation type again ranks among the three most important predictors for \( R_{\text{net}} \) (Supplementary Fig. 5), together with bioclimatic subzone and landscape-scale dominant vegetation. The predictive ability of vegetation type for normalized fluxes of \( H, LE \) and \( G \) is similar to that of non-normalized fluxes (Supplementary Fig. 5). Vegetation type is among the top three predictors for normalized \( SW_{\text{net}} \) (\( n.SW_{\text{net}} \)) and even the most important predictor for normalized \( LW_{\text{net}} \) (\( n.LW_{\text{net}} \)). Vegetation type is also an important predictor of albedo and surface temperature \( (T_{\text{surf}}) \), which are directly related to \( SW_{\text{net}} \) and \( LW_{\text{net}} \) (Supplementary Fig. 5).

Magnitude of the terrestrial Arctic SEB across land cover types

Using a linear mixed-model analysis (Methods), we estimate the mean (±95% confidence interval) surface energy fluxes for the terrestrial

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**Fig. 1** | Relative importance of 15 drivers of the surface energy budget (SEB) for average summer surface energy flux magnitudes at non-glacier sites. Bars show the mean (bar height) and range (lines for each bar) of explained variance (%) averaged across all possible models with 2 predictors for each SEB-driver and corresponding summer magnitudes of surface energy fluxes (W m⁻²): (a) \( R_{\text{net}} \): net radiation, (b) \( H \): sensible heat flux, (c) \( LE \): latent heat flux, (d) \( G \): ground heat flux. SEB-drivers: Vegetation type (dark green); local-scale, in situ vegetation type; CAVM type (green); landscape-scale, dominant vegetation type (surrounding area with radius of 500 m); CAVM subzone (light green); bioclimatic subzone; Permafrost extent (light blue); permafrost spatial extent; Permafrost ice content (grey); permafrost ground ice content; Temperature (red); mean annual air temperature; Summer warmth (dark orange); summer warmth index; Continentality (orange): Conrad’s continentality index; Precipitation (light purple): mean annual precipitation; Snow amount (dark purple): mean annual snow water equivalent; Snow duration (purple): median annual snow cover duration; Cloud cover (light orange): mean cloud cover; Cloud temperature (yellow): mean cloud-top temperature; Latitude (dark blue): latitude (WGS84); Altitude (light blue): mean altitude (surrounding area with radius of 500 m; see Methods and Supplementary Table 1). n: average nr. of sites in parentheses. Results are based on the vegetation subset of our data (excluding glacier sites): nr. of sites: 31, nr. of site years: 234, period: 1994–2021. We repeated the analysis with additional surface energy fluxes, including normalized fluxes expressed as percentage of maximum potential incoming shortwave radiation (indicated with “n.” prefix in Supplementary Fig. 5). Source data are provided as a Source Data file.
Arctic (including vegetated and glacier sites) in summer (June–August) and across the entire year (Table 1). We find that vegetation type has a significant relationship with the mean magnitude of \( H \), \( LE \), \( SW_{\text{net}} \), and \( LW_{\text{net}} \) in summer ("Effect significance" in Table 1). At the yearly timescale, we find a statistically significant relationship of vegetation type with \( R_{\text{net}} \) (Table 1). For other surface energy fluxes including \( H \) and \( LE \), available data is incomplete at this timescale, which hinders a proper assessment of their yearly magnitude and of the SEB closure (Supplementary Discussion).

Using a post-hoc analysis of the linear mixed-model results (Methods), we test the pairwise differences of summer surface energy flux magnitudes among vegetation types. We find strong differences for \( H \), \( LE \) and \( LW_{\text{net}} \) among vegetation types, which are similar to even higher magnitude than differences between glacier and vegetation types (Supplementary Table 4). For example, for summer \( LE \), the strongest difference (\( P \)-value < 0.001) is found between barren tundra (mean estimate = 0 W m\(^{-2} \)) and boreal peat bog (mean estimate = 75 W m\(^{-2} \)). For summer \( H \), almost equally strong differences (\( P \)-value < 0.05) are found between barren tundra (mean estimate = -18 W m\(^{-2} \)) and erect shrub tundra (mean estimate = -38 W m\(^{-2} \)) as well as prostrate shrub tundra (mean estimate = -39 W m\(^{-2} \)), respectively. For summer \( LW_{\text{net}} \), we again find the strongest differences between barren tundra (mean estimate = -29 W m\(^{-2} \)) and erect-shrub tundra (mean estimate = -32 W m\(^{-2} \)) as well as prostrate-shrub tundra (mean estimate = -49 W m\(^{-2} \)). Most significant pairwise differences among vegetation types include comparisons to either barren or boreal peat bog and differences among prostrate-shrub tundra, erect-shrub tundra and wetlands are not or only marginally significant (Table 1; Supplementary Table 4).

In a supplementary analysis with normalized fluxes and the vegetation data subset only (excluding glaciers, Supplementary Table 5), we find that vegetation type effects on \( H \) and \( LE \) are significant for each summer month (June–August). For other surface energy fluxes, we find that effect significance changes throughout the summer season; for example, vegetation type is significantly related to albedo and \( R_{\text{net}} \) in June and July, respectively, and to \( G \) in August (Supplementary Table 5).

### Seasonality of the Arctic SEB across vegetation types

The cumulative summer energy budget depends on both the magnitude and the seasonality of SEB fluxes. In the Arctic, the seasonality of SEB fluxes is largely governed by the seasonal changes in incoming radiation, temperature, cloud cover and associated melt and onset of snow cover\(^ {13,38} \). To assess the role of vegetation type for the seasonal change in SEB-flux magnitudes, we quantify the timing of SEB-flux "summer-regimes" relative to the timing of the snow-free date in spring and the snow-onset date in autumn\(^ {13,36} \). Specifically, we characterize the typical seasonal development of mean daily surface energy fluxes for different vegetation types and glacier sites (Fig. 2; Supplementary Fig. 6) using a subset of the data covering the recent two decades (Methods). We define the summer regime for \( R_{\text{net}} \), \( H \), \( G \), and \( T_{\text{surf}} \) as the time period when daily mean values exceed 0 W m\(^{-2} \) and 0°C, respectively. For albedo, we define the summer-regime as the time period when daily mean values are below the mean of the yearly minimum and maximum (Methods). Finally, we compare the timing of the summer regime period of \( R_{\text{net}} \), \( H \), \( G \), \( T_{\text{surf}} \) and albedo to the timing of MODIS\(^ {34} \)-observed spring snow-free date and autumn snow-onset date aggregated for each vegetation type (Fig. 3).

We find that for \( R_{\text{net}} \), \( H \) and \( G \), across vegetation types, transitions into the summer-regime occur significantly earlier than the spring
snow-free date (mean day of year ± s.d. = 151 ± 10; difference in days to the snow-free date for Rnet: −56 ± 27; H: −33 ± 18; G: −39 ± 11; Welch t-test *P* < 0.05 for all). The start into the summer-regime for Tsurf and albedo is not significantly different from the snow-free date (Fig. 3). The timing of the end of the summer-regime is not significantly different from the snow-free date (mean day of year ± s.d. = 275 ± 10) for all surface energy fluxes, except G, which drops below 0 Wm⁻² before snow cover onset (difference in days to the snow-free date for Rnet: −3 ± 7; H: −10 ± 11; Tsurf: 8 ± 21; albedo: 12 ± 8; G: −19 ± 20; Welch t-test *P* < 0.05 for G).

For Rnet and H, variability among vegetation types is larger for the start of summer-regime timings compared to the end. Standard deviations for G show the opposite pattern (i.e., are small at the start of season and large at end of season; Fig. 3). For H, the range in start of summer-regime timing relative to the snow-free date is 41 days, with the earliest occurring in erect-shrub tundra (60 days before the snow-free date) and the latest in prostrate-shrub tundra and boreal peat bogs (20 and 19 days before the snow-free date, respectively). An even larger range of 74 days is estimated for the timing in Rnet, which occurs earliest in erect-shrub tundra (108 days before the snow-free date) and...
latest in boreal peat bogs (34 days before the snow-free date). By comparison, the ranges in end-timings across vegetation types are 19 days for H and 17 days for $R_{\text{net}}$. For G, the range in relative start of summer-regime timing is 19 days (earliest in prostrate-shrub tundra: 51 days before the snow-free date; latest in boreal peat bogs and erect-shrub tundra: 32 and 33 days before the snow-onset date, respectively), compared to the 50-day range in end of summer-timing (earliest in boreal peat bogs: 56 days before the snow-onset date; latest in graminoid tundra: 6 days before the snow-onset date).

Discussion

Our quantitative assessment of surface energy budget (SEB) observations across the treeless, terrestrial Arctic shows that vegetation type is a powerful predictor of summer (JJA) surface energy fluxes, especially for latent and sensible heat fluxes. The results remain robust for normalized surface energy fluxes that are adjusted for potential incoming shortwave radiation and indicate that differences among vegetation types can be as significant as differences between glaciated and vegetated surfaces.

One reason for the strong predictive power of vegetation type could be that vegetation types reflect integrative proxies of distinct combinations of environmental conditions that control the SEB, including temperature, topography, soil moisture, and permafrost characteristics. However, it has also been shown that the CAVM classes, upon which our vegetation types are largely based, do differ in SEB-relevant traits and functions such as vegetation height, productivity and albedo, and therefore, causal effects of vegetation types can also be expected. We argue that it is likely a combination of both reasons behind the observed predictive power of vegetation type. Further research will be needed to identify the specific vegetation trait combinations that are most relevant for the SEB in the Arctic, including traits not represented by the main CAVM classes we used (Supplementary Discussion), and to better constrain the implications of changing Arctic vegetation productivity, plant height and shrub abundance for the SEB. Nevertheless, our results highlight the potential for improving the predictions of Arctic surface energy fluxes, specifically of summer latent and sensible heat fluxes, by a more comprehensive treatment of vegetation types and how environmental conditions interact with associated vegetation functional traits.

Our variance partitioning analysis also reveals a low predictive power of cloud cover, which is counter-intuitive, but can be explained by the persistence of high fractional cloud cover and its consequent low spatial variability across large parts of the Arctic in summer. Therefore, even though cloud cover has a large effect on the summer latent and sensible heat fluxes, especially in the case of boreal peat bogs and shrub-dominated tundra (Table 1), all of which show sensible heat fluxes of equal or greater magnitude than latent heat fluxes. Boreal peat bogs are characterized by high moss coverage lacking stomatal control of water vapor exchange with the atmosphere. Future changes in peatland cover depend on complex vegetation-water cycle feedbacks that additionally can be mediated by permafrost thaw and microtopography. These feedbacks remain poorly understood, partially because most current coupled Earth system models lack a representation of peatland functional types. Nevertheless, in case that boreal peatlands were to expand further north into the Arctic tundra with climate warming, our results suggest a potential shift of surface energy partitioning towards latent heat flux, with implications for current and future evaporative water loss, precipitation and soil water availability.

In the case of summer sensible heat flux, differences between barren and shrub-dominated tundra are of similar magnitude to differences between glacier and other vegetation types (Supplementary Table 4). Interestingly, barren tundra, similar to glaciers but in contrast to all other vegetation types, has a negative summer sensible heat flux, indicating that barren tundra areas are currently a heat sink. Barren tundra covers around one-fifth of the terrestrial Arctic area and is expected to decrease under Arctic climate warming, which suggests a potential positive feedback to climate warming. However, barren tundra is only covered by one study site in our in situ observations dataset and generally underrepresented in the surface energy budget literature (Supplementary Discussion). Therefore, our results need to be interpreted with caution and further research is needed to assess potential climate feedbacks with more certainty.

In this study, we synthesize observations on the seasonality of surface energy fluxes for a consistent classification of vegetation types across the Arctic. Our results indicate that vegetation types differ in the seasonal timing of surface energy flux summer-regime start and end, relative to the spring snow-free and the autumn snow-onset date, respectively. The timing of snow-cover disappearance in spring and onset in autumn is a major factor controlling both the SEB and vegetation activity in the Arctic. However, vegetation type can also affect the distribution, trapping and density of snow cover, with important consequences for snowmelt and snow onset, as well as for carbon, water and energy fluxes. Our results suggest elevated variability among vegetation types in the estimated start (and end) dates of net positive $R_{\text{net}}$ and (H and G) relative to the spring snow-free (and autumn snow-onset) dates. For example, we show an estimated start of net positive H relative to the snow-free date that occurs 40 days earlier in erect-shrub tundra compared to prostrate-shrub tundra, which could be indicative of erect-shrub vegetation protruding through the snow cover earlier compared to prostrate-shrub vegetation. While erect-shrub and prostrate-shrub tundra show similar average summer magnitudes in H (Table 1), these temporal differences can have implications for the cumulative sensible energy flux to the atmosphere. The nature of multiple interactions among vegetation types and snow cover is complex and trends in the timing of snow-free and -onset dates, as well as vegetation phenology are highly heterogeneous across the Arctic. Resolving related consequences for surface energy fluxes, the soil thermal regime and permafrost thaw need further and more detailed investigations. We contend that in this effort, the seasonality of surface energy fluxes is as important as their magnitude.
To conclude, changes in the surface energy budget can affect the composition, structure and function of Arctic vegetation. The Arctic system is highly sensitive to climate change, exerts key land-feedbacks relevant for global climate dynamics, and harbors a range of vegetation types with unique traits including mosses and lichens. For the future, widespread and rapid redistribution of Arctic vegetation is predicted. Understanding and predicting how these changes in turn affect climate is essential for reducing persisting uncertainties in climate projections. The potentially important but still uncertain role of Arctic vegetation for climate feedbacks has been highlighted before. Previous studies have shown that local estimates of surface energy fluxes are improved if land surface components of Earth system models account for differentiated Arctic PFTs at several high-latitude validation sites and regions. Here, we provide quantitative evidence of the importance of vegetation types for predicting Arctic surface energy budgets at circumpolar scale and support recent calls for refined accounting of high-latitude vegetation types and associated vegetation functions in land surface components of Earth system models.

Methods

Surface energy fluxes and components

In our study, we focused on the circumpolar land north of 60° latitude, and specifically on the extent of the circumpolar Arctic vegetation map (CAVM). We obtained half-hourly and hourly in situ observations of energy fluxes and meteorological variables from the monitoring networks FLUXNET (fluxnet.org; FLUXNET2015 dataset), AmeriFlux (ameriflux.lbl.gov), AON (aon.iab.uaf.edu), ICOS (icos-cp.eu), GEM (g-e-m.dk), GC-Net (cires1.colorado.edu/steffen/gcnet) and PROMICE (promice.dk; Supplementary Table 3). We did not include observations from the European Flux Database Cluster (EFDC, europe-fluxdata.eu) because these data are largely located outside the domain of the CAVM.

We aggregated surface energy fluxes and components (Supplementary Table 1) to daily resolution as follows: (i) we extracted only directly measured data and excluded gap-filled data by filtering according to quality information; (ii) we performed a basic outlier filtering (excluding shortwave and longwave radiation flux values >1400 Wm⁻² in case of incoming/outgoing radiation <0 Wm⁻², excluding albedo values <0 and >1, excluding air and surface temperatures < −100 °C; (iii) we converted all times of measurements to local standard time (i.e. without daylight saving time); (iv) we calculated daily (i.e. 24 h) mean, minimum and maximum values for all days and surface energy fluxes and components where a minimum of 65% of data was available with a maximum temporal gap of 4.8 h; (v) we extracted metadata (units, measurement heights, original variable names, instrumentation) for all sites and variables; (vi) when data for the same time and location were available from several networks (partial overlapping of FLUXNET and AON with AmeriFlux), we averaged respective daily values across networks; (vii) in case data for the same time and location were measured by several sensors at one site (replicated measurements), we averaged across replicates; (viii) we harmonized units for all variables; (ix) we harmonized the flux direction convention for non-radiative energy fluxes (i.e. H, LE, and G; Supplementary Table 1) as “positive away from surface”; (x) we derived net radiation (Rn), net shortwave radiation (SWnet), net longwave radiation (LWnet) and albedo from corresponding daily aggregated incoming and outgoing shortwave and longwave radiation, respectively, if not otherwise available; (xi) we derived normalized fluxes for Rn (n.Rn), SWnet (n.SWnet), LWnet (n.LWnet), H (n.H), LE (n.LE) and G (n.G) as the percentage (%) of daily maximum potential incoming shortwave radiation based on location and topographical conditions.

Drivers of the surface energy budget (SEB-drivers)

We characterized all study sites available in the SEB-data according to environmental covariates (named SEB-drivers hereafter; Supplementary Table 1) that potentially have important effects on the magnitude and seasonality of surface energy fluxes from ancillary geographic data (Supplementary Fig. 4, Supplementary Table 3). We identified these relevant SEB-drivers according to our literature synthesis and consequent correlation analysis (Supplementary Discussion, Supplementary Figs. 7–9).

As the main SEB-driver of interest, we focused on the local-scale, in situ vegetation type (Vegetation type variable), which reflects the main classes described in the CAVM map (barren complexes, graminoid tundra, prostrate dwarf-shrub tundra, erect-shrub tundra, wetland complexes, glacier), plus boreal peat bogs.

To derive this in situ vegetation type variable, we extracted for each study site in the SEB-data the vegetation descriptions from adequate literature references (Supplementary Table 2). We categorized each site’s vegetation according to the most adequate CAVM-class by using the following decision chain: (i) assign the CAVM-class where most described species from in situ vegetation descriptions and Table S1 in ref. are in accordance. Take into account species’ ecological niche sizes (e.g. stenotypic plants are better indicators than eurytypic plants); (ii) if there is no species list and/or in case there are several CAVM candidate classes, take into account the general habitat and ecosystem descriptions (including community vertical and horizontal structure, soil moisture and acidity, topography); (iii) if there are still several CAVM candidate classes, take into account the bioclimatic subzone and evaluate the exact location of the site with available satellite data; (iv) if there are still several CAVM candidate classes, assign the most dominant CAVM-class; (v) in case of uncertainties, consult with the study author(s); (vi) If the vegetation is not similar to any CAVM-class, describe it according to the description of the study author(s) and/or adequate references (Supplementary Table 2).

This categorization revealed 1 barren tundra site (1 B3), 12 graminoid tundra sites (10 G4, 1 G3 and 1 G1), 3 prostrate-shrub tundra sites (2 P2 and 1 P1), 4 erect-shrub tundra sites (2 S2 and 2 S1), 8 wetland sites (3 W3, 3 W2 and 2 W1), 33 glacier sites (GL), and three sites that were not similar to any CAVM-class but clearly identified as boreal peat bogs (Supplementary Figs. 1–3; Supplementary Table 2).

For each study site in the SEB-data, we extracted the landscape-scale, dominant vegetation type in the site-surrounding area (radius = 500 m, CAVM type variable) from the raster version of the widely used original version and provides information at 1 km² spatial resolution and pan-Arctic scale north of the Arctic treeline. Compared to the Vegetation type variable, the CAVM-type is based on the analysis of a combination of large-scale satellite and environmental data, but both variables refer to the same class definition. The CAVM-classes are based on the plant physiognomy of the zonal vegetation in a given area, analogous to the widely applied Braun-Blanquet approach for plant communities on the ground.

The CAVM types used in this study reflect these main plant physiognomies (plus one glacier class) that are named according to the following dominant plant growth forms: B: barren and barren complexes (4 sites), G: graminoid tundra (10 sites), P: prostrate dwarf-shrub tundra (1 site), S: erect-shrub tundra (10 sites), W: wetland complexes...
For each study site, we averaged the mean annual air temperature (°C), the annual sum of precipitation (mm) and the annual sum of snow water equivalent (Snow amount variable, mm; de aggregated these categories into the following classes for glacier and non-Arctic zones are largely based on a combination of Arctic phytogeographic zones, dominant growth forms of plants and summer temperatures. Hence, these bioclimatic subzones are generally well aligned with summer warmth index (SWI) classes.

A confusion matrix showing the classification of study sites into Vegetation type and Permafrost ice content categories is shown in Supplementary Table 7.

For each study site, we extracted the bioclimatic subzone (CAVM subzone variable) as described in the circumpolar Arctic vegetation map (CAVM168). These five bioclimatic subzones (A-E) and additional classes for glacier and non-Arctic zones are largely based on a combination of Arctic phytogeographic zones6, dominant growth forms of plants and summer temperatures. Hence, these bioclimatic subzones are generally well aligned with summer warmth index (SWI) classes. A confusion matrix showing the classification of study sites into Vegetation type and CAVM subzone categories is shown in Supplementary Table 7.

For each study site, we extracted the median snow cover duration (Snow duration variable) from satellite-sensed daily snow cover (MODIS MOD10C141; Supplementary Table 3). Snow duration was calculated for each year as the number of days between the spring snow-free date (i.e. mean of days of year for last “snow” day and first “no snow” day MODIS categories) and the autumn snow-onset date (i.e. mean of days of year for last “no snow” day and first “snow” day MODIS categories). Yearly snow duration, snow-free date and snow-onset date for each study site were then aggregated by calculating the median across the years 2000–2020.

For each study site, we extracted mean annual cloud cover (%) and cloud-top temperature (°C) from monthly satellite imaging radiometer data (“cldamt” and “tc” products; ISCCP-Basic-H series67,68; Supplementary Fig. 4f, g; Supplementary Table 3) and averaged these variables for each study site across the years 1984–2016.

For each study site, we extracted the corresponding permafrost extent as described in the Circum-Arctic permafrost and ground ice map68 (NSIDC gdd318_map_circumArctic version 2; Supplementary Fig. 4b; Supplementary Table 3). This map describes 4 categories of permafrost extent, based on the percentage of the ground that is underlain by permafrost. There are additionally 5 separate categories for glaciers, relic permafrost, inland lakes, oceans and land with no permafrost. For the Permafrost extent variable used in this study, we aggregated these categories into the following five classes: continuous permafrost (C; 90–100% extent; 21 sites); discontinuous permafrost: (D; 50–90% extent; 5 sites); sporadic or isolated patches of permafrost (S; <50% extent; 4 sites); ocean/inland seas (o; 2 sites) and glaciers (g; 32 sites). A confusion matrix showing the classification of study sites into Vegetation type and Permafrost extent categories is shown in Supplementary Table 8.

Using the same permafrost data69,70 (Supplementary Fig. 4b; Supplementary Table 3), for each study site we extracted the corresponding permafrost ground-ice content class: high (h; >20% ice content; 8 sites), medium (m; 10–20% ice content; 7 sites), low (l; 0–10% ice content; 15 sites), ocean/inland seas (o; 2 sites), and glaciers (g; 32 sites). A confusion matrix showing the classification of study sites into Vegetation type and Permafrost ice content categories is shown in Supplementary Table 9.

For each study site we extracted the average altitude (m a.s.l.), slope (°) and northness of the aspect (1 if north-exposed, −1 if south-exposed; derived from the cosine of aspect in radians) in the surrounding area (radius = 500 m) from the satellite-sensed digital elevation model raster mosaic at 100 m spatial resolution (ArcticDEM: Arcticdem_mosaic_100_m_v3.0; ref. 70; Supplementary Fig. 4c; Supplementary Table 3).

Data analysis
For our analyses, we focused on the surface energy fluxes and components net radiation (Rnet, Wm⁻²), sensible heat flux (H, Wm⁻²), latent heat flux (LE, Wm⁻²), ground heat flux (G, Wm⁻²), net shortwave radiation (SWnet, Wm⁻²), net longwave radiation (LWnet, Wm⁻²), albedo (unitless), and surface temperature (Tsurf, °C), air temperature (Tair, °C) and the difference between surface and air temperature (Tsurf-Tair, °C). We included albedo and Tsurf because they are directly related to the radiative SEB as follows:

\[
R_{\text{net}} = SW_{\text{in}}(1 - \text{albedo}) + LW_{\text{in}} - \epsilon \sigma T_{\text{surf}}^4,
\]

where \(SW_{\text{in}}\) and \(LW_{\text{in}}\) are the incoming shortwave and longwave radiation, respectively (Wm⁻²), \(\epsilon\) is the surface emissivity (≈1) and \(\sigma\) is the Stefan-Boltzmann constant. We repeated our analyses for normalized fluxes of \(R_{\text{net}}\) (n.Rnet), \(SW_{\text{net}}\) (n.SWnet), \(LW_{\text{net}}\) (n.LWnet), \(H\) (n.H), LE (n.LE) and G (n.G), which are all expressed in percent of potential incoming shortwave radiation90 (%; Supplementary Table 1). We included albedo and Tsurf because they are directly related to the radiative SEB as follows:

\[
R_{\text{net}} = SW_{\text{in}}(1 - \text{albedo}) + LW_{\text{in}} - \epsilon \sigma T_{\text{surf}}^4,
\]

where \(SW_{\text{in}}\) and \(LW_{\text{in}}\) are the incoming shortwave and longwave radiation, respectively (Wm⁻²), \(\epsilon\) is the surface emissivity (≈1) and \(\sigma\) is the Stefan-Boltzmann constant. We repeated our analyses for normalized fluxes of \(R_{\text{net}}\) (n.Rnet), \(SW_{\text{net}}\) (n.SWnet), \(LW_{\text{net}}\) (n.LWnet), \(H\) (n.H), LE (n.LE) and G (n.G), which are all expressed in percent of potential incoming shortwave radiation90 (%; Supplementary Table 1).
Vegetation type and derived mean ± s.e. for each DOY and surface (DOY) and study site. In a second step, we grouped study sites by moving average for each DOY (Fig. 2).

We estimated the magnitude of the surface energy fluxes $R_{\text{net}}, \text{SW}_{\text{net}}, \text{LW}_{\text{net}}, H, \text{LE}$, and $G$ for each Vegetation type at seasonal timescale (JJA) and yearly timescale (Y) using the full SEB-dataset (nr. sites = 64, nr. site years = 652; Table 1; Supplementary Table 4). We repeated this analysis for the monthly aggregated, normalized (i.e. potential incoming radiation-adjusted) summer fluxes $n.R_{\text{net}}, n.\text{SW}_{\text{net}}, n.\text{LW}_{\text{net}}, n.H, n.\text{LE}, n.G$, $\text{albedo}$ and $T_{\text{surf}}$ using the vegetation data subset (excluding glacier sites; nr. of sites: 31, nr. of site years: 234; Supplementary Table 5).

In both analyses, we averaged the daily mean values of the surface energy fluxes for each timescale, year and study site, where at least 80% of days with measurements were available. We then averaged surface energy flux values across years for each study site and estimated the mean ± 95% confidence interval (CI) as a function of Vegetation type by using a linear mixed-model analysis. Specifically, we modeled the study-site aggregated means of each surface energy flux as a function of Vegetation type (fixed effect) and the corresponding data distribution network (i.e. Ameriflux, FLUXNET etc.; random effect; Supplementary Table 2). To compare differences of summer surface energy flux estimates among Vegetation types, we applied a consequent post-hoc pairwise comparison with bonferroni correction of significance estimates (Supplementary Table 4).

With a cut-off of $0$ Wm$^{-2}$ all year in most cases. Using this data, we compared the timing of the summer regime of $R_{\text{net}}, H, G, T_{\text{surf}}$ and albedo to the timing of the snow-free period (Snow duration) for each Vegetation type. Specifically, we aggregated the snow-free and autumn snow-onset dates for each Vegetation type and subtracted these from the start and end of the summer regime period of the selected surface energy fluxes, respectively. Finally, we aggregated the start and end of summer-regime timings across Vegetation types for each selected surface energy flux variable, to test the differences in the timing of the surface energy flux summer-regime and snow-free/snow-onset dates, using corresponding two-sample Welch’s $t$-tests (Fig. 3).

**Data availability**

Source data are provided with this paper. The complete in situ observations surface energy budget components dataset (SEB-data), the SEB-driver dataset, as well as the literature synthesis dataset generated in this study have been deposited in the PANGAEA database under accession code: https://doi.pangaea.de/10.1594/PANGAEA.949792. AmeriFlux data can be accessed at: https://ameriflux.bnl.gov/login/?redirect_to=/data/download-data/AON data can be accessed at: http://aonlab.uaf.edu/data_access FLUXNET (including GEM and ICOS) data can be accessed at: https://fluxnet.org/data/download-data/GC-Net data can be accessed at: http://cires.colorado.edu/science/groups/steffen/gcnets/PROMICE data can be accessed at: https://promise.org/download-data/Circumpolar Arctic Vegetation Map data can be accessed at: https://data.mendeley.com/datasets/c4j5xwr6vk/1 Bioclimatic subzones can be accessed at: http://www.arcticatlas.org/maps/themes/cp/cpbz Climate data can be accessed at: https://chelsa-climate.org/ Snow cover data can be accessed at: https://nsidc.org/data/MOD10LC/versions/6 Cloud data can be accessed at: https://www.ncei.noaa.gov/data/international-satellite-cloud-climate-project-isccep-h-series-data/access/iscbbox-basic Permafrost data can be accessed at: ftp://sidads.colorado.edu/pub/DATASETS/fldc/ggd319_map_circumboreal/Altitude data can be accessed at: http://data.pgc.umn.edu/elev/dem/sets/ArcticDEM/mosaic/v3.0/100m/ Source data are provided with this paper.

**Code availability**

Code underlying this study is available in a Github repository and can be accessed at: https://github.com/oehrij/ArcticSEBSynthesis.

**References**

1. Serreze, M. C. & Barry, R. G. Processes and impacts of Arctic amplification: a research synthesis. Glob. Planet. Change 77, 85–96 (2011).
2. Chylek, P. et al. Annual mean arctic amplification 1970–2020: observed and simulated by CMIP6 climate models. Geophys. Res. Lett. 49, https://doi.org/10.1029/2021GL099371 (2022).
3. Box, J. E. et al. Key indicators of Arctic climate change: 1971–2017. Environ. Res. Lett. 14, 045010 (2019).
4. Meredith, M. et al. Polar Regions. In: Special Report on the Ocean and Cryosphere in a Changing Climate (eds Pörtner, H.-O., et al.) Ch.3 (IPCC, 2019).
5. McRostie, M. R., Stroeve, J., Serreze, M., Forbes, B. C. & Screen, J. A. New climate models reveal faster and larger increases in Arctic precipitation than previously projected. Nat. Commun. 12, 6765 (2021).
6. Elmendorf, S. C. et al. Plot-scale evidence of tundra vegetation change and links to recent summer warming. Nat. Clim. Chang. 2, 453–457 (2012).
7. Myrseth, I. H. et al. Complexity revealed in the greening of the Arctic. Nat. Clim. Chang. 10, 106–117 (2020).
8. Bjorkman, A. D. et al. Plant functional trait change across a warming tundra biome. Nature 562, 57–62 (2018).
9. Assmann, J. J. et al. Local snow melt and temperature—but not regional sea ice-explain variation in spring phenology in coastal Arctic tundra. Glob. Chang. Biol. 25, 2258–2274 (2019).

10. Rosbakh, S. et al. Siberian plants shift their phenology in response to climate change. Glob. Chang. Biol. 27, 4435–4448 (2021).

11. Loranty, M. M. et al. Reviews and syntheses: changing ecosystem influences on soil thermal regimes in northern high-latitude permafrost regions. Biogeosciences 15(17), 5287–5313 (2018).

12. Wild, M. et al. The global energy balance from a surface perspective. Clim. Dyn. 40, 3107–3134 (2013).

13. Bonan, G. Surface Energy Fluxes. In: Ecological Climatology: Concepts and Applications. 3rd edn, 193-208 (Cambridge University Press, 2015).

14. Sellers, P. J. et al. Modeling the exchanges of energy, water, and carbon between continents and the atmosphere. Science 275, 502–509 (1997).

15. Lund, M. et al. Spatiotemporal variability in surface energy balance across tundra, snow and ice in Greenland. Ambio 46, 81–93 (2017).

16. Duncan, B. N. et al. Space-based observations for understanding changes in the arctic-boreal zone. Rev. Geophys. 58, https://doi.org/10.1029/2019RG000652 (2020).

17. Loranty, M. M. et al. Reviews and syntheses: changing ecosystem influences on soil thermal regimes in northern high-latitude permafrost regions. Biogeosciences 15(17), 5287–5313 (2018).

18. Wullschleger, S. D. et al. Plant functional types in Earth system models: past experiences and future directions for application of dynamic vegetation models in high-latitude ecosystems. Ann. Bot. 114, 1–16 (2014).

19. Sulman, B. N. et al. Integrating Arctic plant functional types in a land surface model using above- and belowground field observations. J. Adv. Model. Earth Syst. 13, https://doi.org/10.1029/2020MS002366 (2021).

20. Raynolds, M. K. et al. A raster version of the Circumpolar Arctic Vegetation Map (CAVM). Remote Sens. Environ. 232, 111297 (2019).

21. El Sharif, H. et al. Surface energy budgets of Arctic tundra during growing season. J. Geophys. Res. Atmos. 124(13), 6999–7017 (2019).

22. Beringer, J., Chapin, F. S. III, Thompson, C. C. & McGuire, A. D. Surface energy exchanges along a tundra-forest transition and feedbacks to climate. Agric. Meteorol. 131(3-4), 143–161 (2005).

23. McFadden, J. P., Chapin, F. S. III & Hollinger, D. Y. Subgrid-scale variability in the surface energy balance of arctic tundra. J. Geophys. Res. Atmos. 103(D22), 28947–28961 (1998).

24. Justz, J., Eugster, W., Heijmans, M. & Schepanski-Strub, G. Converting radiation and soil heat fluxes in Arctic shrub and wet sedge tundra. Biogeosciences 13, 4049–4066 (2016).

25. Loranty, M. M., Goetz, S. J. & Beck, P. S. A. Tundra vegetation effects on pan-Arctic albedo. Environ. Res. Lett. 6(2), 024014 (2011).

26. Kropp, H. et al. Shallow soils are warmer under trees and tall shrubs across Arctic and Boreal ecosystems. Environ. Res. Lett. 16, 015001 (2020).

27. Chapin, F. S., Eugster, W., McFadden, J. P., Lynch, A. H. & Walker, D. A. Summer differences among Arctic ecosystems in regional climate forcing. J. Clim. 13, 2002–2010 (2000).

28. Pastorello, G. et al. The FLUXNET2015 dataset and the ONEFlux processing pipeline for eddy covariance data. Sci. Data 7, 225 (2020).

29. Novick, K. A. et al. The AmeriFlux network: a coalition of the willing. Agric. Meteorol. 249, 444–456 (2018).

30. Fausto, R. S. et al. Programme for monitoring of the Greenland Ice Sheet (PROMICE) automatic weather station data. Earth Syst. Sci. Data 13, 3819–3845 (2021).

31. Euskirchen, E. S. et al. Interannual and seasonal patterns of carbon dioxide, water, and energy fluxes from ectoral and thermokarst-impacted ecosystems on carbon-rich permafrost soils in Northeastern Siberia. J. Geophys. Res.: Biogeosci. 122, 2651–2668 (2017).

32. Euskirchen, E. S., Bret-Harte, M. S., Shaver, G. R., Edgar, C. W. & Romanovsky, V. E. Long-term release of carbon dioxide from Arctic Tundra Ecosystems in Alaska. Ecosystems 20, 960–974 (2017).

33. Steffen, K., Box J., E. & Abdalati, W. Greenland climate network: GC-Net. CRREL Special Report 98-103 (CRREL, 1996).

34. Vandecruys, B. et al. Firn cold content evolution at nine sites on the Greenland Ice Sheet between 1988 and 2017. J. Glaciol. 66, 591–602 (2020).

35. López-Blanco, E. et al. Multi-year data-model evaluation reveals the importance of nutrient availability over climate in arctic ecosystem C dynamics. Environ. Res. Lett. 15, 094007 (2020).

36. Christensen, T. R. et al. Multiple ecosystem effects of extreme weather events in the Arctic. Ecosystems 24, 122–136 (2021).

37. Bartsch, A., Höfler, A., Kriokslettner, C. & Trafaier, A. Land cover mapping in Northern High Latitude Permafrost Regions with Satellite Data: achievements and remaining challenges. Remote Sens. 8(12), 979 (2016).

38. Cox, C. J. et al. Drivers and environmental responses to the changing annual snow cycle of northern Alaska. Bull. Am. Meteor. Soc. 98, 2559–2577 (2017).

39. Grünberg, I., Wilcox, E. J., Zwieback, S., Marsh, P. & Boike, J. Linking tundra vegetation, snow, soil temperature, and permafrost. Biogeosciences 17, 4261–4279 (2020).

40. Wilcox, E. J. et al. Tundra shrub expansion may amplify permafrost thaw by advancing snowmelt timing. Arct. Sci. 5, 202–217 (2019).

41. Hall, D. K., Riggs G. A., Solmonson, V. & Sips, N. M. MODIS/Terra Snow Cover Daily L3 Global 0.05Deg CMG. NASA National Snow and Ice Data Center DAAC, https://doi.org/10.5067/modis/mod10c1.008 (2015).

42. Raynolds, M. K., Comiso, J. C., Walker, D. A. & Verbyla, D. Relationship between satellite-derived land surface temperatures, arctic vegetation types, and NDVI. Remote Sens. ENV. 112(4), 1894–1894 (2008).

43. Shupe, M. D. et al. Clouds at arctic atmospheric observatories. part I: occurrence and macrophysical properties. J. Appl. Meteor. Climatol. 50, 626–644 (2011).

44. McVicar, T. R. et al. Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation. J. Hydrol. 416, 182–205 (2012).

45. Liljedahl, A. K. et al. Nonlinear controls on evapotranspiration in arctic coastal wetlands. Biogeosciences 8(11), 3375–3389 (2011).

46. Helbig, M. et al. Increasing contribution of peatlands to boreal evapotranspiration in a warming climate. Nat. Clim. Chang. 10, 555–560 (2020).

47. Shi, X. et al. Extending a land-surface model with Sphagnum moss to simulate responses of a northern temperate bog to whole ecosystem warming and elevated CO2. Biogeosciences 18, 467–486 (2021).

48. Stiegler, C., Lund, M., Christensen, T. R., Mastepanov, M. & Lindroth, A. Two years with extreme and little snowfall: effects on energy partitioning and surface energy exchange in a high-Arctic tundra ecosystem. Cryosphere 10, 1395–1413 (2016).

49. Bjorkman, A. D., Elmendorf, S. C., Beamish, A. L., Vellend, M. & Henry, G. H. R. Contrasting effects of warming and increased snowfall on Arctic tundra plant phenology over the past two decades. Glob. Chang. Biol. 21, 4651–4661 (2015).

50. Westergaard-Nielsen, A. et al. Transitions in high-Arctic vegetation growth patterns and ecosystem productivity tracked with automated cameras from 2000 to 2013. Ambio 46, 39–52 (2017).

51. Lund, M. et al. Trends in CO2 exchange in a high Arctic tundra heath, 2000–2010. J. Geophys. Res.: Biogeosci. 117(G2), https://doi.org/10.1029/2011jg001901 (2012).

52. Liston, G. E., McFadden, J. P., Sturm, M. & Pielke, R. A. Modelled changes in arctic tundra snow, energy and moisture fluxes due to increased shrubs. Glob. Chang. Biol. 8(1), 17–32 (2002).
53. Pallandt, M. et al. Representativeness assessment of the pan-Arctic eddy-covariance site network, and optimized future enhancements. Biogeosci. Discuss. 1-42, https://doi.org/10.5194/bg-2021-133 (2021).

54. Lawrence, D. M. et al. The Community Land Model version 5: Description of new features, benchmarking, and impact of forcing uncertainty. J. Adv. Model. Earth Syst., https://doi.org/10.1029/2018MS001583 (2019).

55. Pearson, R. G. et al. Shifts in Arctic vegetation and associated feedbacks under climate change. Nat. Clim. Chang. 3, 673–677 (2013).

56. Kruse, S. & Herzschuh, U. Regional opportunities for tundra conservation in the next 1000 years. elife 11, https://doi.org/10.7554/elif.e75163 (2022).

57. Meyer, G., Humphreys, E. R., Melton, J. R., Cannon, A. J. & Lafleur, P. M. Simulating shrubs and their energy and carbon dioxide fluxes in Canada’s Low Arctic with the Canadian Land Surface Scheme Including Biogeochemical Cycles (CLASSIC). Biogeosciences 18, 3263–3283 (2021).

58. Helbig, M. et al. The positive net radiative greenhouse gas forcing of increasing methane emissions from a thawing boreal forest-wetland landscape. Glob. Chang. Biol. 23, 2413–2427 (2017).

59. Seyyednasrollah, B. Solrad: To calculate solar radiation and related variables based on location, time and topographical conditions (v0.99.0). Zenodo, https://doi.org/10.5281/zenodo.1249673 (2018).

60. CAVM Team. Circumpolar Arctic Vegetation Map. (1:7,500,000 scale). Conservation of Arctic Flora and Fauna (CAFF) Map No. 1. (2003).

61. Karger D.N. et al. Data from: Climatologies at high resolution for the earth’s land surface areas. EnviDat. https://doi.org/10.16904/envi.dat.228.v2.1 (2018).

62. Karger, D. N., Wilson, A. M., Mahony, N. E. & Jetz, W. Global daily 1 km land surface precipitation based on cloud cover informed downsampling. Sci. Data 8(1), 1–18 (2021).

63. Karger, D. N. et al. Climatologies at high resolution for the earth’s land surface areas. Sci. Data 4, 170122 (2017).

64. Conrad, V. Usual formulas of continentality and their limits of validity. Eos, Trans. Am. Geophys. Union 27(5), 663–664 (1946).

65. Yurtsev, B. A. Floristic division of the Arctic. J. Veg. Sci. 5(6), 765–776 (1994).

66. Walker, D. A. et al. Circumpolar Arctic vegetation: a hierarchical review and roadmap toward an internationally consistent approach to survey, archive and classify tundra plot data. Environ. Res. Lett. 11, 055005 (2016).

67. Rossw, W. et al. International Satellite Cloud Climatology Project (ISCCP) Climate Data Record, H-Series. NOAA National Centers for Environmental Information, https://doi.org/10.7289/v5zq281s (2017).

68. Young, A. H., Knapp, K. R., Inamdar, A., Hankins, W. & Rossw, W. B. The International Satellite Cloud Climatology Project H-Series climate data record product. Earth Syst. Sci. Data 10(1), 583–593 (2018).

69. Heginbottom, J., Brown, J., Ferrians, O. & Melnikov, E. S. Circum-Arctic Map of Permafrost and Ground-Ice Conditions, Version 2. NSIDC, https://doi.org/10.7285/skbg-kf16 (2002).

70. Porter, C. et al. “ArcticDEM”. V3 [02.09.2020] Harvard Dataverse. https://doi.org/10.7910/dvn/ohhuk (2018).

71. R Core Team. R: A language and environment for statistical computing. (R Foundation for Statistical Computing, 2020).

72. Lindeman, R. H., Merenda, P. F. & Gold, R. Z. Introduction to Bivariate and Multivariate Analysis. (Scott, Foresman, Glenview, IL, 1980).

73. Grömping, U. Relative importance for linear regression in R: the package relaimpo. J. Stat. Softw. 17, 1–27 (2006).

74. Hothorn, T., Bretz, F. & Westfall, P. Simultaneous inference in general parametric models. Biom. J. 50, 346–363 (2008).

75. Garonna, I. et al. Strong contribution of autumn phenology to changes in satellite-derived growing season length estimates across Europe (1982–2011). Glob. Chang. Biol. 20, 3457–3470 (2014).

76. Oehri, J., Schmid, B., Schaepman-Strub, G. & Niklaus, P. A. Terrestrial land-cover type richness is positively linked to landscape-level functioning. Nat. Commun. 11, 154 (2020).

77. Oehri, J. et al. Harmonized in-situ observations of surface energy fluxes and environmental drivers at 64 Arctic vegetation and glacier sites. Pangaea https://doi.org/10.1594/PANGAEA.949792 (2022).

78. Oehri, J. et al. Vegetation type is an important predictor of the Arctic summer land surface energy budget. Zenodo. https://doi.org/10.5281/zenodo.7125844 (2022).

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Author contributions

Study design, methods and analysis were conceived by: J.Oe., G.S.S., J.-S.K., R.G. Data was contributed by: J.Oe., I.G., J.Bo., B.V., C.W.E., D.N.K., M.J.-K., E.L.-B., M.M., S.M., K.S., F.-J.W.P., N.P., W.L.Q., T.S., O.S., J.Be., M.S.B.-H., T.R.C., J.F.D., R.S.F., M.G., A.V.R., B.R.K.R., R.C.S., P.C.S., J.A.G., R.J.H., A.K., M.K., M.‐I.B., T.F., S.N.W., G.d.B., L.D.R., I.S., E.A.G.S., D.H., L.K., J.P., D.v.A., C.W. Data was processed and analyzed by: J.Oe., V.Z., I.G., M.R.C. Article drafting was done by: J.Oe., G.S.S., J.-S.K., R.G., H.K., I.G., O.S., E.S.E. Article figures were done by: J.Oe., I.G. Revising article for intellectual content was done by: J.Oe., G.S.S., J.-S.K., R.G., H.K., I.G., V.Z., O.S., E.S.E., M.R.C., G.M., P.D.B., J.F.D., A.d.S., R.J.H., I.S., L.K., E.P., A.R., J.Bo., N.B.M., J.Be., E.-L., B.P., R.C.S., M.K., F.-J.W.P., J.A.G., M.M., C.W., M.J.-K., D.N.K., W.L.Q., J.P., D.v.A., T.R.C., M.Z.H., R.S.S., M.‐S., B.v., G.Y.F., M.W., B.H., D.M., F.D., M.I.B., T.S., A.K., A.V.R., S.N.W., S.Mo., A.L.A., R.E., B.R.K.R., D.H., L.D.R., H.J., E.A.G.S., C.J.C., A.A.G., J.P.M., R.S.F., M.G., M.U., G.d.B., M.S.B.-H., M.L., K.S., T.F., A.O., C.W.E., J.OI., S.D.C.

Competing interests

The authors declare no competing interests.

Additional information

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