

Article

Permafrost Degradation and Vegetation Growth Beyond the Polar Circle in Siberia

Viacheslav I. Kharuk ^{1,2,3,*} , Sergei T. Im ^{1,3,4,5} , Il'ya A. Petrov ^{1,2,3}  and Evgeny G. Shvetsov ¹

¹ Sukachev Institute of Forests, Federal Scientific Center, Russian Academy of Science, Siberian Branch, Akademgorodok 50/28, Krasnoyarsk 660036, Russia; stim@ksc.krasn.ru (S.T.I.); petrovilsoran@gmail.com (I.A.P.); eugeneshvetsov11@yandex.ru (E.G.S.)

² Institute of Space and Information Technologies, Siberian Federal University, Svobodny Str. 79, Krasnoyarsk 660041, Russia

³ Laboratory of Biodiversity and Ecology, Tomsk State University, Lenin Str. 36, Tomsk 634050, Russia

⁴ Institute of Ecology and Geography, Siberian Federal University, Svobodny Str. 79, Krasnoyarsk 660041, Russia

⁵ Institute of Space Research and High Technologies, Reshetnev Siberian State University of Science and Technology, Krasnoyarsky Rabochy Str. 31, Krasnoyarsk 660014, Russia

* Correspondence: v7sib@mail.ru

Abstract: Permafrost thawing is potentially a crucial but poorly investigated factor that influences vegetation dynamics in the Arctic. We studied the permafrost thaw rate beyond the Polar Circle in Siberia. We analyzed its influence on the larch (*Larix* spp.) growth and Arctic vegetation (sparse larch forests, tundra, and forest–tundra communities) productivity (NPP). We checked the following hypotheses: (1) satellite gravimetry is valid for permafrost thawing analysis; (2) meltwater runoff stimulated trees' growth and NPP. We used satellite (GRACE, Terra/MODIS) and field data, and larch tree radial growth index measurements. We found a continuous negative trend in the terrestrial water content ($r^2 = 0.67$) caused by permafrost thawing beyond the Polar Circle. Runoff is maximal in West and Mid Siberia ($9.7 \pm 2.9 \text{ kg/m}^2/\text{y}$) and decreases in the eastward direction with minimal values in the Chukotka Peninsula sector ($-2.9 \pm 3.2 \text{ kg/m}^2/\text{y}$). We found that the growth increment of larch trees positively correlated with meltwater runoff ($0.5 \dots 0.6$), whereas the correlation with soil water content was negative ($-0.55 \dots -0.85$). Permafrost thawing leads to an increase in the Arctic vegetation productivity. We found a positive trend in NPP throughout the Siberian Arctic ($r^2 = 0.30$). NPP negatively correlated with soil water content ($r = -0.55$) and positively with meltwater runoff (West Siberia, $r = 0.7$). An increase in VPD (vapor pressure deficit) and air and soil temperatures stimulated the larch growth and vegetation NPP ($r = 0.5 \dots 0.9$ and $r = 0.6 \dots 0.9$, respectively). Generally, permafrost degradation leads to improved hydrothermal conditions for trees and vegetation growth and contributes to the preservation of the Arctic as a carbon sink despite the increase in burning rate.

Keywords: permafrost thawing; permafrost thawing water runoff; gravimetric measurement; cryolithozone; larch forests; forest–tundra; tundra; Arctic vegetation productivity



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1. Introduction

In the Siberian Arctic, the air temperature increase is about four times higher in comparison with southward [1]. That would have serious consequences for ecosystems, permafrost stability, hydrological systems, and infrastructure integrity within the cryolithozone [2–6]. Warming-driving permafrost thawing is an important factor that may influence trees' growth and vegetation productivity (NPP). Potentially, permafrost degradation may

improve the soils' hydrology regime and lead to an increase in the active layer depth. Outside the Arctic, on the southern edge of cryolithozone, permafrost thawing considered as additional water source during seasonal water stress. However, data on this problem are scarce [1,7–10]. An air temperature increase by +1 °C, according to prognostic estimates, may lead to a decrease of 25% in the permafrost within the upper 3 m soil layer [11]. Alongside continuous permafrost thawing, thawing of the ice-reach soils is accompanied by thermokarst, including lake formation. Meanwhile, in spite of documented permafrost thawing, within some parts of the cryolithozone, including the northeast Arctic, carbon- and ice-reach soils will be stable after 2100 even under a pessimistic climate-warming scenario [6].

Warming at high latitudes is accompanied by an increase in vegetation GPP/NPP, including the “greening tundra” phenomenon [12,13]. However, warming leads to an increase in wildfires' frequency and intensity [14]. Overall, permafrost thawing, alongside elevating air temperature, is considered a primary driver of vegetation dynamics within the permafrost area [12].

Estimates of the warming influence on the permafrost thawing and soil moisture are based mostly on the on-ground data or satellite microwave data [7,8]. Alongside that, satellite (GRACE) gravimetry also contains information related to permafrost thawing [15]. Gravimetric data are sensitive to all variables that influence local mass anomalies, including water mass anomalies. Namely, water mass anomalies are the primary variable that influences GRACE-derived measurements. The most important results obtained based on gravimetry are updates on the ice sheets thawing in Greenland and the Arctic [16,17]. There are also indications that gravimetry is useful for the analysis of moisture regime changes that influence tree (*Larix* spp.) growth in the Arctic [13,18].

Geographically, studies of permafrost thawing are located mostly within the cryolithozone in North America, whereas vast permafrost areas in Siberia are rather poorly studied. Yet, most studies focused on the permafrost temperature change, whereas measurements of the permafrost thawing depth and meltwater runoff are rare [7,9,12,19,20]. We checked the following hypothesis: warming-driven permafrost thawing (a) promotes trees' growth increase (*Larix sibirica* Ledeb., *L. gmelinii* Rupr.), among the dominant tree species in the Arctic, and (b) promotes vegetation NPP increase.

The goals of this study were as follows: (1) permafrost thawing water runoff estimation in Siberia; (2) water anomalies and meltwater runoff influence larch (*Larix* spp.) growth and vegetation GPP/NPP beyond the Polar Circle in Siberia.

2. Materials and Methods

2.1. Study Area

The total analyzed area was $\sim 3 \times 10^6$ sq. km, located beyond the Polar Circle (66.6° N–78.0° N; 60° E–180° E, 168° W–180° W). We removed from the analysis the islands and coastline. All the data were transformed to the Albers equal area conic projection and the nominal 463 m pixel size corresponding to the MODIS-based NPP data. Vegetation types in the study area include sparse larch stands, tundra, and forest–tundra communities (Figure 1). The climate of the region is sharply continental with frequent cyclones and anticyclones. The polar day is characterized by intense insolation. Cloudy weather with drizzling rains is common. The majority of precipitation falls between late May and late September (mean summer precipitation 180 mm). A stable snow cover occurred in the third week of September and it thawed in the beginning of June. The snow depth ranges from 0.4 to 0.8 m at higher elevations and by up to 8–9 m in the foothills and in flat areas. The permafrost depth is up to 1400 m. “Taliks” (thawed soils) may occur under the riverbeds. The active layer may exceed 2.0 m depending on exposure, vegetation cover, the

moisture content, and the soil type. Low fertility and high moisture are typical for tundra soils. Polygonal wetlands with “baijarkhs” (permafrost-caused hillocks) are typical. The majority of tree species are presented by larch (*Larix gmelinii*, *L. sibirica*, *L. cajanderi* Mayr.) with a small proportion of birch (*Betula* spp.). Siberian pine (*Pinus sibirica* Du Tour) and spruce (*Picea obovata* Ledeb.) grow along the creeks and river valleys within the southwest part of the area [21,22].

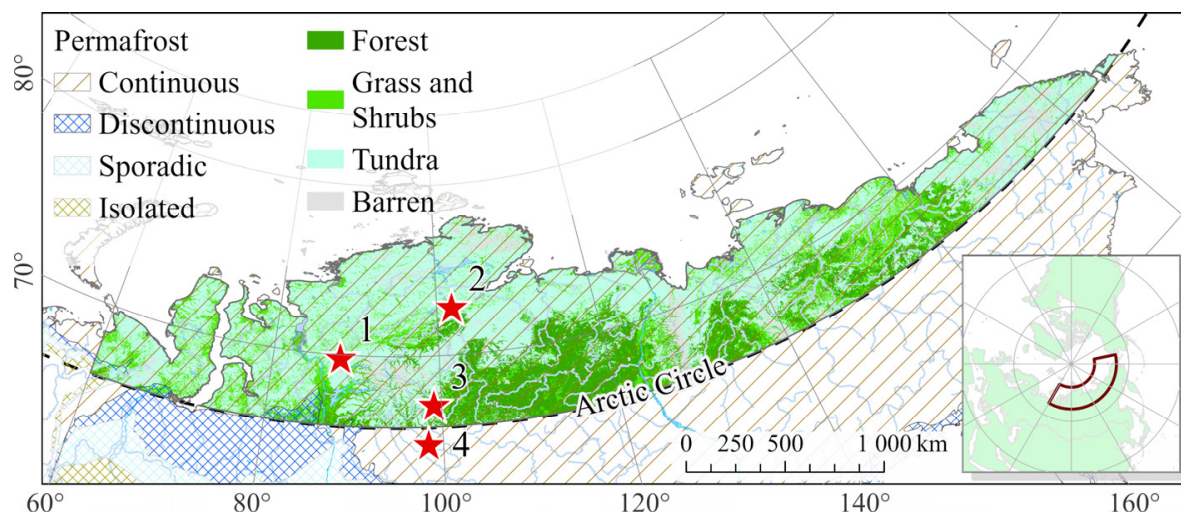


Figure 1. The study area is located within continuous permafrost mostly. Stars indicate on-ground study sites (1—Pyasino, 2—Ary-Mas, 3—Kotuy, 4—Emb). Background: vegetation landcover classes (according to VEGA PRO map <http://pro-vega.ru/eng>, accessed on 19 November 2024) and permafrost types (adapted with permission from [23]).

2.2. Methods

We used satellite GRACE-based gravimetry and MODIS-derived NPP (Net Primary Productivity) data. Trees’ radial growth index (GI) values were obtained based on the dendrochronology analysis of tree samples taken during fieldwork.

2.2.1. GRACE Data

We used monthly mass grid (land) products based on GRACE and GRACE-FO remote sensing data (<https://grace.jpl.nasa.gov/data/get-data/monthly-mass-grids-land>, accessed on 19 November 2024) [24]. The GRACE mission is supported by the NASA MEASURES Program. The results of GRACE measurement given in EWTA (Equivalent of Water Thickness Anomalies) were extracted from the TELLUS_GRAC_L3_GFZ_RL06_LND_v04 and TELLUS_GRFO_L3_GFZ_RL06.1_LND_v04 products [25]. The data were downloaded from the EarthData geoportal (<https://search.earthdata.nasa.gov>, accessed on 19 November 2024) in GeoTIFF format. The monthly land mass grids contain water mass anomalies given as EWTA in meters derived from GRACE and GRACE-FO time-variable gravity observations during the specified timespan (monthly) and relative to the specified time-mean reference period (2004–2009 years).

The EWTA represents the total terrestrial water storage anomalies from soil moisture, snow, surface water (incl. rivers, lakes, reservoirs, etc.), as well as groundwater and aquifers. In fact, EWTA represents water anomalies relevant to the seasonal thawing layer and warming-driven permafrost thawing, since the water content in a deeper layer is constant. In addition, EWTA is sensitive to changes in precipitation and evapotranspiration, carbon accumulation, decomposition, and fire-caused loss. Those issues are analyzed in Section 2.2.5. The spatial sampling of all grids is 1 degree (above the Arctic Circle cell is $\sim 94 \times 40$ km²) in both latitude and longitude [24]. The time coverage of the data is

2003–2023. EWTA values are presented in meters. In this study, alongside with EWTA term, we use the terms “water anomalies” or “water runoff” where applicable.

Gravimetric data were calculated both for the hydrological year (from September of the previous year to August of the current year inclusively) and for the vegetation growth period (JJA).

2.2.2. MODIS Data

We analyzed changes in the NPP based on the MODIS MOD17A3HGF product. According to [26], annual NPP (NPP_{annual}) was calculated using the following equations:

$$\begin{aligned} NPP_{annual} &= 0.8 \cdot (GPP_{annual} - MR_{annual}), \text{ if } GPP_{annual} - MR_{annual} \geq 0 \\ NPP_{annual} &= 0, \text{ if } GPP_{annual} - MR_{annual} < 0 \end{aligned} \quad (1)$$

where MR_{annual} —annual plant maintenance respiration [kgC/ha];

$$GPP_{annual} = \sum_{year} GPP_{daily} \quad (2)$$

$$GPP_{daily} = 0.45 \cdot e_{max} \cdot TMIN_{scalar} \cdot VPD_{scalar} \cdot SWR \cdot FPAR, \quad (3)$$

where GPP_{daily} —daily gross primary productivity [kgC/ha]; e_{max} —maximum radiation conversion efficiency; $FPAR$ —fraction of absorbed photosynthetically active radiation; SWR —net incident shortwave radiation, $TMIN_{scalar}$ —daily minimum temperature; $TMIN_{max}$ —daily minimum temperature at which $e = e_{max}$ (for optimal VPD); $TMIN_{min}$ —daily minimum temperature at which $e = 0.0$; VPD_{scalar} —daylight average vapor pressure deficit; VPD_{max} —daylight average vapor pressure deficit at which $e = e_{max}$ (for optimal $TMIN$) [Pa]; VPD_{min} —daylight average vapor pressure deficit at which $e = 0.0$; $TMIN$ —minimum daily temperature. The annual NPP data were extracted from the MOD17A3HGF from 2007 to 2023 with a 463 m spatial resolution [27].

The fires were mapped using a geospatial database created by the Sukachev Institute of Forests, the Siberian Branch of the Russian Academy of Sciences. The database uses satellite data obtained from the NOAA/AVHRR, TERRA/AQUA/MODIS, and SNPP/NOAA-20/VIIRS platforms. To exclude anthropogenic thermal anomalies, data about settlements were used (Open Street Map, <https://www.openstreetmap.org/>, accessed on 19 November 2024). Using high-resolution Google Earth data, thermal anomalies associated with petroleum and gas fields were excluded from the analysis. To estimate pyrogenic carbon emissions in the tundra, a value of 1.13 kg C/m², as described in the literature concerning northeastern Siberia, was used [28].

2.2.3. Climate Data Processing

We used climate data extracted from the ERA5 Land database. ERA5 Land was created by the European Centre for Medium-Range Weather Forecasts with a spatial resolution of 0.1 degrees (~9 km). ERA5 Land data are calculated based on a reanalysis of ground measurements, satellite imagery, and land cover and relief maps [29]. Monthly data on air temperature (T2m; °C), precipitation (TP; m), evaporation (E; m), and soil temperature (ST; m; at a depth of 0–100 cm) were downloaded using the Copernicus Climate Change Service [29]. Soil temperature was considered for a layer of 0–100 cm, which corresponded mainly to the rooted zone. The data were preprocessed using R-Studio (v. 23.12.01; <https://posit.co/download/rstudio-desktop>, accessed on 19 November 2024). To estimate the influence of climate on the EWTA and vegetation cover dynamics, we calculated maps of Spearman’s correlation coefficients ($p < 0.05$). These maps showed the spatial heterogeneity of the climate impact on changes in EWTA and NPP during 2007–2023.

VPD (vapor pressure deficit) was calculated using the DewtoVPD function realized in the plantecophys Python library and based on the air and dew temperatures and barometric surface pressure [30].

2.2.4. Test Site Description and Dendrochronology Analysis

On-ground studies were conducted at four sites: Ary-Mas, Pyasino, Kotuy, and Emb (Figure 1). The Pyasino site (69°39' N; 88°02' E) is located within lowlands and wetlands surrounded by offshoots of the Putorana plateau. Sparse and open forests are formed mostly by *Larix sibirica* with an admixture of *Picea obovata* and *Betula* sp. Trees grow mainly within lowlands and river valleys. Larch's height is 6.6–9.1 m, diameter is 13–23 cm, and age is 65–120 y (with maximum up to 500 y). Shrubs and herbaceous species are presented mostly by *Salix* spp., *Duschekia fruticosa* (Rupr.) Pouzar, *Betula* sp., *Ledum palustre* L., *Vaccinium vitis-idaea* L., *Carex* sp., and *Dryas* sp., with moss (*Hylocomium* sp.) and lichens (*Cladonia* spp.) in ground cover. Annual precipitation is about 760 mm, and annual air temperature is about −10 °C (Figure A1e–h).

The forest at the Ary-Mas site (72°27' N; 101°57' E) is composed of *Larix gmelinii* and occupies the high southern bank of the Novaya River at elevations of up to 80 m a.s.l. Trees occur in strips 0.5–1.5 km wide and approximately 20 km in length along the river. Stands are mostly sparse and growing on the wet gley soils. Trees' age is 140–300 y, height is 4.5–6.1 m, and diameter is 13–16 cm. Shrubs and herbaceous species are presented mostly by *Salix* spp., *Betula* spp., *Ledum palustre*, *Vaccinium vitis-idaea*, *Carex* sp., and *Equisetum* sp. Moss and lichen are presented mostly by *Hylocomium* sp., *Dicranum* sp., and *Cladonia* spp. There is an annual precipitation of 250 mm and a mean air temperature of −12 °C (Figure A1a–d). The mean July temperature is +12 °C. The coldest months are January and February (mean monthly temperature is −32 °C). The soil thawing depth is about 10–30 cm under moss cover, 50–70 cm in mineralized areas, and may exceed 100 cm on steep slopes.

The Kotuy site (67°38' N; 99°11' E) is located within the Kotuy River watershed on the Putorana Plateau. Stands (which are mostly of low-closure) are formed by *L. gmelinii* on the clay permafrost soils. Trees' height is 4.5–7 m, diameter is 6–8 cm, and age is 160–180 y (with maximum > 500 y). Shrubs and herbaceous species include *Duschekia fruticosa*, *Betula* sp., *Salix* spp., *Vaccinium* spp., and *Carex* sp., with lichens (*Cladonia* spp.) and mosses (e.g., *Hylocomium* sp.) in ground cover. Annual precipitation is 375 mm, and mean July and January temperatures are +14 °C and −34 °C, respectively (Figure A1i–l). The soil thawing depth is about 35 cm under moss cover and exceeds 100 cm in mineralized areas.

The Emb site (65°48' N; 98°25' E) is located within the Embechime River valley, Central Siberia. This is a hilly area with gently sloping, flat-topped hills with elevations exceeding 900 m above mean sea level. Sparse stands are composed of *Larix gmelinii* that are rarely mixed with *Betula* sp. Larch's mean height, diameter, and age are 8.5 m, 12.5 cm, and 250 years, respectively. Shrubs and herbaceous species are presented by *Betula* sp., *Duschekia fruticosa*, *Ledum palustre*, *Ribes* spp., and *Vaccinium* spp., with lichens (*Cladonia* spp.) and mosses (*Pleurozium* sp.) in ground cover. Soils are brown and cryogenic. The mean annual precipitation is 440 mm. Mean summer, winter, and annual temperatures are +11 °C, −34 °C, and −12 °C, respectively (Figure A1m–p).

Dendrochronological analysis was carried out at the four test sites: Ary-Mas (3 sample plots, 60 model trees), Kotuy (2 sample plots, 66 model trees), Pyasino (10 sample plots, 242 model trees), and Emb (7 sample plots, 67 model trees) (Figure 1). Wood samples were measured using the LINTAB-6 platform with an accuracy of 0.01 mm [31]. As a result, a series of radial increments for each tree (in mm) were determined. The TSAP and COFECHA programs were used to check the quality of dating [32]. We applied a detrending procedure to account for the age trend by transforming the time series of tree-ring widths

to a series of unitless indices with a mean of 1.0 and relatively constant variance [33]. We averaged tree-ring chronologies of individual trees to calculate generalized indexed tree-ring chronologies. For each test site, an indexed tree-ring chronology was constructed using the ARSTAN program; detrending was performed based on the linear regression or negative exponential curve [34].

2.2.5. Assessment of the Meltwater Runoff

We used GRACE EWTA, MODIS NPP, MODIS-based fire carbon emissions, and ERA5-Land total precipitation and evaporation data to assess meltwater runoff. We estimated changes in total water mass (ΔG_m) during 2007–2023 using the following equation:

$$\Delta G_m = G_{m(2007-2009)} - G_{m(2021-2023)}, \quad (4)$$

where $G_{m(2007-2009)}$ and $G_{m(2021-2023)}$ are the mean EWTA (or water anomalies, WA) during 2007–2009 and 2021–2023, respectively. A positive value of ΔG_m means water runoff and negative—water accumulation. In Equation (1), the year 2007 is chosen since that is the beginning of the water anomaly (WA) decrease (Figure 2). To smooth variability, we averaged three years at the beginning (2007–2009) and the end (2021–2023) of the study period.

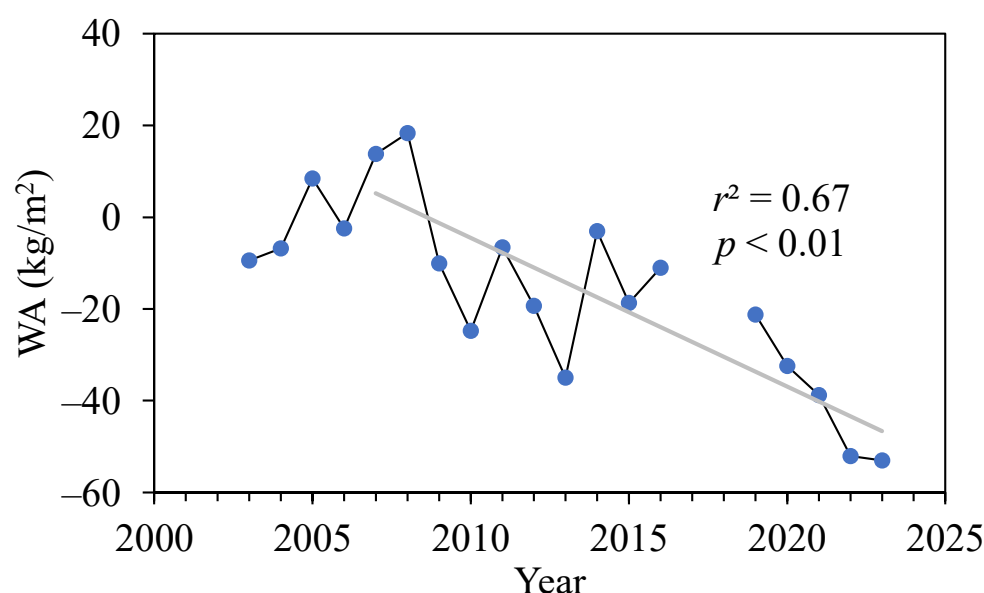


Figure 2. Within the entire Siberian Arctic, a stable decreasing trend ($p < 0.01$, grey line) of water anomalies (WAs) has been observed since 2007.

The total gravimetry data are influenced by vegetation cover mass ($\sum V_m$) changes, mass loss caused by wildfires (carbon emissions, $\sum F$), and differences ($P-E$) between precipitation (P) and evaporation (E) values. To account for mass changes caused by vegetation growth, we used NPP estimations extracted from the MODIS MOD17A2HGF product [26].

The sum of annual NPP ($\sum \text{NPP}$) during 2007–2023 was calculated. Alongside the biomass accumulation, the produced NPP was partly decayed due to biological decomposition. To estimate loss caused by decomposition, a first-order exponential decay function was applied, which estimates the percent mass remaining at a given time elapsed since the beginning of litter decomposition (Figure 3) [35–37]:

$$y = e^{-k*t}, \quad (5)$$

where t —is study period (2007–2023); and k —is the decomposition rate, which for arctic tundra is about $\sim 0.03 \text{ g g}^{-1} \text{ y}^{-1}$ [36,38,39].

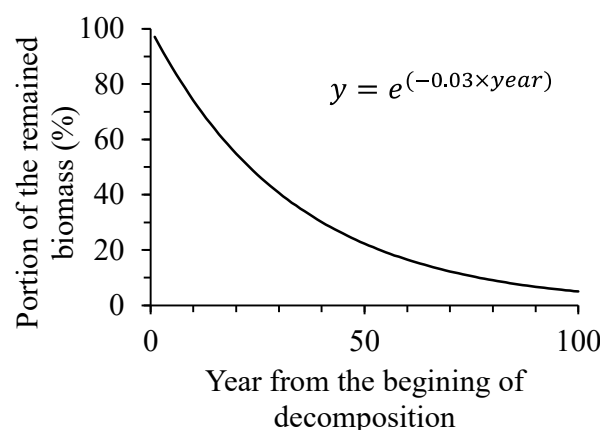


Figure 3. Portion of the biomass remaining in the given year since the beginning of decomposition.

We used function (6) to assess the remained biomass with the following equation:

$$\sum V_m = \sum_{t=2007}^{2023} \left(\text{NPP}_t * e^{-k(2023-t+1)} \right), \quad (6)$$

We estimated wildfire-caused carbon loss using the following procedure. We mapped fire events using the geospatial fire database created by the Sukachev Institute of Forest, SB RAS. This database uses satellite fire detections obtained using the NOAA/AVHRR, TERRA/AQUA/MODIS, and SNPP/NOAA-20/VIRS platforms. We used settlement data from Open Street Map (<https://www.openstreetmap.org/>, accessed on 19 November 2024) to exclude thermal anomalies of anthropogenic origin. We also excluded from further analysis thermal anomalies related to gas flares in oil and gas fields using high-resolution data from Google Earth. In the case of larch forest stands in northern Siberia, emission estimates ranged between 3 and 3.44 kgC m^{-2} [40–42]. The final estimate of carbon emissions was based on the data published by Tsvetkov [40]. To estimate pyrogenic emissions in the tundra, a value of 1.13 kgC m^{-2} obtained for northeastern Siberia was used [28].

We applied linear regressions to account for annual changes in differences (α) between annual precipitation (P) and evapotranspiration (P-E):

$$y = \alpha * t + \beta, \quad (7)$$

where t is time (yrs), and β is the intercept coefficient.

Finally, the corrected meltwater runoff (WR) was estimated by Equation (5):

$$WR = \Delta G_m + \sum V_m - \sum F - l * \alpha, \quad (8)$$

where WR is the meltwater runoff; $\sum F$ is the carbon emissions caused by fires; $\sum V_m$ is the remaining biomass; α is the delta for (P-E); and l is the analyzed period length (2007–2023).

2.2.6. Statistical Analysis

We applied ISODATA unsupervised classification in the ERDAS Imagine software (version 9.2, <https://hexagon.com/products/erdas-imagine>, accessed on 19 November 2024) to merge pixels to clusters (zones) with similar EWTA dynamics. In total, five zones were identified.

Statistical calculations were realized using StatSoft Statistica (<http://statsoft.ru>, accessed on 19 November 2024), R-Project (<https://www.r-project.org>), and R-Studio (<https://posit.co/download/rstudio-desktop/>, accessed on 19 November 2024) software.

We used Pearson's and Spearman's correlation coefficients and linear regressions to estimate the relationship between the estimated variables. The significance of correlation coefficients and regression equations was assessed using the *t*-test and *F*-test.

The Theil–Sen estimator was applied to calculate maps of EWTA, climate, and productivity (GPP) trends. The Theil–Sen estimator is a non-parametric method that fits a regression line through the median of the slopes determined by all pairs of sample points [43], and it is more robust than simple linear regressions [44]. This estimator is less sensitive to outliers, and it is more accurate than simple linear regression [45]. We used the Theil–Sen estimator realized in the Python library pymannkendall 1.4.2 (<https://pypi.org/project/pymannkendall> (accessed on 1 December 2022)) imported into ESRI ArcGIS Desktop 10.8.1 (<https://www.esri-cis.com/ru-ru/arcgis/products/arcgis-desktop/overview>, accessed on 19 November 2024). As a result, a set of raster trend maps was generated, and *p*-levels were estimated.

3. Results

3.1. Meltwater Runoff Raw Data (WR_r)

Water runoff dominated within the Siberian Arctic with the exception of the eastern part (the Chukotka Peninsula, Figure 4).

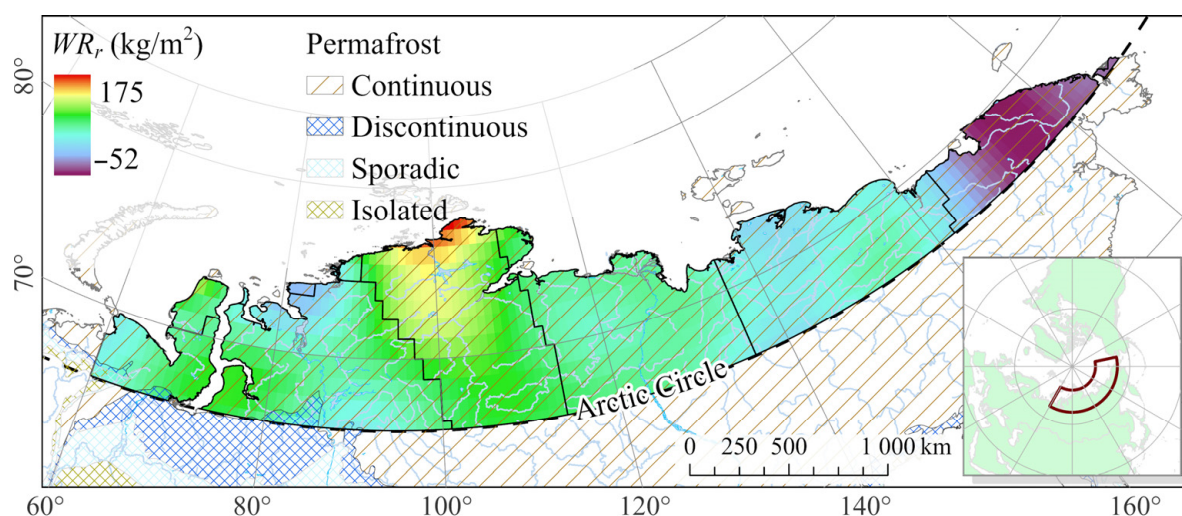


Figure 4. A map of WR_r (raw data) changes beyond the Arctic Circle ($\Delta G_m = G_m(2007-2009) - G_m(2021-2023)$). Mean ΔG_m is 52 kg/m^2 ($\sigma = 38$; min = -52 , max = 175). Positive ΔG_m means runoff and negative ΔG_m means water accumulation. Insert is the study area location.

Throughout the Arctic, the values of WR_r formed five main clusters: West and Mid Siberian (WestSib and MidSib), the Lena River (LenaRiver), East Siberian (EastSib), and Chukotka Peninsula (ChukotkaPen) (Figure 5).

Water accumulation was observed within the ChukotkaPen cluster only. On average, during 2007–2023, the mean water runoff rate (row data) was about $\sim 3 \text{ kg/m}^2/\text{y}$ ($r^2 = 0.67$) (Figure 6).

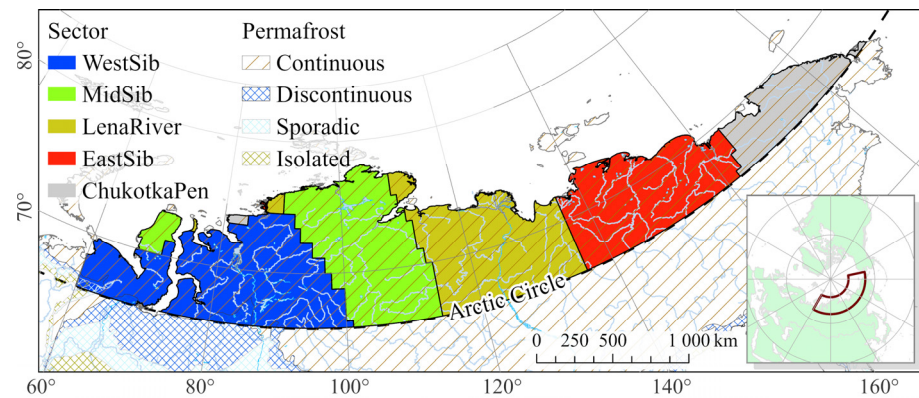


Figure 5. The Arctic's clusters with different values of meltwater runoff (WR_r). Legend: WestSib, MidSib, LenaRiver, EastSib, and ChukotkaPen are the West Siberia, Mid Siberia, Lena River, East Siberia, and Chukotka Peninsula clusters, respectively. Insert is the study area location.

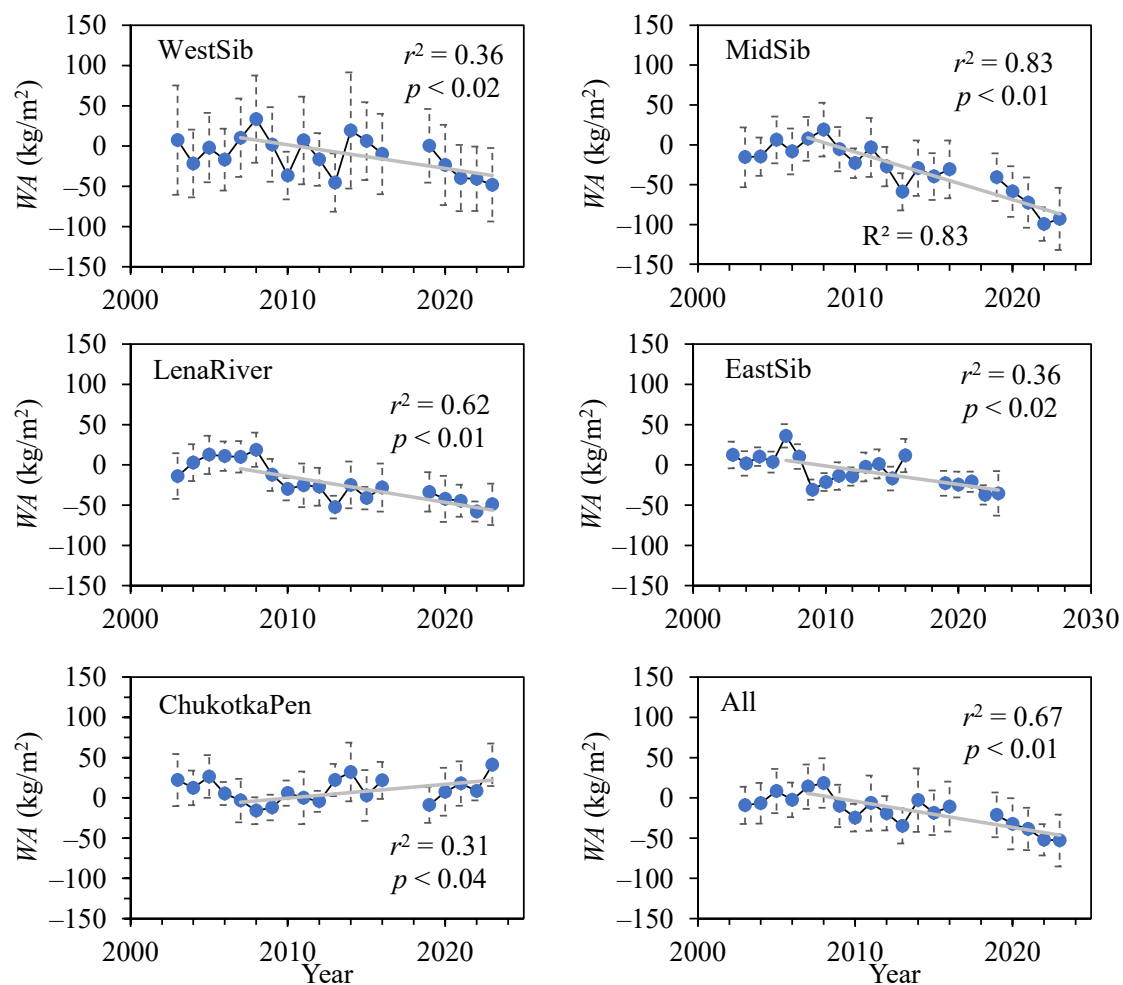


Figure 6. The WA (raw data) dynamics within Arctic sectors (Figure 5). On average, during 2007–2023, the mean water runoff rate was about $\sim 3 \text{ kg/m}^2/\text{y}$ ($r^2 = 0.67$). Vertical lines show the 95% confidence interval, grey lines indicate trends. The years 2017 and 2018 were excluded because $>25\%$ of the data were missed. Abbreviations: WestSib, MidSib, LenaRiver, EastSib, and ChukotkaPen are the West Siberia, Mid Siberia, Lena River, East Siberia, and Chukotka Peninsula clusters, respectively.

3.2. Data Used for the Water Runoff Corrections: Mapped Data of NPP, $\sum V_m$, and Fire-Caused Carbon Loss

We corrected WR_r raw data based on mapped values of NPP, $\sum V_m$, and fire-caused carbon loss (Figures 7 and 8).

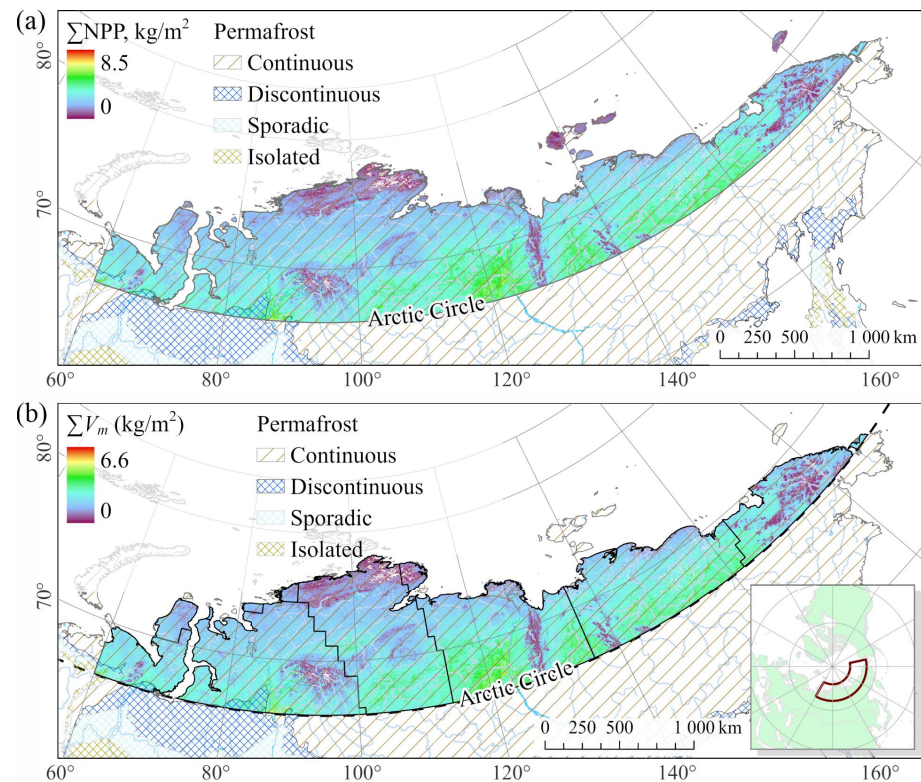


Figure 7. (a) The accumulated NPP (ΣNPP) during 2007–2023. Mean ΣNPP is 2.6 kg/m^2 ($\sigma = 1.1$; min = 0, max = 8.5). (b) Map of the remaining biomass (ΣV_m). Mean ΣV_m is 2.1 kg/m^2 ($\sigma = 0.8$; min = 0.1, max = 6.6).

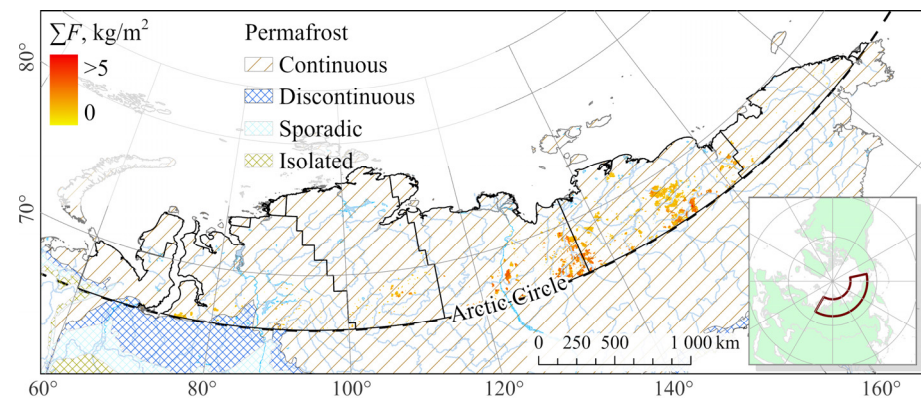


Figure 8. Total fire-caused carbon loss (ΣF) during 2007–2023. Mean ΣF is 0.06 kg/m^2 ($\sigma = 0.35$; min = 0, max = 11.16).

The mean annual fire-caused carbon loss was $8.6 (\sigma = 17.5) \text{ Mt C/y}$ or $0.08 \text{ kg C/m}^2/\text{y}$. The percentage of the annual burned area was about $0.17 \pm 0.34\%/\text{year}$ (Figure 8).

3.3. Corrected Meltwater Runoff (WR)

The map of corrected meltwater runoff within the total study area is presented in Figure 9a. Water runoff within given Arctic sectors is given in Figure 9b and in Table 1. Thus, the mean annual WR within the Siberian Arctic is $7.7 \pm 4.4 \text{ kg/m}^2/\text{y}$. Maximal values occurred in the West and Mid Siberian sectors (about $9.7 \text{ kg/m}^2/\text{y}$), and negative ones (i.e., water accumulation) were observed in the Chukotka Peninsula sector ($-2.9 \pm 3.2 \text{ kg/m}^2/\text{y}$) (Table 1).

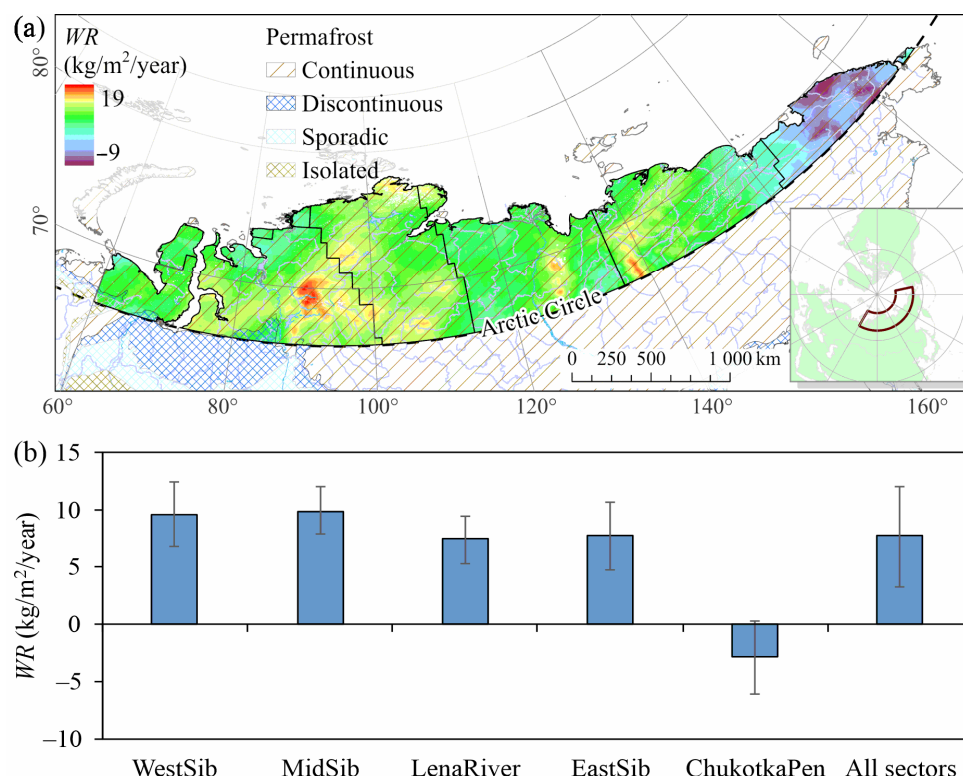


Figure 9. (a) Map of the mean (2007–2023) annual water runoff within the Arctic. Mean WR is 7.7 kg/m²/year ($\sigma = 4.4$, min = −9.9, max = 19.1). Positive and negative WR corresponded to water runoff and water accumulation, respectively. (b) Meltwater runoff within given Arctic sectors. Whiskers show standard deviations.

Table 1. Meltwater runoff within the Arctic sectors. ΔG_m is the total WR_r change, ΣNPP is the primary productivity, ΣV_m is a correction for the biomass decay, ΣF is the biomass loss caused by carbon emissions, α is the difference between precipitation and evapotranspiration ($P-E$), WR is the meltwater runoff.

#	Sector	Area (km ²)	ΔG_m (kg/m ² /y)	ΣV_m (kg/m ² /y)	ΣF (kg/m ² /y)	α (kg/m ² /y)	WR (kg/m ² /y)
1	WestSib	281,496	3.3 ± 1.1	0.12 ± 0.04	0.001 ± 0.008	−6.3 ± 2.5	9.7 ± 2.9
2	MidSib	646,954	5.6 ± 1.3	0.11 ± 0.05	0.001 ± 0.008	−4.3 ± 2.0	9.7 ± 2.1
3	LenaRiver	690,721	3.3 ± 0.5	0.14 ± 0.06	0.006 ± 0.031	−4.0 ± 2.0	7.4 ± 2.0
4	EastSib	813,231	2.0 ± 0.6	0.14 ± 0.04	0.009 ± 0.031	−5.6 ± 3.0	7.7 ± 2.9
5	ChukotkaPen	588,946	−1.9 ± 1.0	0.10 ± 0.05	0.001 ± 0.009	1.1 ± 2.4	−2.9 ± 3.2
	All sectors	3,021,348	3.2 ± 2.2	0.12 ± 0.05	0.004 ± 0.021	−4.5 ± 3.1	7.7 ± 4.4

Note: Mean values ± standard deviation. Abbreviations: WestSib, MidSib, LenaRiver, EastSib, and ChukotkaPen are the West Siberia, Mid Siberia, Lena River, East Siberia, and Chukotka Peninsula sectors, respectively.

3.4. Meltwater Influence on the Vegetation Productivity

Within the Arctic, positive NPP trends prevailed (~15%, whereas negative trends were observed in about ~1% of the area). Positive trends were observed mainly within the western Arctic (Figure 10a). Generally, NPP within the Arctic showed a significant increasing trend (Figure 10b).

The NPP correlated with WA mostly within northern and central parts of the western Arctic sectors (WestSib and MidSib) with local positive correlations within the LenaRiver and EastSib sectors (Figures 11a and A2). Throughout the Arctic, NPP positively correlated with WA within 4.5% of the area, whereas negative and insignificant correlations were observed in 1% and 94% of the area, respectively ($p < 0.1$).

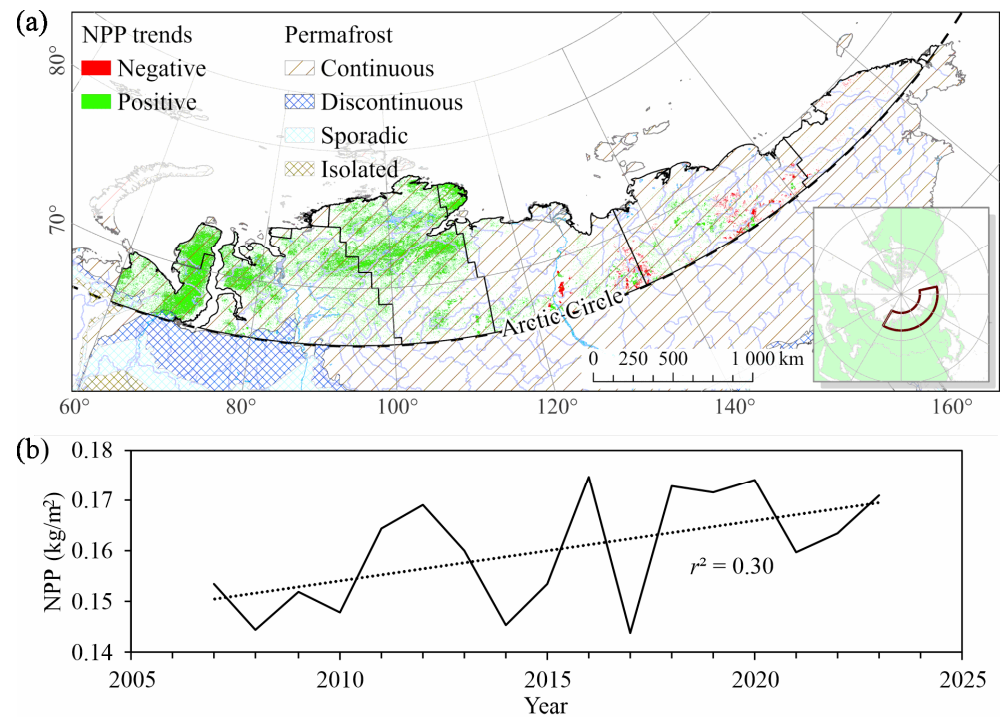


Figure 10. (a) Map of NPP trends, (b) and the mean NPP dynamics within the Siberian Arctic (dotted line, $p < 0.05$). Positive and negative trends occurred within ~15% of the Arctic and ~1%, respectively.

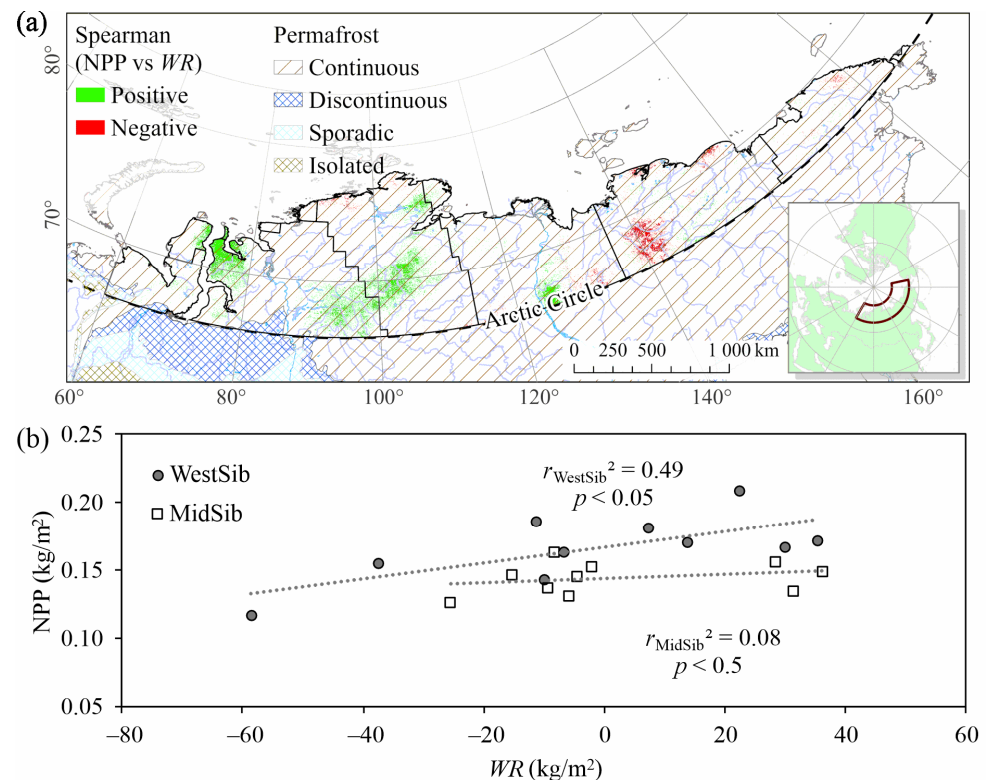


Figure 11. (a) Map of Spearman correlations ($p < 0.1$) between NPP and water runoff (WR). Positive Spearman correlations are observed within 4.5% of the analyzed area, negative—1%, and insignificant—94%. (b) NPP positively correlated with meltwater runoff within the WestSib sector and, much lower but significantly, in the MidSib sector. Within the other sectors, positive correlations are local (Figure A2).

NPP significantly correlated with water runoff in the West Siberia sector ($r = 0.7$; Figure 11b). The latter referred to the higher rate of permafrost thawing in the West Siberian

plain [20]. Throughout the Arctic, the mean correlation between NPP and WA is 0.55 ($p < 0.05$) (Figure A2).

Alongside water soil content and meltwater runoff, NPP correlated with precipitation (negatively) and with VPD air and soil temperatures (positively; Figure 12).

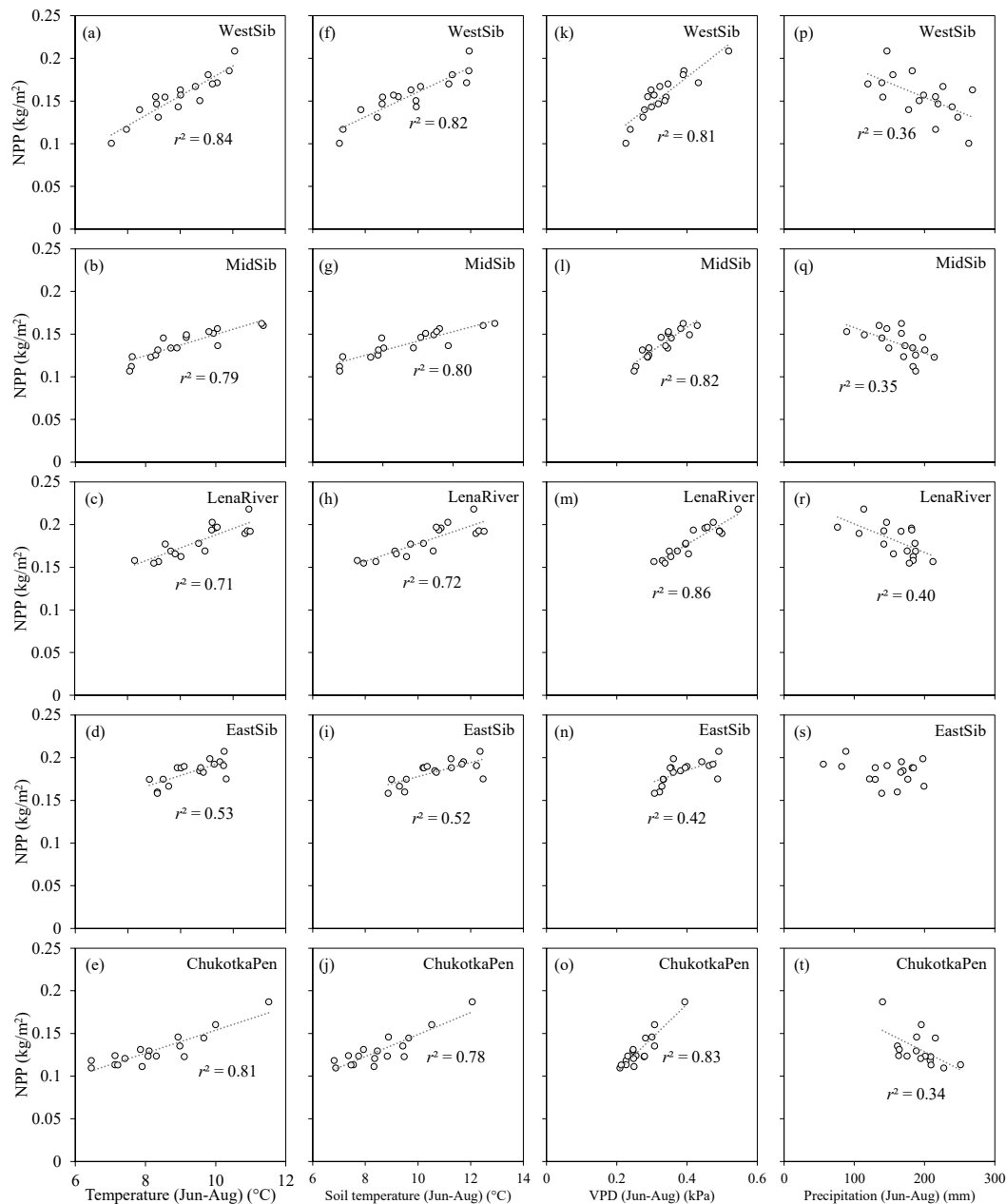


Figure 12. NPP correlations with summer ((a–e); $p < 0.01$) air and soil temperatures ((f–j); $p < 0.01$), vapor pressure deficit (VPD; (k–o); $p < 0.01$), and precipitation ((p–t); $p < 0.01$) within the Arctic sectors.

3.5. Meltwater Runoff Influence on the Larch Trees' Growth

Larch trees' growth index (GI) significantly correlated with water anomalies during the growth period (JJA; $r = -0.64 \dots -0.85$), i.e., the less moisture in the active layer, the higher the GI of larch trees, though an exception is a Pyasino site. Meanwhile, for the hydrological year, correlations were significant for all sites ($r = -0.55 \dots -0.76$). Similarly, the more meltwater runoff, the higher the tree's growth ($r = 0.5 \dots 0.6$; Figures 1 and 13a).

Alongside that, larch GI positively correlated with air and soil temperatures and vapor pressure deficit (VPD), whereas negatively with precipitation (Figure 13b). Note:

although, for the Embechime site, correlations were insignificant due to a shorter interval of observations (until 2012 only).

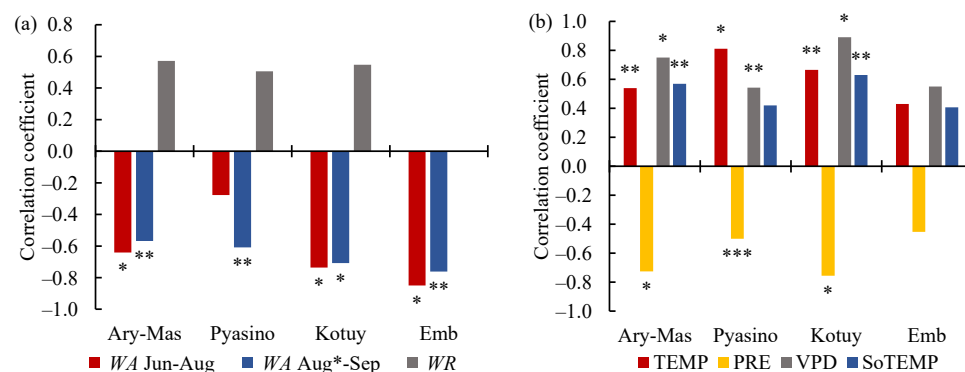


Figure 13. (a) Correlations between larch growth index (GI) and water anomalies (WAs) in JJA (red) and the hydrological year (August–September, blue) (since 2003). Grey columns: correlations between GI and water runoff (WR) (since 2007, $p < 0.2$). (b) Correlations between GI and JJA air (TEMP) and soil temperatures (SoTEMP), precipitation (PRE), and vapor pressure deficit (VPD). Significances at $p < 0.01$, $p < 0.05$, and $p < 0.1$ are indicated by one (*), two (**), and three (***) asterisks. Abbreviations: Ary-Mas, Pyasino, Kotuy, and Emb are the on-ground sites (Figure 1).

4. Discussion

The largest increase in permafrost temperature was observed in the Arctic continuous permafrost zone [19]. In the Siberian Arctic, that has led to permafrost thawing, with a continuous decrease in soil water content since 2007 with accompanying meltwater runoff (about $7.7 \pm 4.4 \text{ kg/m}^2/\text{y}$). Meltwater runoff reached maximal values in the WesSib sector ($9.7 \pm 2.9 \text{ kg/m}^2/\text{y}$), which coincided with the reported high rate of permafrost thawing in the West Siberian plain [20]. Throughout the Arctic, water runoff is decreasing in the eastward direction, with the lowest values in the Chukotka Peninsula ($-2.9 \pm 3.2 \text{ kg/m}^2/\text{y}$) (Figures 2 and 9; Table 1). The latter should be considered the Pacific Ocean influence on the hydrothermal regime in the Chukotka permafrost.

Vegetation productivity and trees' growth index positively correlated with meltwater runoff and a soil moisture decrease (Figures 11, 13 and A2). Larch trees responded to the meltwater runoff with an increase in the growth index ($r = 0.5 \dots 0.6$). Positive correlations between NPP and meltwater runoff dominated in the western part of the Arctic (over 10% of the area), which is relevant to higher permafrost thawing (up to 2–8 m) in West Siberia [20].

In general, a decrease in soil water content resulted in an increase in vegetation NPP in the Arctic ($r^2 = 0.31$) (Figure A2). It known that waterlogging is widespread in the Arctic [21]. The temperature of those so-called "cold wet soils" is among the factors that limit vegetation growth. Due to the high heat capacity of water, soils' temperature is dependent on the moisture content. Therefore, soils' water content increase leads to a decrease in NPP ($r = -0.7$) and larch growth ($r = -0.55 \dots -0.85$), whereas soil temperature increase stimulated larch growth and vegetation NPP ($r = 0.5 \dots 0.9$ and $r = 0.6 \dots 0.9$, respectively). Earlier positive correlations between larch growth, NPP, and soil moisture were reported for the Mid-Siberian Arctic [13,18]. A similar stimulation of larch (*L. gmelinii*) growth produced by permafrost thawing was reported for the mountains of northeastern China [10,46]. Meanwhile, seasonal water stress in trees also occurred in spring when air temperatures were high while the water supply was blocked in still-frozen soil [10,47]. Thus, the observed decrease in water content, together with meltwater runoff, indicated an improvement in the hydrothermal regime in the Arctic soils.

Alongside that, permafrost degradation and meltwater runoff evidently led to an active layer increase with a consequent positive influence on the vegetation NPP and tree growth. For example, a wildfire-driven increase in the active layer leads to a strong increase in tree growth due to the hydrothermal regime improvement and nutrient supply increase [22]. However, quantitative estimations of that phenomenon need further studies due its complexity, including different soils' water capacities. Thus, improvement of the soils' hydrothermal regime stimulated tree growth and a continuous increase in NPP throughout the Arctic ($r^2 = 0.3$) (Figure 10). Meanwhile, accelerated NPP caused negative feedback since the ground cover is a thermal insulator that decreases permafrost thawing [12].

It is known that permafrost thawing reduce soils' waterlogging, increases soil drainage and active layer depth, and enriches the root layer with oxygen and biogenic elements [23]. However, along with runoff, meltwater "conservation" is observed to be forming bogs and ponds due to the thermokarst, especially in the case of ice-enriched soils [6]. Warming also stimulates solifluction, i.e., the flow of waterlogged soils on slopes [12,48]. Thus, in the Taimyr Peninsula, the frequency of landslides has strongly (>10 times) increased in the last decade. Notably, it was accompanied by a sharp (>20 times) increase in carbon fixation [49]. In some regions, the thawing of permafrost soils was stimulated by an increase in "warm rains" [12]. However, within the studied area, we found a negative precipitation influence on larch trees and vegetation growth (Figure 12p–r,t and Figure 13b).

The main factors determining the dynamics of gravitational mass (i.e., satellite GRACE data) include, along with the mass of water (in solid and liquid states), the NPP, precipitation, and wildfires' variations. The precipitation and evapotranspiration influences are taken into account with equation (5). The estimated fire-caused carbon loss was surprisingly low compared to NPP (about 2 orders; Table 1). However, the majority of carbon emissions occurred south of the Arctic Circle [50]. To consider NPP decay, we used the decay coefficient ($k = 0.03 \text{ g g}^{-1} \text{ y}^{-1}$; Equation (3)) [36,38,39]. That coefficient may differ in different phytocenoses, but relevant data are not available in the literature. In addition, it is necessary to estimate NPP consumption in the Arctic by the heterotrophs, but those data are scattered.

In general, warming-driven permafrost thawing stimulated trees' growth and vegetation productivity in the Arctic, which, despite an elevating burning rate, still maintains the status of a carbon sink.

5. Conclusions

Based on satellite gravimetry, we reveal a continuous decrease in the terrestrial water content in the Siberian Arctic. That process is accompanied by an increase in meltwater runoff (with a mean rate of about $7.4 \text{ kg/m}^2/\text{y}$). Water runoff has reached its maximal values in West and Mid Siberia ($9.7 \pm 2.9 \text{ kg/m}^2/\text{y}$), and it is decreasing in the eastward direction with about zero runoff in the Chukotka Peninsula ($-2.9 \pm 3.2 \text{ kg/m}^2/\text{y}$). Warming-driven permafrost degradation promotes larch trees' growth and an increase in vegetation NPP. In the warming climate, permafrost thawing leads to an improvement in soils' hydrothermal regime, which, in turn, stimulates vegetation growth and supports the Arctic as a carbon sink despite the burning rate increase.

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Data Availability Statement: The data presented in this study are openly available: climate data at <https://cds.climate.copernicus.eu> (accessed on 6 November 2024); EWTA at <https://podaac-opendap.jpl.nasa.gov/opendap/hyrax/allData/tellus/L3> (accessed on 15 May 2024), reference number [24]; NPP at <https://lpdaac.usgs.gov/products/mod17a3hgv006/> (accessed on 15 May 2024), reference number [27]. Wildfire-caused carbon loss data are available from E.G.S.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

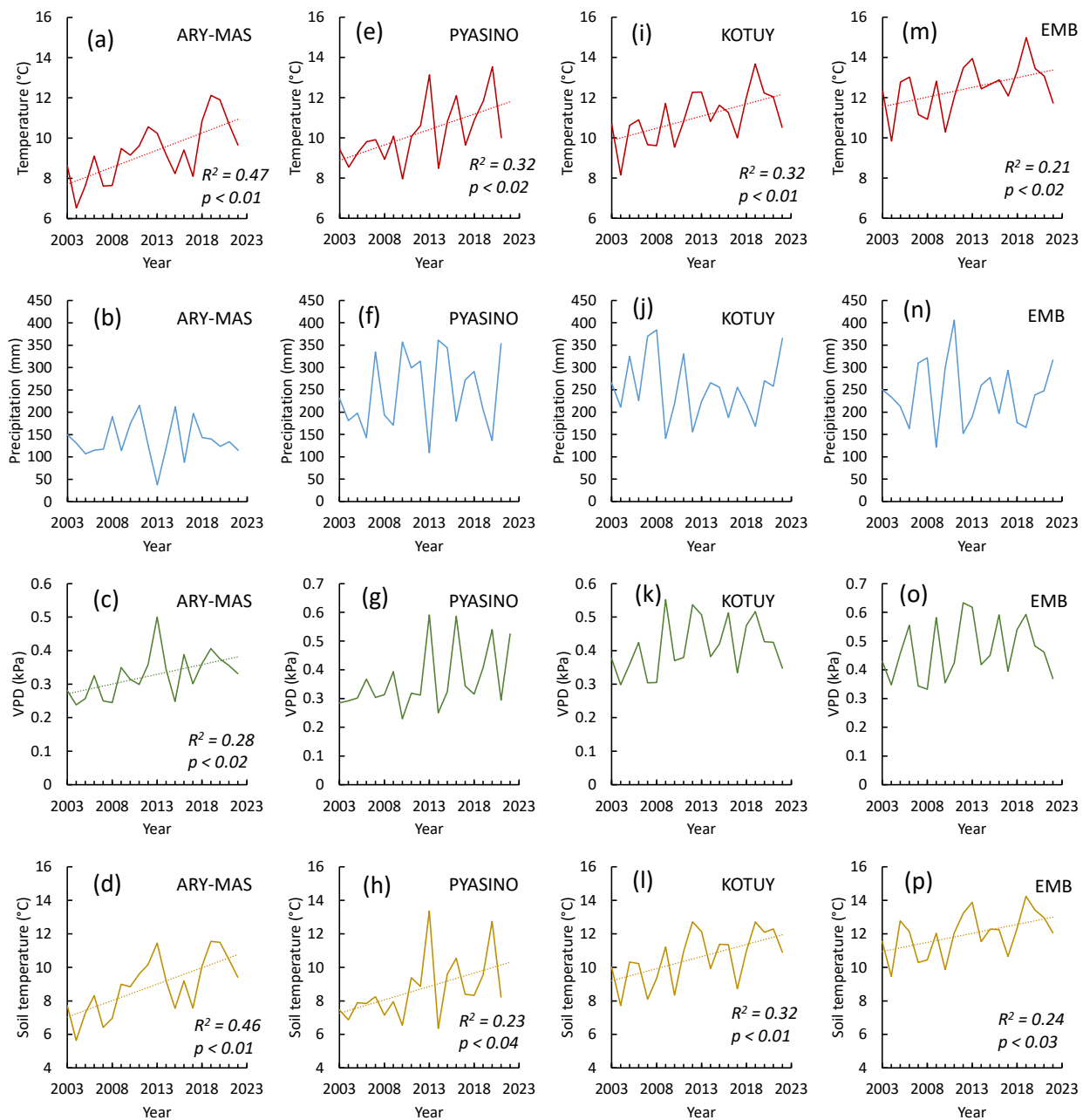


Figure A1. Climate variables of ARY-MAS (a–d), PYASINO (e–h), KOTUY (i–l), and EMB (m–p) sites (based on ERA5 Land data): summer temperature (a,e,i,m); summer precipitation (b,f,j,n); summer VPD (c,g,k,o); summer soil temperature (d,h,l,p); dotted lines indicate trends.

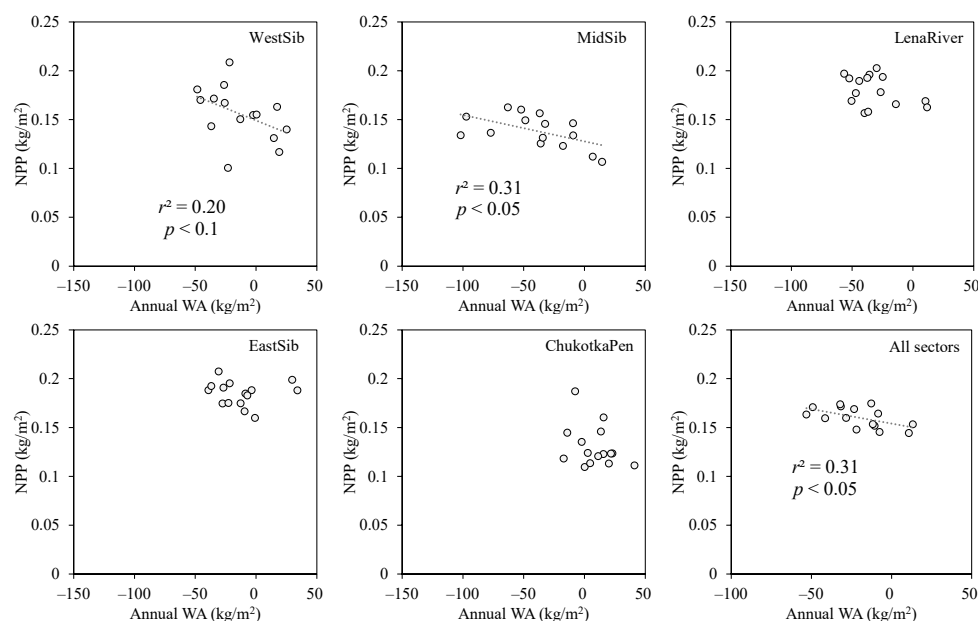


Figure A2. Correlations between NPP and WA (water anomalies) within the Arctic sectors. Significant correlations were observed in the WestSib and MidSib sectors.

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