



Salix polaris growth rings are an unreliable proxy for satellite-derived tundra productivity on Svalbard

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ABSTRACT

The Arctic is warming nearly four times faster than the global average, with Svalbard among the regions experiencing the most extreme warming. This has likely driven widespread “greening” of the archipelago, yet in-situ data on tundra productivity in Svalbard remain scarce, and satellite-based measurements are challenged by cloud cover and low sun angles. This study assessed whether *Salix polaris* growth ring width can serve as a proxy for large-scale tundra productivity on Svalbard, quantified using NDVI. The results indicate that *S. polaris* growth rings are not a reliable indicator, as only two of nine sites returned a significant ($p < 0.05$) ring width-NDVI relationship, associations across sites were very weak ($R^2 < 0.05$), and predictive performance of ring-width timeseries for local interannual tundra NDVI based on unseen sites was very poor (Nash-Sutcliffe Efficiency < -2). These findings contrast with studies on other *Salix* species and small-scale biomass changes. *S. polaris* radial growth increased with summer temperature and thawing degree-days but decreased with freezing degree-days and delayed snowmelt at multiple sites, while other climatic effects were site-specific. NDVI responded more consistently to climate, increasing with summer temperature, thawing degree-days, and summer precipitation, and decreasing with delayed snowmelt and winter precipitation. Differences in how *S. polaris* radial growth and NDVI respond to climate, along with the influence of abundant non-vascular vegetation on NDVI, likely explain why *S. polaris* growth rings are mostly unsuitable as a proxy for large-scale tundra productivity in this High Arctic tundra region, as approximated by satellite-derived NDVI.

1. Introduction

As a result of climate change, the Arctic has been subjected to unprecedented temperature increases, with the polar region warming almost four times faster than the rest of the planet (Rantanen et al., 2022). The northern Barents Sea, where the Svalbard archipelago is located, exhibits some of the most exceptional warming rates observed worldwide (Isaksen et al., 2022; Karlsen et al., 2024; Rantanen et al., 2022). As one of the most rapidly warming terrestrial regions in the High Arctic, Svalbard provides an important natural laboratory for studying ecological responses to accelerated climate change.

One of the effects of increasing temperatures in the Arctic is ‘Arctic greening’, referring to widespread increases in tundra vegetation productivity, biomass or leaf area, or changes in vegetation composition (Frost et al., 2023; Karlsen et al., 2024; Myers-Smith et al., 2020). In remote sensing studies, Arctic greening is typically defined as positive

trends in vegetation indices such as NDVI, whereas in field-based studies it refers to observed increases in vegetation biomass or structural change (Myers-Smith et al., 2020). Across both perspectives, Arctic greening has often been linked to shrub expansion (Epstein et al., 2013; Forbes et al., 2010; Frost et al., 2023, 2025; Mekonnen et al., 2021; Myers-Smith et al., 2020; Tape et al., 2006). Gaining more insight into the increasing tundra productivity can be crucial, as changes in vegetation structure in tundra ecosystems can have various consequences, such as changes in permafrost dynamics (Blok et al., 2010; Frost et al., 2017; Wilcox et al., 2019), the surface energy exchange (Chapin et al., 2005; Marsh et al., 2010), carbon stocks (Schaefer et al., 2011; Schuur et al., 2015) or wildlife activity (Boelman et al., 2011; Rickbeil et al., 2018; Van Hemert et al., 2015). Understanding the dynamics of tundra productivity is therefore important, making Arctic greening a key focus of scientific research (Frost et al., 2023).

However, limited in-situ data on tundra productivity poses a

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significant challenge. Most studies on tundra productivity in the Arctic use satellite imagery, and NDVI data in particular (Karlsen et al., 2024; Kooistra et al., 2024; Myers-Smith et al., 2020). While NDVI is often used as a proxy for vegetation productivity, it represents an index of surface greenness rather than a direct measure of tundra productivity. In addition, satellite observations in areas above the Arctic Circle are limited to a brief summer period, and even then, image quality is often compromised by cloud cover and low solar angles (Karlsen et al., 2024; Myers-Smith et al., 2020). Interpreting NDVI in these environments is further complicated by factors such as snowmelt dynamics, standing water, and sub-pixel heterogeneity (Beamish et al., 2020; Nelson et al., 2022).

To overcome such limitations, integrating remotely sensed data with in-situ data could greatly enhance the quality of research on changes in tundra productivity in the Arctic (Myers-Smith et al., 2020). Growth ring data could provide insight into tundra productivity dynamics of the past, which is not always possible with satellite imagery. It can also provide context for understanding current and future conditions of vegetation systems in the Arctic (Goetz et al., 2010; Myers-Smith et al., 2020). However, not all woody species respond the same way to changes in climate, meaning that the reliability of growth rings as a proxy for tundra productivity on a wider scale depends on the species (Brehaut and Danby, 2018; Goetz et al., 2010). In previous studies, growth rings of several willow species (*Salix pulchra*, *Salix lanata*, *Salix glauca*, and *Salix alaxensis*) have shown significant positive correlations with NDVI values representing overall tundra productivity (Andreu-Hayles et al., 2020; Blok et al., 2011; Forbes et al., 2010; Prendin et al., 2019). The polar willow (*Salix polaris* Wahlenb.) is native to Svalbard and found widely across the archipelago. It was therefore identified as a species that could potentially serve as a great subject of study to fill this research gap.

S. polaris is a mat-forming prostrate dwarf shrub that is relatively common across the High Arctic and one of the only woody plants that can grow under the harsh conditions of Svalbard (Elven et al., 2020; Nakatsubo et al., 2010; Stupianek et al., 2019). Despite its small size, this species is crucial for dendrochronological research in this part of the world. Earlier studies have shown that the radial growth of *S. polaris* is primarily driven by summer temperature (Buchwal et al., 2013; Le Moullec et al., 2018), while additional factors such as precipitation, soil moisture, and rain-on-snow events also contribute to variation in radial growth (Opala-Owczarek et al., 2017; Owczarek and Opala, 2016; Le Moullec et al., 2020). *S. polaris* growth rings are considered to have a high potential to be a useful proxy for climate changes (Owczarek et al., 2014). Le Moullec et al. (2018) have demonstrated that *S. polaris* ring growth can be a robust proxy for the aboveground biomass of a vascular plant community on Svalbard. Together, these findings indicate that *S. polaris* could be a promising in-situ indicator of tundra productivity, although this potential has not yet been evaluated.

Given this potential, *S. polaris* growth rings could help address the current lack of in-situ data on tundra productivity in Svalbard, which is a major limitation for Arctic ecological research. While current studies mostly rely on satellite imagery, this approach is constrained by the limited availability of consistent satellite data. Although *S. polaris* growth ring data has been used to analyse changes in the climate or community-level biomass, the potential of this species to act as a proxy for large-scale tundra productivity is underexplored. If *S. polaris* growth rings would prove to be a reliable proxy for overall Arctic plant productivity, they could greatly enhance current research by complementing remotely sensed data, as well as providing insight into past productivity trends in periods without satellite observations.

This study therefore aims to evaluate the potential of *S. polaris* growth rings as a proxy for overall aboveground tundra plant productivity on Svalbard as approximated by satellite-derived NDVI data. This aim is based on some major assumptions. One assumption is that MODIS

NDVI is indicative of site-level plant community productivity on Svalbard, despite known limitations of satellite data in the High Arctic. Satellite-based NDVI has been shown to correspond with plant productivity on Svalbard (Johansen and Tømmervik, 2014; Karlsen et al., 2018), and is used in this study as a large-scale approximation of overall plant productivity. A second assumption is that site-level *S. polaris* ring growth indices reflect site-level shrub productivity, consistent with findings by Le Moullec et al. (2018), who reported positive correlations between annual ring growth and above-ground biomass production for both the species itself ($r = 0.56$) as well as the vascular plant community as a whole ($r = 0.70$). As NDVI captures photosynthetically active aboveground biomass while ring width reflects radial growth of woody stem tissue, these metrics do not measure the same aspect of vegetation productivity. Instead, both are assumed to respond to the same seasonal climatic drivers, which forms the basis for evaluating *S. polaris* ring width as a proxy for broader tundra productivity. Therefore, to provide further insight into the results of the study objective, regardless of whether *S. polaris* growth rings prove to be a reliable proxy for aboveground tundra productivity or not, this study also focuses on the sensitivity of *S. polaris* and NDVI to key seasonal climatic variables, such as temperature, precipitation, and timing of snowmelt.

The following hypotheses were tested:

- 1) *S. polaris* radial growth is positively correlated with satellite-derived NDVI data and can thus serve as a proxy for overall aboveground tundra plant productivity on Svalbard;
- 2) *S. polaris* radial growth is primarily controlled by summer temperatures, with secondary influences from precipitation and snowmelt timing; and
- 3) NDVI responds to climatic variables in a manner broadly consistent with *S. polaris* growth, with summer temperatures exerting the strongest positive effect.

2. Materials and methods

2.1. Study area and species

The Svalbard archipelago (74°–81°N, 10°–35°E) covers a total area of roughly 62,000 km², with over 60% covered by glaciers, and only about 13% vegetated (Johansen et al., 2011). Meteorological data from Svalbard Airport indicate that between 2000 and 2024, the mean annual temperature varied from −6.1°C in 2003 to −0.1°C in 2016, while the total annual precipitation ranged between 122 mm in 2012 to 310 mm in 2016 (NCCS, 2024; Vickers et al., 2024). Climate change has a large impact on Svalbard's climate, as the archipelago is locally warming seven times faster than the global average (Nordli et al., 2020).

S. polaris, the focal species in this study, can be found anywhere in the High Arctic except for Greenland (WFO, 2025). It is also the only shrub species to be abundant in most of Svalbard's habitats, including polar deserts (Elven et al., 2020; Le Moullec et al., 2020). The dwarf shrub grows no more than 10 cm in height and is generally a later colonizer of deglaciated areas (Buchwal et al., 2013; Fujiyoshi et al., 2011; Nakatsubo et al., 2010). As one of the few widespread woody species in Svalbard, *S. polaris* can live for decades and is therefore valuable for dendrochronology, though its annual rings are sometimes partially incomplete or missing altogether, complicating reconstruction of annual growth (Buchwal et al., 2013; Le Moullec et al., 2020).

2.2. Data collection

2.2.1. Growth ring data

Growth ring data for *S. polaris* were compiled from existing datasets covering nine sites across Svalbard (Fig. 1). Series for Barentsøya, Edgeøya, Hornsund, Kapp Linné, Ny-Ålesund, and Sørkapp were

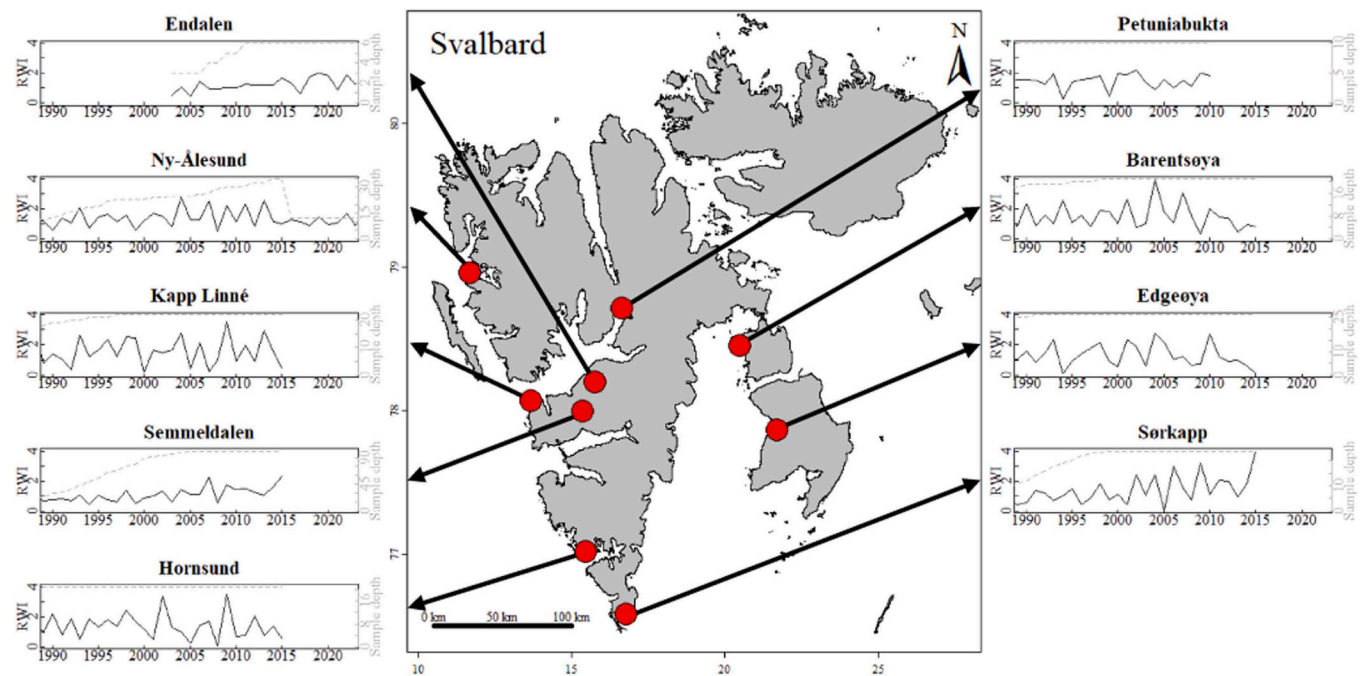


Fig. 1. The nine *Salix polaris* sample sites on Svalbard and their respective chronologies. The black line shows the RWI (Ring Width Index) values, while the dotted grey line shows the sample depth. Designed after Le Moullec et al. (2020).

obtained from Le Moullec et al. (2020), Semmeldalen from Le Moullec et al. (2018), Petuniabukta from Buchwal et al. (2013) and Endalen and a more recent series for Ny-Ålesund from Magnússon et al. (2025). For Ny-Ålesund, chronologies from both sources were combined after detrending to extend the timeframe of the record. The sampling strategies and shrub- and section-level replication of the different datasets varied slightly, but all studies sampled undamaged individuals with clear morphology, and used similar processing methods (see Table S1 and Text S1 for details).

Data series were based on a minimum of three sections per shrub (Magnússon et al., 2025), usually five to six (Le Moullec et al., 2018, 2020) and for one series over ten (Buchwal et al., 2013), always including root, root-collar and shoot fragments. All authors prepared cross-sections using a GSL1 microtome (Gärtner et al., 2013) at a thickness of approximately 15–20 μm . These sections were stained, dehydrated, permanently mounted on microscope slides, and digitized at variable magnifications using light microscopes with attached cameras. Ring widths were then measured along two to four radii per cross-section and hierarchically cross-dated within sections, within shrubs, and between shrubs at each site (further details in Text S1) to ensure accurate assignment of annual growth rings (Le Moullec et al., 2020). The section-level ring-width series were subsequently detrended for age-related growth trends using the C-method (Biondi and Qeadan, 2008) with pith offset set to zero to calculate standardized Ring Width Index (RWI) values. Only series with significant correlations ($\alpha = 0.05$) with the site mean, calculated over 20-year segments, were included. Chronologies required a minimum sample depth of three shrubs. The final chronologies represent average yearly RWI values per site (Fig. 1). The ring width chronologies were created using the ‘dplR’ package in R (Bunn, 2008). Table S1 lists sampling strategy, shrub- and section replication, chronology statistics and numbers and ages of samples per chronology.

2.2.2. NDVI data

The Normalized Difference Vegetation Index (NDVI) is used in this study as an approximation of overall aboveground tundra plant productivity. Satellite-based NDVI has been shown to correspond well with

plant productivity on Svalbard (Johansen and Tømmervik, 2014; Karlsen et al., 2018), but it should be noted that NDVI primarily reflects surface greenness, and its interpretation as a direct measure of tundra productivity requires caution, particularly at high latitudes where non-vascular plants such as mosses, low sun angles, and snow cover can influence the signal (Beamish et al., 2020; Frost et al., 2025). The NDVI dataset used in this study was created by Karlsen (2023) using MODIS satellite imagery. This dataset provides a cloud-free NDVI raster of Svalbard with an approximate pixel resolution of 232 m, and contains daily NDVI values from May 10 to September 20 for each year between 2000 and 2022. To create a cloud-free dataset, missing days were gap-filled using kernel ridge regression, which performed well with a root mean square error of 0.007, ensuring a continuous and reliable dataset (Karlsen et al., 2022).

For each growth ring site, NDVI values were extracted within a two kilometre buffer, excluding non-vegetated pixels ($\text{NDVI} < 0.2$ during the entire 23-year period), with the ‘terra’ package in R (Hijmans, 2024). The remaining number of pixels ranged from 39 at Ny-Ålesund to 97 at Semmeldalen (Figure S1), which was deemed sufficient to continue the analysis.

To assess primary production, this study used two NDVI measures. Time-integrated NDVI (TI NDVI) sums daily NDVI values over the growing season and is highly correlated with aboveground vegetation productivity (Bhatt et al., 2021; Epstein et al., 2017; Hendricks et al., 2023; Yan et al., 2022). The growing season was defined using an NDVI threshold of 0.05, applied separately for each site-year combination, allowing for different start and end dates of the growing season. This same threshold has been applied for research in the Arctic before (Bhatt et al., 2021; Hendricks et al., 2023).

The second measure, onset-to-peak NDVI (OP NDVI), sums NDVI from the onset to the peak of the growing season and was developed specifically for conditions on Svalbard, where cloud cover can obscure satellite imagery (Karlsen et al., 2018). Season onset was defined as the moment when NDVI exceeded 63% of the mean NDVI between 10 July and 5 August, and the peak was the annual maximum NDVI. Although OP NDVI has demonstrated better performance than TI NDVI for Svalbard vegetation (Karlsen et al., 2024), its application in research has

been limited. Both metrics were used to provide complementary perspectives on productivity.

2.2.3. Climate data

Climatic variables were obtained from the Copernicus Arctic Regional Reanalysis (CARRA) dataset (Schyberg et al., 2020). This dataset is based on local observations and state-of-the-art prediction models. With a resolution of 2.5 kilometres, it describes the Arctic climate much more accurately than other gridded climate datasets, such as ERA5 (Køltzow et al., 2022; Schyberg et al., 2020).

A total of four different climatic variables were downloaded using the Copernicus Climate Data Store API in Python: total precipitation, 2 m temperature, snow depth water equivalent, and snow density (Table 1). The first three variables were used to calculate the climatic variables used in the data analysis, while the snow density data was used to compare the snow depth data to in-situ observations from weather stations.

Svalbard is covered by both the eastern and western domains of the CARRA dataset, but the eastern domain is recommended for data retrieval (Nielsen et al., 2022). Climate data were downloaded at selected times (midnight and noon for temperature, and 15:00 for snow variables) to ensure representative daily values. Daily resolution time series for the nine study sites were extracted following Schimanke (2023). Additionally, timeseries for coordinates of weather stations on Svalbard were extracted for validation against in-situ data (NCCS, 2024). Before comparing the CARRA data and the weather station data, both datasets were converted to matching units. For precipitation, the data was already in the correct unit, whereas the temperature data was converted from Kelvin to Celsius. Snow depth data was converted from kg m⁻² to cm using the snow density data from CARRA (kg m⁻² / kg m⁻³ * 100).

Validation was performed using the Kling-Gupta efficiency (Gupta and Kling, 2011), which accounts for bias and variance and is more robust than the Nash-Sutcliffe efficiency (Knoben et al., 2019). A KGE score of over -0.41 means that the predicted data is more accurate than a model simply predicting the mean (Knoben et al., 2019), though negative values higher than that are not necessarily good. CARRA outperformed a mean-predicting model for temperature, precipitation, and snow depth, with particularly strong performance for temperature, moderate for snow depth, and weaker for precipitation (Table 2).

The temperature, precipitation and snow depth data were then used to calculate the climatic variables that were used in the data analysis (Table 3). These variables were aggregated to yearly values to align with growth ring and NDVI data. The calculations for these climatic variables were largely based on previous studies, except for snowmelt timing, which was refined through a process of trial and error based on inspection of snow depth graphs. The yearly values of each climatic variable were visualized to check for any highly illogical values (Figure S4-S11).

Table 1
Summary of requested data from the CARRA dataset for each of the four climatic variables that were downloaded.

Parameter	Precipitation	Temperature	Snow depth	Snow density
Domain	East domain	East domain	East domain	East domain
Level type	Surface or atmosphere	Surface or atmosphere	Surface or atmosphere	Surface or atmosphere
Variable	Total precipitation (kg m ⁻²)	2 m temperature (K)	Snow depth water equivalent (kg m ⁻²)	Snow density (kg m ⁻³)
Product type	Forecast	Analysis	Analysis	Analysis
Time	00:00	00:00, 12:00	15:00	15:00
Leadtime h	24	N/A	N/A	N/A
Year	1990–2024	1990–2024	1990–2024	1990–2024
Month	January–December	January–December	January–December	January–December
Day	1–31	1–31	1–31	1–31
Data format	GRIB	GRIB	GRIB	GRIB

Table 2
Kling-Gupta efficiency (KGE) scores comparing CARRA data to weather station observations for temperature, precipitation, and snow depth.

Weather station	Temperature KGE	Precipitation KGE	Snow depth KGE
Svalbard	0.905	-0.254	0.592
Lufthavn			
Ny-Ålesund	0.841	0.356	0.650
Hornsund	0.909	0.170	0.258
Sveagruva	0.744	-0.198	0.198

Table 3
Climatic variables that were used for data analysis and their definitions.

Variable	Definition
Summer temperature	Mean June – August temperature
Winter temperature	Mean November – April temperature
Spring temperature	Mean March – May temperature
Thawing degree-days	Sum of all positive daily mean temperature (°C) values
Freezing degree-days	Sum of all negative daily mean temperature (°C) values
Summer precipitation	Mean June – August precipitation
Winter precipitation	Mean November – April precipitation
Snowmelt timing	First Julian day of the year when the snow depth is zero for five consecutive days, and at least 20 of the following 30 days also have a snow depth of zero

2.3. Data analysis

2.3.1. Growth ring and NDVI correlation

Kendall correlation coefficients (Kendall, 1938) were calculated for each of the nine sites to assess relationships between *S. polaris* RWI values and NDVI. Most sites had 16 overlapping years (2000–2015), while Ny-Ålesund, Endalen, and Petuniabukta had 23, 22, and 11 overlapping years, respectively.

To assess large-scale patterns, all observations were combined in a linear mixed-effects model with NDVI as the response and either RWI or mean annual ring width (μm) as the predictor. Unlike RWI, which is scaled within site, absolute ring width values are unscaled, just like the NDVI values, making them useful for this test to capture potential relationships with NDVI across sites. Linear mixed-effects models were fitted using the ‘nlme’ package in R (Pinheiro et al., 2025), with a random intercept for ‘Site’ and a first-order autoregressive correlation structure (AR(1)) per site. Models were evaluated for normally distributed residuals using QQ-plots, and for homoscedasticity using residual plots against fitted values. The coefficient of determination for fixed effects (ring-width proxy) was calculated according to Nakagawa and

Schielzeth (2013). To evaluate the theoretical predictive capabilities of newly obtained absolute ring-width timeseries for tundra productivity (TI and OP NDVI), the range-normalized root mean square error (NRMSE) and Nash-Sutcliffe efficiency (NSE) of marginal predictions were evaluated using a leave-one-site-out approach. Predictive metrics (NRMSE, NSE) were averaged across sites, weighted for available years per site.

2.3.2. Growth ring and climate correlation

Relationships between growth ring widths and climate variables were tested at each site using generalized least squares (GLS) models with first-order autocorrelation (AR(1)) to account for temporal dependencies. A combined dataset of all sample sites was analysed with a linear mixed-effects model, including all climatic variables as candidate predictors, 'Site' as a random effect and a first-order autoregressive correlation structure (AR(1)) per site. Model selection based on AIC was used to identify the most parsimonious model. Multicollinearity was addressed by inspecting VIFs and correlation matrices; variables with VIF values > 5 or strong pairwise correlations ($|r| > 0.7$) were excluded. Wald tests were used to assess significance in the mixed-effects models. Residual distributions were checked as described in 2.5.1. Both analyses were conducted using the 'nlme' package (Pinheiro et al., 2025), with model selection based on AIC performed using the 'dredge' function in the 'MuMIn' package (Bartoń, 2025).

2.3.3. NDVI and climate correlation

Relationships with climate variables were analysed for TI NDVI and OP NDVI separately, following the same procedure as described for growth ring widths under 2.5.2.

2.3.4. Role of site vegetation cover

Finally, we explore the dependency of correlation among RWI and

NDVI records on local plant communities by performing a PCA on simplified plant community areal cover percentages in the NDVI footprint area and fitted RWI – NDVI correlations (for TI and OP NDVI) and key RWI-climate relations (TDD, FDD, summer and winter precipitation) to the PC axes (see methods in Text S2). Vegetation classes were aggregated from Johansen et al. (2011) and included non-vegetated, sparsely vegetated, moss dominated, vascular dominated and mixed vegetation (Figure S12, Table S15).

3. Results

3.1. Growth ring width and NDVI relationships

Kendall's tau correlation analysis revealed a significant positive relationship between RWI and both TI and OP NDVI at Endalen (TI: $\tau = 0.337$, $p = 0.0398$; OP: $\tau = 0.326$, $p = 0.0468$). At Sørkapp, a significant positive relationship between RWI and TI NDVI was found (TI: $\tau = 0.383$, $p = 0.0413$). No statistically significant correlations were found at any of the other sample sites (Fig. 2; Table S2).

Results of the linear mixed-effects models showed a significant positive relationship between *S. polaris* radial growth and TI NDVI, but not OP NDVI, for all sample sites combined. TI NDVI was significantly associated with both RWI ($\beta = 0.832$, $SE = 0.298$, $t_{140} = 2.796$, $p = 0.006$; Fig. 3 A; Table S3) and absolute ring width ($\beta = 0.024$, $SE = 0.012$, $t_{140} = 2.022$, $p = 0.045$; Fig. 3B; Table S5). For OP NDVI, no significant relationships were found for RWI ($\beta = 0.259$, $SE = 0.175$, $t_{140} = 1.48$, $p = 0.142$; Fig. 3 C; Table S4) or absolute ring width ($\beta = 0.005$, $SE = 0.007$, $t_{140} = 0.732$, $p = 0.465$; Fig. 3D; Table S6). All models had coefficients of determination for fixed effects (ring-widths) of < 0.05. A leave-one-site-out approach resulted in NRMSE and NSE values of 0.433 and -2.01 for OP NDVI, and 0.525 and -4.74 for TI NDVI, indicating very poor prediction of local interannual variability in tundra NDVI

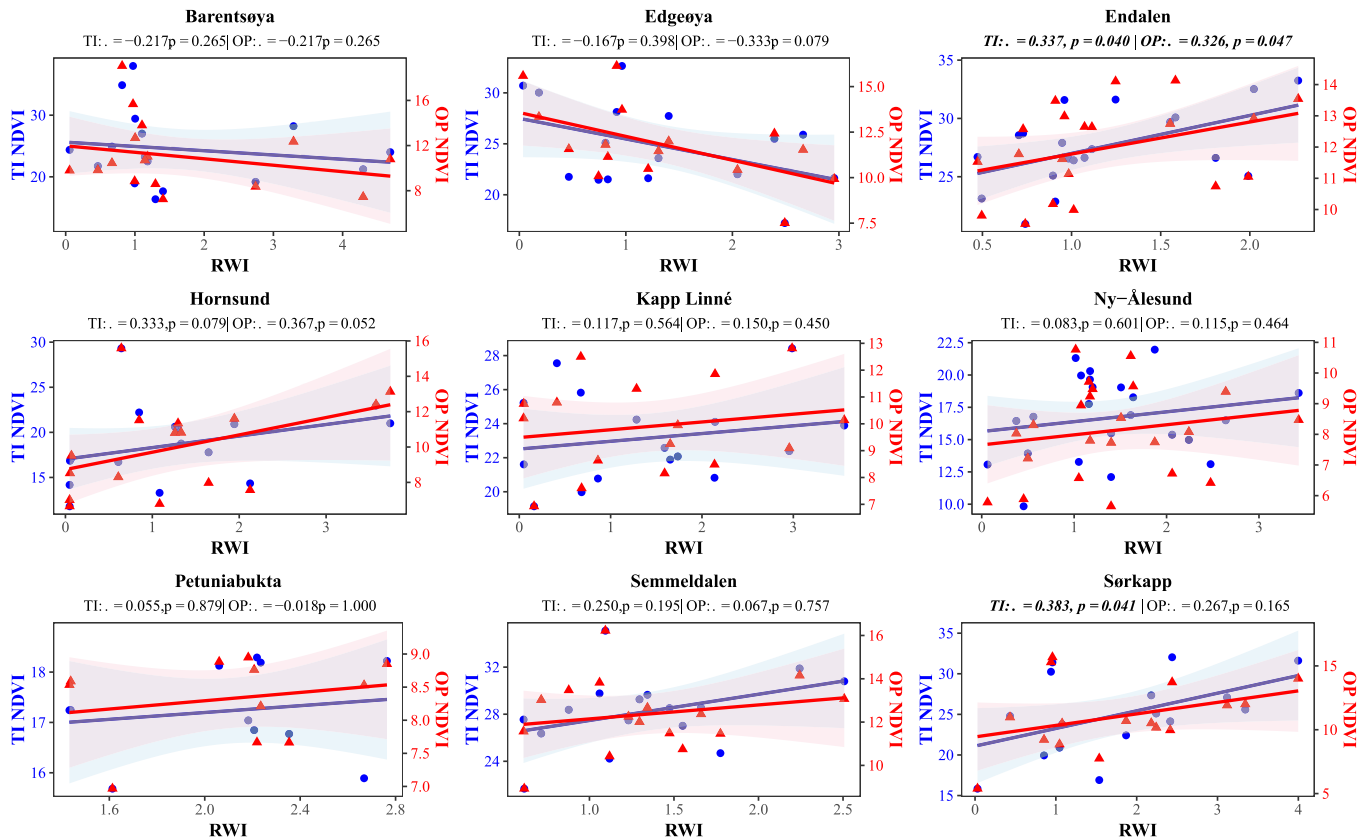


Fig. 2. Relationship between Ring Width Index (RWI) and both TI NDVI and OP NDVI at nine different sample sites on Svalbard. The statistically significant results ($p < 0.05$) are displayed in bold and italic.

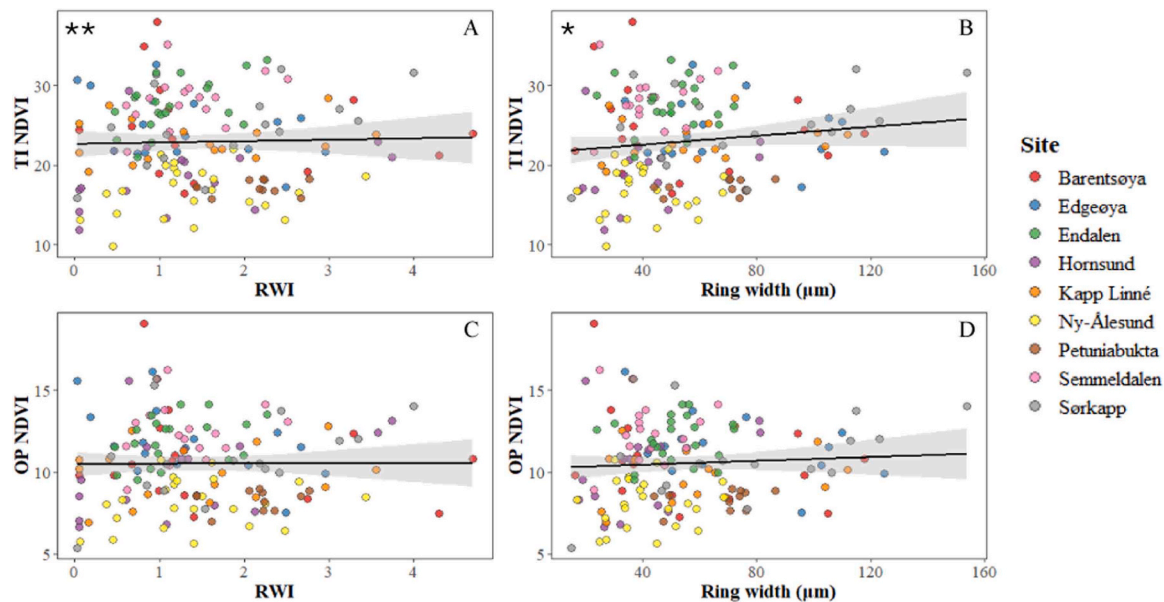


Fig. 3. Relationships between NDVI and *Salix polaris* growth across all sample sites. Panels show (A) TI NDVI vs. RWI, (B) TI NDVI vs. absolute ring width (μm), (C) OP NDVI vs. RWI, and (D) OP NDVI vs. absolute ring width (μm). The black line is a linear fit, with the grey shaded area representing a 95% confidence interval. Asterisks indicate significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

based on absolute ring-width series for hypothetical new growth ring series.

3.2. Climate drivers of RWI and tundra NDVI

Out of the 72 GLS tests for *S. polaris* RWI values (nine sites and eight climatic variables), nineteen significant relationships were identified across five sample sites (Table 4; Table S7). The same number of GLS tests were conducted for each NDVI dataset. For TI NDVI, twenty-five

significant relationships were found across eight of the nine sites (all except Petuniabukta), while OP NDVI produced twelve significant relationships across seven sites, but showed comparable overall patterns to TI NDVI (Table 4; Tables S13 and S14).

Summer temperature and thawing degree-days showed significant positive effects on *S. polaris* RWI values and NDVI at multiple sites. Winter temperature showed a significant positive effect at Sørkapp. A delayed snowmelt timing showed significant negative relationships, indicating that delayed snowmelt limited both NDVI and radial growth.

Table 4

An overview of how climatic variables influence *Salix polaris* RWI and NDVI values based on GLS tests for each individual site. The numbers in the cells represent coefficient estimate values. Bold values indicate significant results.

RWI	Barentsøya	Edgeøya	Endalen	Hornsund	Kapp Linné	Ny-Ålesund	Petuniabukta	Semmeldalen	Sørkapp
Summer temperature	-0.226	0.093	0.748***	0.051	0.014	0.234*	0.521*	0.624***	0.291
Winter temperature	0.086	0.186	0.116	-0.234	0.097	0.131	0.131	0.308	0.331*
Spring temperature	0.127	-0.217	0.358	-0.218	-0.184	0.150	-0.635**	0.166	0.549**
Thawing degree-days	-0.184	0.078	0.691***	-0.010	-0.036	0.188	0.544*	0.602**	0.288
Freezing degree-days	0.009	0.272	-0.157	0.126	0.189	-0.134	-0.070	-0.582***	-0.427**
Summer precipitation	-0.154	-0.282	0.544**	-0.099	0.230	0.029	-0.760***	-0.393*	-0.108
Winter precipitation	0.119	-0.062	0.056	-0.320*	-0.287	0.087	-0.071	0.008	0.433*
Delayed snowmelt timing	-0.016	-0.046	0.057	0.094	0.150	0.142	-0.744***	-0.437*	-0.285
TI NDVI	Barentsøya	Edgeøya	Endalen	Hornsund	Kapp Linné	Ny-Ålesund	Petuniabukta	Semmeldalen	Sørkapp
Summer temperature	0.847***	0.411**	0.489*	0.608***	0.584**	0.486*	0.121	0.531**	0.519**
Winter temperature	0.091	-0.079	-0.034	-0.282	0.104	-0.213	-0.075	-0.009	-0.260
Spring temperature	0.024	0.028	0.145	-0.199	0.241	0.233	-0.096	0.219	0.041
Thawing degree-days	0.714***	0.464**	0.551**	0.495*	0.552**	0.690***	0.185	0.626**	0.446*
Freezing degree-days	-0.133	-0.078	-0.014	0.250	-0.185	0.128	0.049	-0.124	0.236
Summer precipitation	0.113	0.304*	0.464*	0.442*	0.511**	0.380*	0.033	0.416*	0.166
Winter precipitation	-0.168	-0.201	-0.149	-0.385*	0.073	-0.028	-0.078	-0.042	-0.067
Delayed snowmelt timing	-0.314	-0.179	0.058	-0.280	-0.085	-0.101	-0.077	-0.383*	-0.918***
OP NDVI	Barentsøya	Edgeøya	Endalen	Hornsund	Kapp Linné	Ny-Ålesund	Petuniabukta	Semmeldalen	Sørkapp
Summer temperature	0.762***	0.229	0.000	0.467*	0.338	0.249	0.217	0.278	0.513**
Winter temperature	0.082	0.099	0.275	-0.231	0.099	0.282	-0.024	0.062	-0.265
Spring temperature	0.065	0.098	0.178	-0.255	0.109	0.586**	0.045	0.176	-0.031
Thawing degree-days	0.739***	0.321*	0.277	0.313	0.370	0.285	0.261	0.358	0.440*
Freezing degree-days	-0.142	-0.206	-0.330	0.211	-0.156	-0.319	-0.102	-0.171	0.216
Summer precipitation	0.416*	0.256	0.295	0.397	0.522**	0.262	0.174	0.396*	0.336
Winter precipitation	-0.241	-0.027	-0.062	-0.366*	0.019	0.185	-0.126	-0.111	-0.256
Delayed snowmelt timing	-0.261	-0.166	0.190	-0.138	-0.184	0.028	-0.004	-0.236	-0.802***

Significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Freezing degree-days were significantly negatively related to *S. polaris* RWI values but showed no significant relationship with NDVI. Other variables, including spring temperature, and seasonal precipitation, showed mixed or site-specific effects for *S. polaris* RWI values, resulting in both positive and negative significant associations depending on the location (Table 4). Linear mixed-effects models, including site as a random effect and an AR(1) correlation structure, showed that the best-fitting model for *S. polaris* RWI values included only freezing degree-days ($RWI \sim \text{Freezing degree-days} + 1$). Freezing degree-days had a statistically significant negative effect on RWI ($\beta = -0.155$, $SE = 0.053$, $t_{210} = -2.95$, $p = 0.004$; Table 5; Table S10). For TI NDVI, the dredged model included summer temperature, summer precipitation, spring temperature, winter temperature, and winter precipitation (Table S11). Summer temperature, summer precipitation, and spring temperature had significant positive effects, while winter precipitation had a significant negative effect (Table 5). Winter temperature showed no significant effect. The dredged model for OP NDVI showed similar results, but included thawing degree-days instead of summer temperature (Table 5; Table S12).

4. Discussion

4.1. Interpretation of results and comparison to previous studies

4.1.1. Relation between growth ring width and NDVI values

Relationships between *S. polaris* radial growth and NDVI – while significant for TI NDVI – showed very poor predictive performance and explained variance, indicating that *S. polaris* ring widths are not a reliable proxy for local interannual variations in overall aboveground tundra plant productivity as quantified through NDVI. The hypothesised positive relationship was based largely on Le Moullec et al. (2018), who found *S. polaris* growth rings to be a good proxy for vascular plant biomass at the community level. However, an important distinction is that Le Moullec et al. (2018) did not use NDVI, but instead related ring widths directly to harvested aboveground biomass of vascular plant communities. As such, their findings identify *S. polaris* growth rings as a proxy for vascular plant productivity specifically, and do not account for the contribution of non-vascular vegetation to NDVI, such as mosses. These results therefore suggest that the assumption that *S. polaris* ring growth reflects site-level shrub productivity holds at the plot scale for vascular plant communities, but does not extend reliably to overall tundra productivity as captured by MODIS NDVI. Although previous research has shown strong relations between aboveground biomass and Landsat NDVI (Johansen and Tømmervik, 2014), this could point towards discrepancies between actual dynamics of primary productivity and biomass growth and NDVI. Similar inconsistencies have been observed in Canadian subarctic tundra with generally weak correlations between NDVI and ring-width indices in shrubs and trees (Brehaut and Danby, 2018), highlighting the context-dependence of NDVI – growth ring width relationships. NDVI dynamics for Svalbard may also be

strongly influenced by moss tundra relative to vascular plants (Karlsen et al., 2024; Vickers et al., 2016). Site-specific relations show clear divergence in the degree of correlation between growth ring widths and NDVI, with few sites showing significant association (Fig. 2). Figure S12 shows the vegetation community composition of sampling sites based on Landsat classifications (Johansen et al., 2009). Although no robust conclusions can be drawn based on nine sites, we do observe that the degree of correlation between RWI and NDVI shows a tendency for negative correlation ($p = 0.067$) with coverage of moss-dominated vegetation types versus vascular plant dominated communities (PCA analysis, Text S2, Figure S13). In moss tundra, scattered vascular plants may contribute minimally to NDVI signal (Karlsen et al., 2022; Vickers et al., 2016), and NDVI values can be atypically high directly after snowmelt compared to areas where vascular plants dominate (Vickers et al., 2016) as bryophytes lack seasonal senescence (Karlsen et al., 2024). Since these trends were strongly driven by only few moss-dominated sites (Barentsøya, Edgeøya), more spatially distributed evidence and more detailed species cover information is necessary to determine the degree to which plant community composition determines the validity of polar shrub growth rings as proxies for larger scale greening dynamics. Furthermore, our results suggest that correlations between RWI and NDVI indices are poor for strongly moss-dominated sites, but also show variable performance for more vascular dominated sites (Fig. S13). This implies that, contrary to the results of Le Moullec et al. (2018) and the assumption underlying this study, *S. polaris* ring widths may not reflect biomass dynamics of vascular plant communities (other than *S. polaris* itself) very well on larger scales. While an alternative explanation could be that NDVI values poorly capture tundra biomass and productivity dynamics, challenging the assumption that NDVI reflects site-level plant community productivity, previous studies on Svalbard have found significant correlations between MODIS and Landsat NDVI and field-measured aboveground biomass (Johansen and Tømmervik, 2014; Karlsen et al., 2018). We propose that an alternative explanation may be that such studies have exclusively focused on aboveground biomass, while growth rings integrate above and belowground biomass growth. A large proportion of *S. polaris* biomass is situated belowground, and above- and belowground parts may exhibit slightly variable climate sensitivity (Buchwal et al., 2013). As approximately 80% of living biomass in Arctic ecosystems is situated belowground (Mokany et al., 2006) further exploring the role of above and belowground biomass in relations between biomass proxies and NDVI is recommended.

4.1.2. Relation between growth ring width and climatic variables

The impact of climatic variables on *S. polaris* radial growth appears largely site-specific rather than regionally consistent. Most climatic variables were not included in the best-performing model, as only freezing degree-days was included, showing a significant negative relationship (Table S10). Site-level analyses nevertheless revealed additional significant effects in roughly a quarter of all tests, with three

Table 5

Results from linear mixed-effects models (including site as a random effect and AR(1) correlation structure) for *Salix polaris* RWI, TI NDVI, and OP NDVI.

Response variable	Climatic variable	Slope	SE	<i>t</i>	df	<i>p</i> value
RWI	Freezing degree-days	-0.155	0.053	-2.950	210	0.004**
	Summer temperature	0.497	0.061	8.173	184	< 0.001***
TI NDVI	Summer precipitation	0.182	0.055	3.306	184	0.001**
	Spring temperature	0.200	0.072	2.799	184	0.006**
	Winter temperature	-0.099	0.075	-1.324	184	0.187
	Winter precipitation	-0.204	0.065	-3.144	184	0.002**
	Thawing degree-days	0.426	0.069	6.199	184	< 0.001***
OP NDVI	Summer precipitation	0.237	0.062	3.848	184	< 0.001***
	Spring temperature	0.210	0.079	2.648	184	0.009**
	Winter temperature	-0.053	0.082	-0.642	184	0.522
	Winter precipitation	-0.289	0.071	-4.063	184	< 0.001***

Significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

sites showing none (Table S7).

Summer temperature and thawing degree-days consistently showed a positive effect on *S. polaris* radial growth, aligning with previous findings highlighting summer temperature as a key driver of *S. polaris* ring growth (Le Moullec et al., 2020; Owczarek and Opala, 2016). The positive influence of thawing degree-days, although not previously examined for this species, matches broader trends in Arctic willows (Walker, 1987). Conversely, freezing degree-days showed negative effects, as expected from their inverse relationship with thawing conditions. Winter temperature showed a positive impact in Sørkapp. The effect of winter temperature was hypothesized to be negative as a result of increasing rain-on-snow events encasing the plant in ice instead of snow, inhibiting growth (Le Moullec et al., 2020; Opala-Owczarek et al., 2017). The positive effect of higher winter temperatures on *S. polaris* growth in Sørkapp may result from earlier snowmelt caused by warmer winters (Kankaanpää et al., 2018), which in turn enhances ring growth at this site.

Snowmelt timing also showed a negative effect, indicating that later snowmelt reduces radial growth. Although no previous studies have examined this relationship for *S. polaris*, research on other Svalbard plant species have shown mixed responses (Cooper et al., 2010; Crichton et al., 2022; Gamon et al., 2013; Jónsdóttir et al., 2022; Livensperger et al., 2015; Mallik et al., 2011). Studies reporting positive effects of early snowmelt suggest that a longer growing season enhances plant performance (Cooper et al., 2010; Jónsdóttir et al., 2022; Mallik et al., 2011). Cooper et al. (2010) also noted that *S. polaris* greens up early after snowmelt, thus being negatively affected by later snowmelt, as its phenological growth has to start later in the year. Given the already short growing season for this species, further shortening likely reduces photosynthesis and consequently radial growth.

Other climatic variables demonstrated more variable and context-dependent effects. Higher spring temperatures had both positive and negative effects on *S. polaris* radial growth, being positive at Sørkapp but strongly negative at Petuniabukta. This contrast was unexpected, as a positive effect of spring temperature was hypothesized. A potential explanation is that higher early-spring temperatures could trigger premature budburst, making plants vulnerable to frost damage (Körner and Alsos, 2009; Paus et al., 1986). However, daily temperature data for Petuniabukta showed almost no late spring frosts. Another explanation could be rain-on-snow events in spring, leading to potential influence of basal icing. The presence of basal ice has been proven to cause direct physiological damage to plants, but can also advance the timing of peak growth by more than a week (Lechler et al., 2025). The formation of basal ice is spatially heterogeneous (Lechler et al., 2025; Peeters et al., 2019), meaning that rain-on-snow impacts likely also differ per location (Le Moullec et al., 2020). Finally, earlier snowmelt in warm springs may have potentially caused late-season drought (Gehrmann et al., 2021; Livensperger et al., 2019), which may have locally limited wood growth. Further monitoring of snowpack properties and site hydrology would be necessary to study the mechanisms behind spatially variable associations of ring growth with winter and spring conditions.

Summer precipitation also showed site-specific effects on *S. polaris* radial growth, being positive in Endalen but negative in Petuniabukta and Semmeldalen. Positive effects align with previous findings from Bjørnøya (Owczarek et al., 2020), while negative effects have been reported in dry sites, where precipitation can reduce growth by lowering solar radiation and temperature (Buchwal et al., 2013). Petuniabukta and Semmeldalen are relatively dry, which may explain the negative responses (Figure S12). Timing of precipitation may also play a role, as late-season moisture influences photosynthesis and the timing of *S. polaris* senescence, with both positive and negative effects reported (Dormann and Woodin, 2002; Enquist and Ebersole, 1994; Gehrmann et al., 2021). Overall, the effect of summer precipitation on radial growth appears to be highly context-dependent.

The final climatic variable that showed both significant positive and negative effects on *S. polaris* ring growth was winter precipitation, being

positive in Sørkapp but negative in Hornsund. While most existing studies report a positive effect because snow protects against frost and provides water (Hallinger et al., 2010; Mallik et al., 2011; Owczarek and Opala, 2016; Schmidt et al., 2010), excessive snowfall can also delay snowmelt (Frei and Henry, 2021), which showed a significant negative effect on ring growth for two sample sites. However, snowmelt timing did not correlate significantly with winter precipitation at any site (Table S8). Additional research may help to gain insight into the context-dependency of both summer and winter precipitation on *S. polaris* ring width growth.

Overall, these findings point to a complex and context-dependent relationship between climate and *S. polaris* radial growth, rather than a single clear pattern across sites.

4.1.3. Relation between NDVI values and climatic variables

Unlike the site-specific responses of *S. polaris* radial growth, NDVI values showed consistent relationships with climatic variables across Svalbard. This may follow from the fact that the use of large-scale MODIS pixels (232 by 232 m) averages out local variation in growth dynamics that are retained in growth ring data. When combining data from all sites, summer temperature or thawing degree-days, summer precipitation, and spring temperature were positively associated with both TI and OP NDVI, while winter precipitation had a negative effect. No climatic variable showed a positive relationship with NDVI at one site and a negative relationship at another, further confirming that climate impacts on NDVI are more consistent across locations than on *S. polaris* radial growth.

The positive effects of temperature and thawing degree-days on both TI NDVI and OP NDVI correspond with existing studies (Andresen et al., 2017; Karlsen et al., 2024; Rumpf et al., 2014; Vickers et al., 2016) and underscore the importance of growing season temperatures in driving High Arctic vegetation productivity as approximated by NDVI. Summer precipitation also showed a positive impact on both TI and OP NDVI across multiple sites. While Bhatt et al. (2021) reported a relatively weak positive correlation between summer precipitation and Arctic NDVI, the effect in this study appears stronger, suggesting that Svalbard plants may be water-limited. This is supported by Livensperger et al. (2019), who found soil moisture to be an important yet understudied driver of plant senescence on Svalbard. All significant relationships between summer precipitation and NDVI were positive, whereas its effect on *S. polaris* radial growth was mixed. This suggests that summer precipitation influences the broader plant community differently than it does *S. polaris*, which may partly explain the weak correlation between *S. polaris* radial growth and NDVI.

Spring temperature positively affected only OP NDVI and only at Ny-Ålesund. A positive effect of spring temperatures on NDVI in the Arctic has been found before (Crichton et al., 2022). This effect was not seen on TI NDVI possibly because OP NDVI reflects the early growing season, while TI NDVI covers the entire season. Since spring temperatures have a big impact on the start of the growing season (Crichton et al., 2022), this may explain the positive relationship with OP NDVI but not TI NDVI.

Higher winter precipitation and later snowmelt timing showed a significant negative impact on both TI and OP NDVI. The negative impact of winter precipitation aligns with prior findings (Crichton et al., 2022), although it was significant only at Hornsund. While winter precipitation was hypothesized to positively affect *S. polaris* growth, it was also negative at Hornsund. The negative effects of delayed timing of snowmelt on NDVI contradicts the hypothesis and several studies suggesting that earlier, rather than later, snowmelt leads to lower NDVI values in the High Arctic (Crichton et al., 2022; Gamon et al., 2013; Moriana-Armendariz et al., 2022). While many of these studies focus on peak NDVI, Gamon et al. (2013) also observed a negative effect of early snowmelt on integrated NDVI, similar to the TI NDVI used here. Other studies report that later snowmelt leads to lower NDVI values due to a shortened growing season (Cooper et al., 2010; Jónsdóttir et al., 2022). These conflicting findings may be due to different NDVI products and

plant species responding differently to snowmelt timing (Karlsen et al., 2014; Rumpf et al., 2014; Semenchuk et al., 2013). The consistently negative trend found in this study may also be influenced by moss coverage, as NDVI values are often much higher in moss-dominated tundra immediately after snowmelt than in areas with less moss (Vickers et al., 2016). Consequently, relationships may differ based on plant species composition, the NDVI product (integrated or peak) or timing (early or entire growing season). However, overall, a later snowmelt reduces the cumulative NDVI values measured in this study.

Neither winter temperatures nor freezing degree-days had significant effects on TI or OP NDVI. The effect of winter temperatures on NDVI on Svalbard was already unclear due to conflicting findings in literature (Crichton et al., 2022; Vickers et al., 2016), and this study does not resolve that uncertainty. Because freezing degree-days are strongly influenced by winter temperatures, it is unsurprising that this variable also showed no significant effect, despite a hypothesized negative impact.

Overall, our results confirm that NDVI on Svalbard is mainly impacted by warmer temperatures, while colder temperatures have little influence, supporting the link between Arctic greening and rising temperatures on Svalbard (Karlsen et al., 2024). The different climatic fingerprint of local growth ring width series and larger scale MODIS NDVI dynamics already partly explains the lack of predictive performance of growth ring series for larger scale productivity indicators.

4.2. Implications for research on Arctic tundra productivity

Despite previous research suggesting that growth rings can serve as a reliable proxy for productivity (Li et al., 2024; Wang et al., 2022; Xu et al., 2017), our findings show that *S. polaris* growth ring widths are not strong predictors for satellite-derived NDVI and therefore unlikely to be good proxies for tundra ecosystem productivity on Svalbard. Earlier studies were mostly performed in temperate forests, where trees dominate net primary productivity. In the Arctic, woody plants are not nearly as dominant and have a smaller impact on large-scale productivity. However, several studies in Arctic ecosystems have reported links between radial shrub growth and NDVI. For instance, Weijers et al. (2018) found that *S. pulchra* ring widths were positively correlated with mean maximum NDVI across an alpine tundra area in the Yukon Territory in northwest Canada, suggesting that radial growth can reflect broader patterns of Arctic-alpine 'greening'. Similarly, Prendin et al. (2019) found a positive relationship between *S. glauca* ring width and growing season NDVI in the southern part of West Greenland, while Andreu-Hayles et al. (2020) found that shrub RWI and peak NDVI were positively correlated at a regional scale for *Salix* spp. and *Alnus viridis* on Alaska's North Slope. The differences between these studies and our findings can likely be partly explained by the differences in latitude and associated environmental conditions. On Svalbard, *S. polaris* specimens can grow no larger than 10 cm in aboveground height, whereas the shrub species and study areas in the previous works support much taller and denser vegetation (Andreu-Hayles et al., 2020; Prendin et al., 2019; Weijers et al., 2018), which likely contributes more strongly to large-scale NDVI signals. Since Svalbard is located in the High Arctic, environmental conditions limit shrub growth and reduce vegetation density compared to lower-latitude tundra regions. Instead, large parts of Svalbard are covered by non-vascular vegetation instead, such as mosses, which further weakens the relationship between woody plant growth and NDVI. Therefore, growth ring data may not be suitable to assess productivity in these systems, posing an important caveat for future research on tundra productivity in the High Arctic.

The indication that woody plants on Svalbard do not contribute much to large-scale tundra productivity could also mean that shrubs may not influence Arctic greening as much as previously thought, at least in the High Arctic. Past studies have suggested that shrub expansion is the main driver of Arctic greening in large parts of the Arctic (Epstein et al., 2013; Forbes et al., 2010; Frost et al., 2023; Mekonnen

et al., 2021; Tape et al., 2006). Although this study examined radial growth rather than shrub expansion, the limited contribution of *S. polaris* to NDVI values suggests that shrubs alone may not explain greening patterns on Svalbard. Future research should therefore consider the role of other plant groups, such as forbs, graminoids, and mosses, and ideally incorporate data on shrub expansion.

However, *S. polaris* growth rings may still be useful at smaller scales, particularly in areas with relatively low moss cover and high vascular plant dominance. In such contexts, growth rings could accurately reflect NDVI values. This aligns with Le Moullec et al. (2018), who found *S. polaris* growth rings to be a good proxy for vascular plant biomass at small scales. Testing this relationship across more sites would be necessary to determine whether *S. polaris* radial growth can indicate vascular plant dynamics at larger scales across Svalbard.

Finally, this study sheds light on the role of different climate sensitivities of specific shrub species and overall tundra NDVI in explaining mismatches between growth ring and NDVI dynamics. This suggests that growth ring data may be a more suitable proxy in ecosystems where the climatic sensitivity of overall tundra productivity or biomass, NDVI and radial growth of indicator species overlaps more consistently.

4.3. Limitations and recommendations

Several limitations should be considered for this study. First, the growth ring samples were collected and measured by different people, which may have introduced slight methodological differences in specimen selection or ring counting. Since counting *S. polaris* rings is intricate, missing even a single ring can misalign subsequent years and potentially affect the analyses. Limitations also arise from the NDVI and climate data, both of which were partially predicted. Many NDVI values in the Karlsen (2023) dataset were estimated due to cloud cover and low sun angles, with gap-filling performed using kernel ridge regression (RMSE = 0.007; Karlsen et al., 2022). Similarly, much of the CARRA climate data was estimated to create a complete grid (Nielsen et al., 2022). Comparisons with Svalbard weather stations suggested that temperature data were reliable, but precipitation and snow cover data were less accurate, making results involving these variables less robust. The spatial resolution of both datasets also limits the ability to capture microclimatic variation, which can influence *S. polaris* growth. Other factors not considered in this study, such as cloud cover, UV radiation, soil moisture, thaw depth, pH, nutrient availability, and microbial activity may also affect radial growth (Möller et al., 2001; Opala-Owczarek et al., 2017; Tejnecký et al., 2025; Yeloff et al., 2008). Additionally, although first-order temporal autocorrelation structures were applied to account for year-to-year dependencies to make minimal assumptions about lagged effects, the specific mechanisms underlying these carry-over effects of previous-year conditions on radial growth and NDVI were not explicitly modelled. These carry-over effects may contribute to the observed mismatch between *S. polaris* ring-width indices and NDVI. Finally, the temporal overlap between datasets was limited. Climate data spanning 1990–2024 and NDVI data from 2000 to 2022 overlapped only partly with the growth ring records, most of which end in 2015, despite the longest chronology extending back to 1948. Greater overlap would have provided more data points and increased the robustness of the results.

Despite these limitations, the study also highlights approaches that may be useful for future research. This study expands on previous research by using a spatially extensive design, with nine sample sites distributed evenly across the Svalbard archipelago. This ensured representation of diverse climates and vegetation types. Additionally, the study used two NDVI measures, TI NDVI and OP NDVI. While the results were largely similar between the two, including both metrics provided a broader perspective on vegetative productivity across Svalbard. Validation of TI and OP NDVI with spatially distributed time series of annual aboveground biomass or gross primary productivity would be valuable, although such records are currently scarce.

Future studies could investigate additional environmental factors affecting *S. polaris* radial growth, including site conditions such as snow dynamics, soil moisture, nutrients, and sediments. Greater attention to small-scale climate variability could also improve understanding, as this study relied on climate data with a coarse spatial resolution of 2.5 kilometres per pixel. Using higher resolution climate data or field measurements would capture more detailed information and better explain site-specific growth patterns.

The specific mechanisms underlying lagged climate-growth responses in *S. polaris* ring width and NDVI also warrant further investigation, including carry-over effects where growth, climatic, or biotic conditions in one year can influence growth in the next (Magnússon et al., 2026; Skarpe and Van Der Wal, 2002; Wu et al., 2015). Clarifying the causes of such carry-over effects could help explain part of the mismatch observed between ring width indices and NDVI, and improve the broader understanding of Arctic vegetation productivity dynamics.

Additionally, future research could focus on areas with low moss coverage. In regions dominated by vascular plants, *S. polaris* growth rings could be tested against NDVI to assess their reliability as a proxy for vascular plant productivity. If successful, this approach could provide a valuable tool for studying Arctic greening at smaller scales.

5. Conclusion

This study aimed to assess the potential of *S. polaris* growth rings as a proxy for overall aboveground tundra plant productivity on Svalbard using satellite-derived NDVI data, while also exploring the sensitivity of *S. polaris* radial growth and NDVI to various climatic variables. The results indicate that *S. polaris* ring width is positively correlated with NDVI values for the Endalen and Sørkapp sample sites, but not for any of the seven other sites. Overall relationships between *S. polaris* growth ring width and NDVI across sites were weak and showed very poor predictive performance.

The radial growth of *S. polaris* plants on Svalbard was found to increase with higher summer temperatures and thawing degree-days, whereas freezing degree-days and later snowmelt timing showed a negative effect. NDVI values were positively influenced by summer temperature, thawing degree-days, spring temperature, and summer precipitation, while winter precipitation and later snowmelt timing had a negative effect. The relationships between climatic variables and NDVI were more consistent across sample sites than those observed for growth ring data.

Overall, the findings of this study suggest that *S. polaris* growth rings cannot be used to serve as a robust proxy for overall aboveground tundra plant productivity across Svalbard. This conclusion can be partly explained by the findings that *S. polaris* radial growth and larger scale MODIS NDVI values react differently to changes in the climate, and by the potential influence of widespread non-vascular vegetation (e.g. moss) on NDVI patterns.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used GPT-4o, GPT-5, and Claude 3.5 Sonnet in order to help with error handling and creating certain functions during the coding process, as well as text revisions. After using these tools, the authors reviewed and edited the content as needed, and take full responsibility for the content of the published article.

Open Research Statement

Data are openly available and cited in this submission (Magnússon et al., 2025; Karlsen et al., 2024; NCCS, 2024; Schyberg et al., 2020; Le Moullec et al., 2020)

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CRediT authorship contribution statement

Harm Bartholomeus: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Conceptualization. **Tom Verstraten:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Rúna Í. Magnússon:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dendro.2026.126538.

Data availability

All data is available and linked under "Open Research Statement" [Tree-ring growth of *S. polaris* on Svalbard under baseline conditions and artificially enhanced summer rainfall](#) (DANS Data Stations)

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