DENDROMETER MEASUREMENTS OF ARCTIC-ALPINE DWARF SHRUBS AND MICRO-ENVIRONMENTAL DRIVERS OF PLANT GROWTH – DATASET FROM LONG-TERM ALPINE ECOSYSTEM RESEARCH IN CENTRAL NORWAY (LTAER-NO)

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With 6 figures and 1 dataset supplement
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Summary: Here, we present fine-scale measurements of stem diameter variation from three common arctic-alpine dwarf-shrub species monitored in two mountain regions of Central Norway. All three species (*Betula nana, Empetrum nigrum ssp. hermaphroditum*, and *Phyllodoce caerulea*) are abundant within the studied regions and highly important contributors to potential future arctic-alpine vegetation shifts. A profound understanding of their radial growth patterns therefore has the potential to yield crucial information regarding climate-growth relations within these ecosystems. We used high-resolution dendrometers (type DRO) to monitor 120 specimens, taking measurements near the shoot base of one major horizontal stem. Along with the shrub growth measurements, we measured on-site micro-environmental data at each studied site, including shoot zone and root zone temperatures as well as soil moisture. All data were recorded at an hourly scale and are presented as daily mean values. The monitoring period spanned five full years (2015 - 2019), with additional data from 2014 and 2020. Data were collected within one of the most continental climate regions of Europe, the Vågå/Innlandet region, and in the oceanic climate region Geiranger/Møre og Romsdal, spanning a steep climate gradient over just ~100 km horizontal distance. Both study regions are characterized by steep elevational gradients and highly heterogeneous micro-topography. The studied sites were chosen to represent these natural conditions using the transect principle. The collection of our original data is subject of our long-term alpine ecosystem monitoring program since 1991, from which numerous publications function as the basis for a recent project on the use of dendrometer data in alpine ecosystem studies.

Zusammenfassung: Hier präsentieren wir feinskalige Messungen zur Variation des Stammdurchmessers von drei häufig vorkommenden arktisch-alpinen Zwergstraucharten, die in zwei Gebirgsregionen Mittelnorwegens untersucht werden. Alle drei Arten (*Betula nana, Empetrum nigrum ssp. hermaphroditum* und *Phyllodoce caerulea*) kommen in den untersuchten Regionen in hoher Frequenz vor und tragen in hohem Maße zu möglichen künftigen Verschiebungen der arktisch-alpinen Vegetationsmuster bei. Ein tiefgreifender Einblick in ihre radialen Wachstumsmuster kann daher wichtige Informationen über die Klima-Wachstums-Beziehungen innerhalb dieser Ökosysteme liefern. Mit hochauflösenden Dendrometern (Typ DRO), die an der Sprossbasis jeweils eines horizontalen Hauptstämmchens angebracht sind, messen wir an 120 Individuen Veränderungen des Stammdurchmessers. Zusammen mit diesen Strauchwachstumsdaten erheben wir an jedem Standort die Spross- und Wurzelzonentemperaturen sowie die Bodenfeuchte. Sämtliche Daten werden stündlich aufgezeichnet und sind hier als Tagesmittelwerte dargestellt. Der Überwachungszeitraum umfasst fünf volle Jahre (2015 - 2019) mit zusätzlichen Daten aus den Jahren 2014 und 2020. Die Daten werden in einer der kontinentalsten Klimaregionen Europas, der Region Vågå / Innlandet, und in der ozeanischen Klimaregion Geiranger / Møre og Romsdal erhoben, und spannen dabei einen steilen Klimagradienten auf nur ~ 100 km horizontaler Entfernung auf. Beide Untersuchungsgebiete zeichnen sich durch steile Höhengradienten und eine sehr heterogene Mikrotopographie aus. Die Standorte wurden ausgewählt, um diese natürlichen Bedingungen nach dem Transektprinzip darzustellen. Die Erfassung unserer Originaldaten ist seit 1991 Gegenstand unseres Langfristigen Alpinen Ökosystemaren Monitoring-Programms, aus dem zahlreiche Veröffentlichungen als Grundlage für unser aktuelles Projekt zur Verwendung von Dendrometerdaten in alpinen Ökosystemstudien dienen.

Keywords: shoot zone temperature, root zone temperature, soil moisture, stem diameter variation, ecophysiology, microclimatology, mountain ecology, biogeography

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1 Concept and study design

Our dataset is structured along our geographical study design making use of the concept and legend in chapter 2. We designed our study along a regional climate gradient (oceanic---continental), the alpine elevation gradient (both in Fig. 1), and along the micro-topographic gradient (Fig. 2), the latter being associated with wind-blown snow-free ridges, wet depressions, north-facing windward slopes with shallow snowpack, and south-facing slopes with lee-slope snowbeds.

2 Structure, metadata, and legend of our dataset

Our dataset is organized according to the following attributes:

dendro
Stem diameter of shoots measured with dendrometers (type DRO; Ecomatik, Dachau/Germany) near the shoot base as close to the assumed root collar as possible (approximately 1-5 cm above ground). We avoided positions near stones and small depressions, inside the radius of other larger shrub species, and near patches of wind erosion. The dendrometer sensor was placed directly onto the cambium, after dead outer bark was removed. Unit: Micrometer [µm]

dendroStartZero
Annual stem diameter variability curves starting at zero each year (dendro - initial stem diameter at the beginning of the year). Unit: µm

Trz
Soil temperature measured within the root zone (15 cm below ground surface), recorded using ONSET's HOBO loggers (type H21-002) and type S-TMB-002

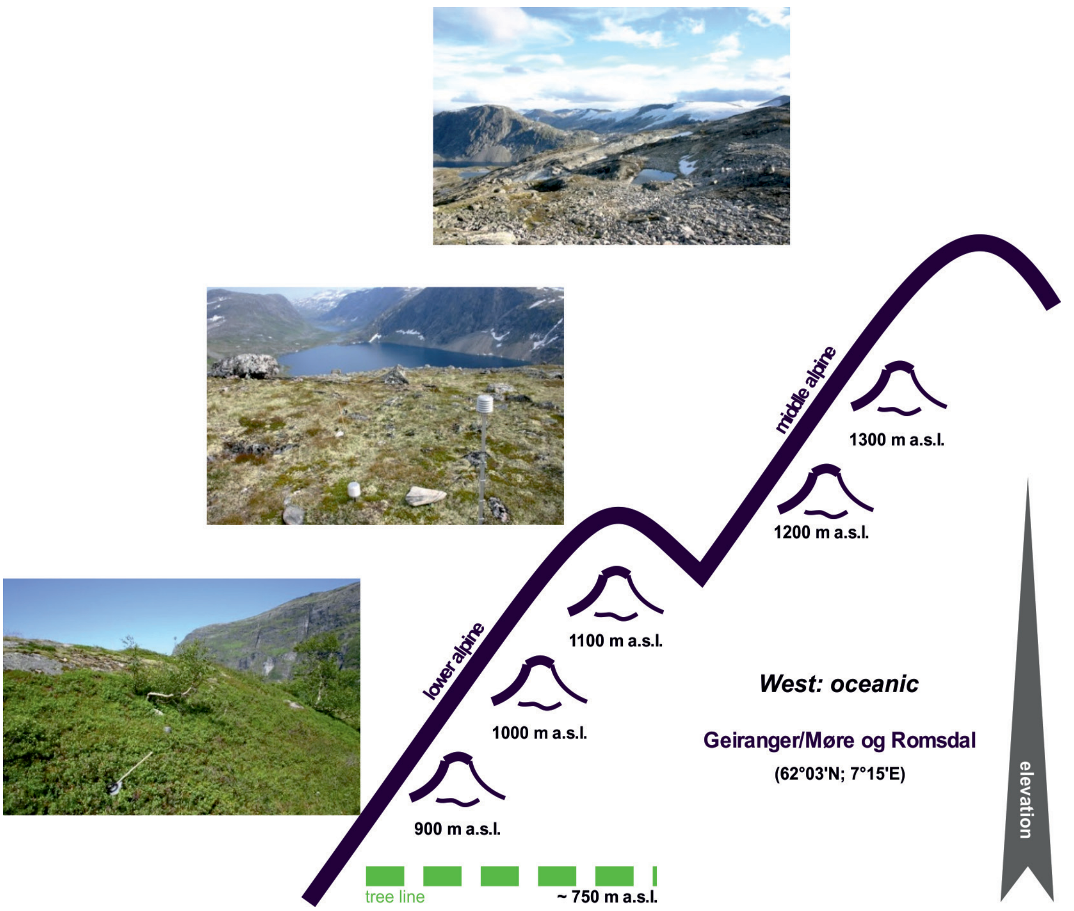


Fig. 1: Study design along the regional climate gradient (oceanic---continental) and along the alpine elevation gradient

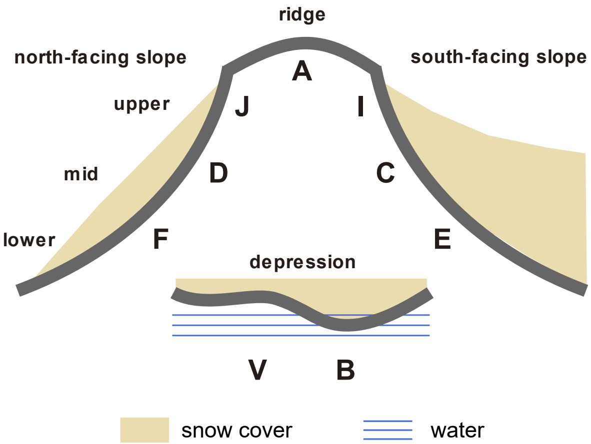


Fig. 2: Study design along the micro-topographic gradient

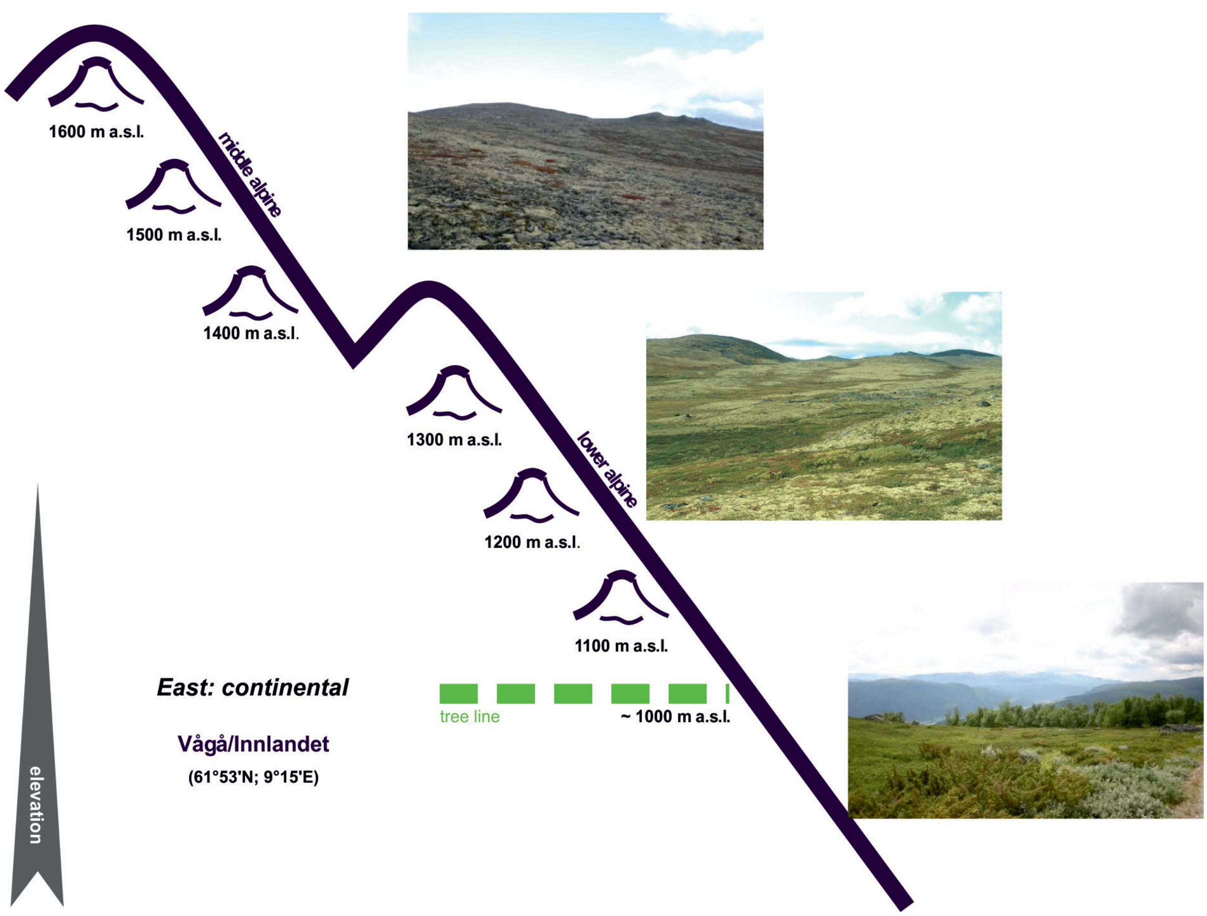
temperature sensors (±0.2 °C accuracy). Unit: °C

Tsz
Air temperature measured within the shoot zone (15 cm above ground surface), recorded using ONSET's HOBO loggers (type H21-002) and type S-TMB-002 temperature sensors (±0.2 °C accuracy). The sensors were equipped with passively ventilated radiation shields. Unit: °C

SMrz
Soil moisture measured within the root zone using type S-SMD-M005 soil moisture sensors (±3% accuracy). Unit: m^3 water/m^3 soil

id
Unique id given to each monitored specimen. Form: Abbreviation for region, elevation, abbreviation for position, abbreviation for species

region
One of two study regions (Fig. 1 and 3):
E: Vågå/Innlandet region (61°53'N; 9°15'E), located within the continental climatic section



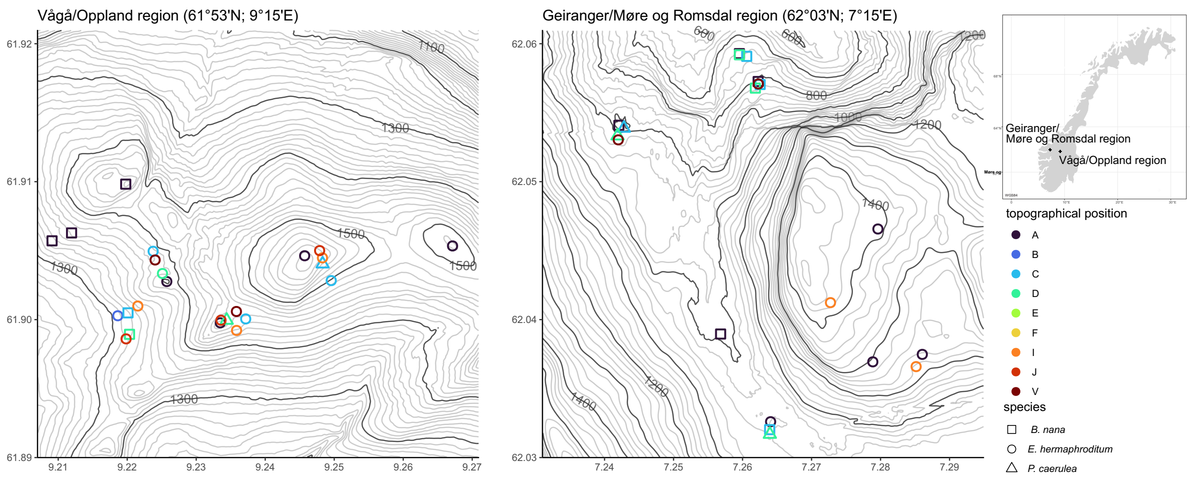


Fig. 3: Map of Norway showing cuts of the studied mountain regions along the elevation gradient

W: Geiranger/Møre og Romsdal region (62°03'N; 7°15'E), located within the slightly to markedly oceanic climatic section of the inner fjords.

elevation
Elevation above sea level. Unit: 100 m a.s.l. (Fig. 1 and 3)

species (Fig. 4 and 6)
One of three monitored dwarf-shrub species: B. nana: *Betula nana*, dwarf birch, deciduous. E. hermaphroditum: *Empetrum nigrum ssp. hermaphroditum*, crowberry, evergreen. P. caerulea: *Phyllodoce caerulea*, blue mountainheath, evergreen.

position (Fig. 2 and 3)
One of the following topographic positions (Fig. 2):

A: Exposed ridge positions. These positions usually experience only very swallow snow cover in winter due to wind redistribution and are subsequently characterized by exceptionally low temperatures in winter and high summer temperatures due to solar radiation. Lichen-dominated vegetation.

B: Positions within local depressions (concave). These positions are characterized by deep snow cover during the winter months and high soil moisture throughout the year. They are temporarily flooded. *Carex-Eriophorum*-dominated vegetation.

C: Positions alongside south-facing mid-slopes. These lee-slope positions experience early and long lasting snow cover, moderate ground-freezing in winter and slightly higher exposure to global radiation than the north-facing slopes. Dwarf shrubs dominate the snowbed vegetation.

D: Positions alongside north-facing mid-slopes. These windward positions experience moderate ground-freezing in winter and less exposure to global radiation than the south-facing slopes. Dwarf shrub dominate the early snowbed vegetation.

E: Positions alongside south-facing slopes (lower slope), lee-slope, late snowbed vegetation.

F: Positions alongside north-facing slopes (lower slope), windward slope. Dwarf shrub dominated snowbed vegetation.

I: Positions alongside south-facing slopes (upper slope), shallow snow cover. Lichen-dominated vegetation.

J: Positions alongside north-facing slopes (upper slope), shallow snow cover. Lichen-dominated vegetation.

V: Positions within local depressions (convex). These positions are characterized by intermediate snow cover during the winter months and high soil moisture throughout the year. They differ from B positions in that they are set on locally elevated sites within the larger depressions and are therefore not flooded. *Rubus chamaemorus-Sphagnum*-dominated vegetation.

date
Date, at which the measurement was taken. (Hourly measurements were aggregated to daily mean values).

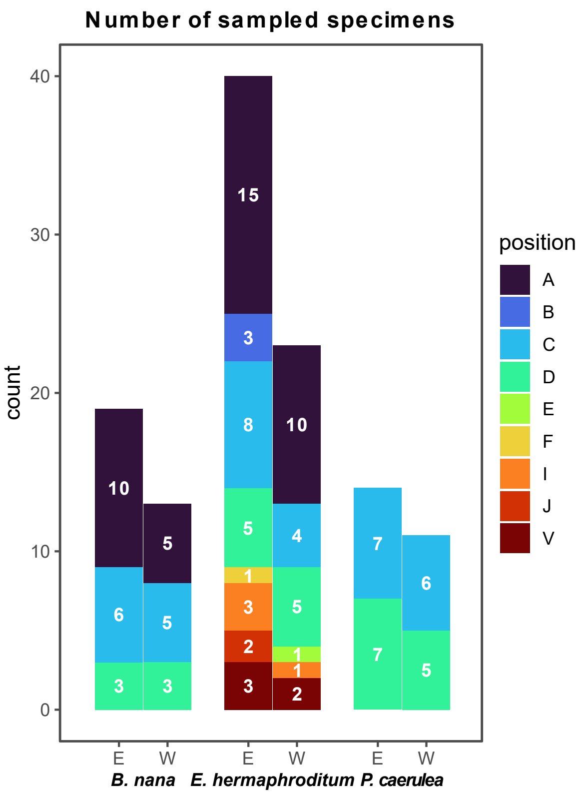


Fig. 4: Number of specimens and sites used in this study

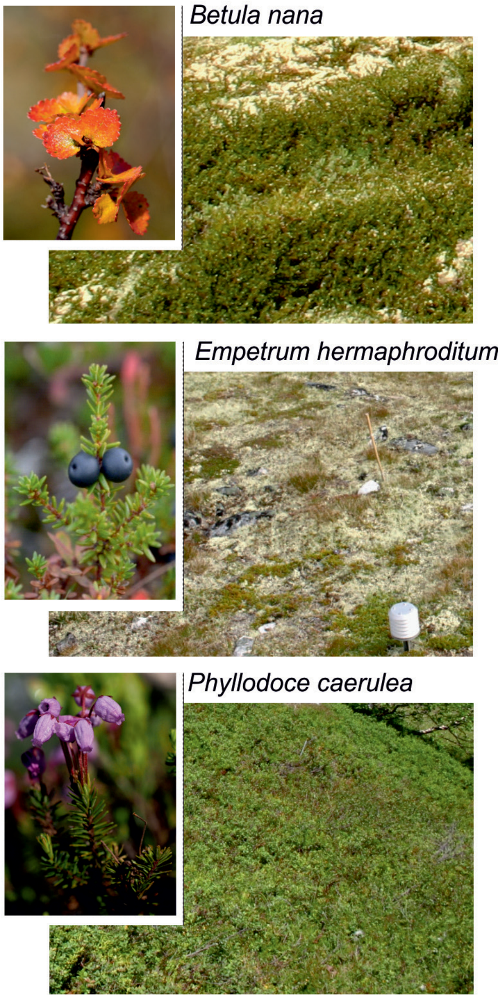


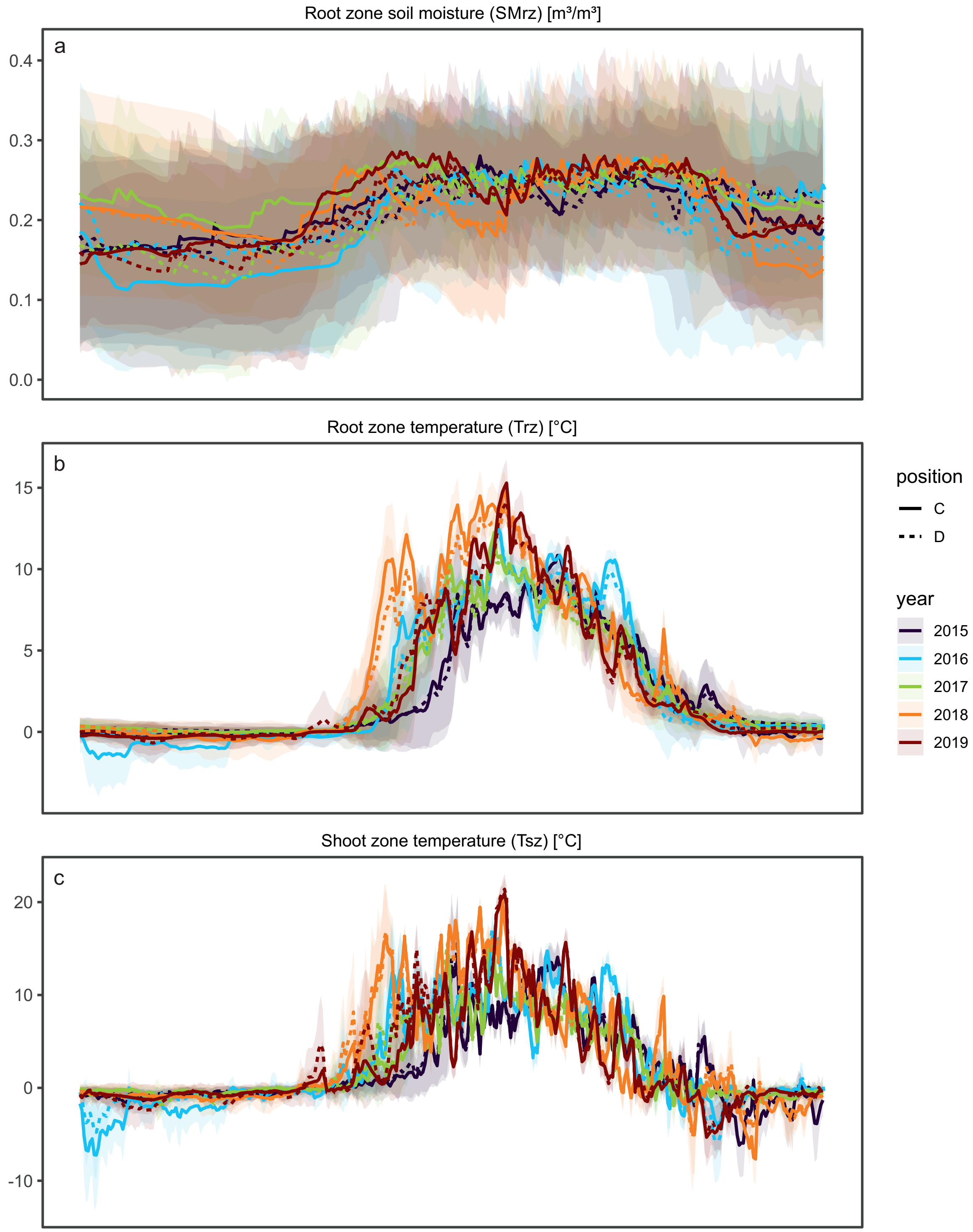
Fig. 5: Photos of shrub species *E. hermaphroditum, Betula nana,* and *Phyllodoce caerulea*

3 Data content

The dataset contains time series with daily-resolution and allows for grouped usage and comparison of this data according to multiple characteristics. Figure 6 shows an exemplary presentation of the time series curves included. Here, we compare two similar positions along north- and south-facing slopes, grouping and averaging the measured data from 39 sites (16 and 23, respectively) according to species (*B. nana* and *E. hermaphroditum*) and topographical position (C and D). This allows for detailed comparison of intra- and inter-annual patterns.

The presented environmental measurements (root zone soil moisture (SMrz), root zone temperature (Trz), and shoot zone temperature (Tsz) reveal that temperatures vary comparatively little between north- and south-facing slopes, with shoot zone temperatures slightly lower at the north-expositions during summer, due to the lower exposure to global radiation. More prominent are the differences in soil moisture, which is markedly lower at the north-facing slopes, especially during winter. This can be attributed to the differing snow conditions. More prominently represented in this graphic (Fig. 6a-c) is the inter-annual variability. The presented curves give detailed insights into differences in timing and magnitude of seasonal temperature and soil moisture variation.

The dendrometer curves (Fig. 6d-e) are illustrated with the same structure, which allows for direct visual comparison of climate-growth relations. Here, we included two of our sampled species, *B. nana* and *E. hermaphroditum,* which represent a deciduous and evergreen species, respectively. Differences in annual patterns and magnitude of stem diameter change are clearly visible from this simple representation (e.g. is the overall magnitude of stem diameter change much higher for *B. nana*, and *E. hermaphroditum* shows markedly higher stem increment at the south-facing slopes, a tendency, which is not present in *B. nana*). In similar fashion, the dataset includes detailed information for all 9 sampled positions along the micro-topographic gradient. Additional possibilities for grouping and analysis include comparison along the regional or elevational gradient.



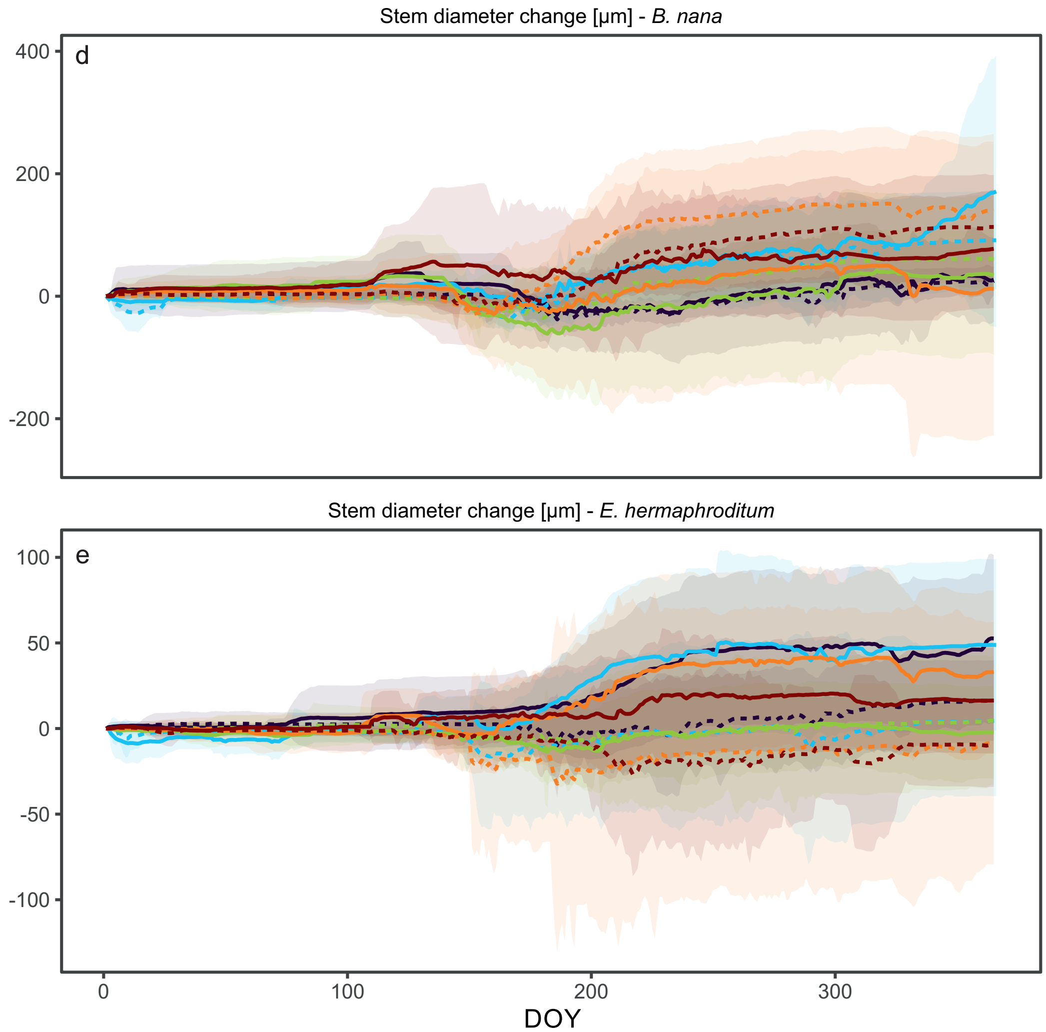


Fig. 6: Exemplary dendrometer series and micro-environmental data from north- (N = 16) and south-facing (N = 23) slopes for two of the studied species, *B. nana* and *E. hermaphrodium.* The presented curves represent averaged series and transparency indicates standard deviation.

4 Background information

We started our long-term alpine ecosystem research program in the central Norwegian mountains (LTAER-NO) in 1992 with studies on the local geo-ecovariance (Köhler at al. 1994) and fine-scale mappings of various structural ecosystem compartments (Löffler 1996, 1997, 1998, 2002a). The results were the basis for a follow-up approach to understand ecosystem functioning at different spatio-temporal scales (Jung et al. 1997; Löffler 1999, 2002b; Löffler and Pape 2003; Löffler and Wundram 1999, 2001, 2003a, b). We continuously increased the complexity of our approach, e.g. also integrating zoological aspects and started trapping arthropods along biogeographical gradients (Löffler et al. 2001). Our data revealed new insights into micro-climatic drivers of vegetation patterns (Löffler 2003) and the micro-environmental role of temperatures near ground (Löffler and Pape 2004), which led to a modelling approach to the vertical energy budget at alpine sites (Pape and Löffler 2004; Löffler and Pape 2004). We addressed the superior impact of snow on the micro-climatic and hydrologic drivers of life near ground (Löffler 2005, 2007b, c; Löffler and Rössler 2005; Schmid and Löffler 2008), followed a multi-gradient approach (Löffler and Finch 2005) and addressed the upscaling issue of climate and ecosystem functioning (Löffler et al. 2006).

The above pioneer phase was accompanied with several projects at the alpine tree-line (Löffler et al. 2004; Rössler and Löffler 2005, 2007; Rössler et al. 2006, 2008; Hellebusch et al. 2009), and on the impact of reindeer in arctic-alpine ecosystems (Löffler 2000, 2004, 2007a; Löffler and Pape 2008; Pape and Löffler 2015a, b, 2016a, b, 2017; Löffler and Pape 2017).

During a second phase, after numerous installations of technical equipment were run, the first time-series of micro-environmental data emerged and offered new opportunities for different novel projects. As such, we started with dendroecological studies on dwarf shrubs (Bär et al. 2005, 2006), developed the first dendrochronology for *Empertum hermaphroditum* (Bär et al. 2007a, b), which was the first of its kind on shrubs worldwide, and started with the first dendrometer measurements on alpine shrubs. Our results from studying annual rings *in E. hermaphroditum* indicated micro-climatic drivers of plant growth besides superior regional climate impact (Bär et al. 2008). In a similar approach, we tested the potential of *Betula nana* for dendroecological studies (Meinardus et al. 2011) and equipped both shrubs species, *E. hermaphroditum* and *B. nana*, with numerous dendrometers along multiple alpine ecological gradients.

Moreover, we used the same sites from which our micro-environmental data revealed new insights into scale-specific climatological mechanisms (Pape et al. 2009; Wundram et al. 2010), used high-resolution aerial photography as a tool to examine the fine-scale topographical nature of the alpine ecosystems (Wundram and Löffler 2007, 2008), analysed spatio-temporal patterns from our arthropod data (Finch et al. 2008; Finch and Löffler 2010; Hågvar et al. 2013; Hein et al. 2013, 2019), and started integrating soil microbial activity studies (Löffler et al. 2008) as well as isotope analyses from precipitation (Zech et al. 2013) and soil (Ackermann et al. 2015). Some of our monitoring sites were subject to biome-wide litter decomposition studies (Djukic et al. 2018), and four of our mountain summits were established as GLORIA sites in 2011 (i.e. NO-BLA).

Our micro-environmental data revealed new insights into the functioning of key arthropod species and functional groups (Hein et al. 2014a, b, 2015; Beckers et al. 2015, 2018, 2020), on phytomass, primary productivity and calorific resources in arctic-alpine ecosystems (Pape and Löffler 2016a, 2017), and were subject to further dendroecological studies on our focus dwarf shrubs species *Betula nana* and *Empetrum hermaphroditum* in comparative approaches (Weijers et al. 2018a, b, c; Weijers and Löffler 2020).

During the recent phase of our long-term program, we used high-resolution near-ground temperature data to assess the thermal niches of alpine plant species (Löffler and Pape 2020), and in combination with soil moisture data also those of soil microbes (Frindte et al. 2019); both approaches ran on a novel machine learning approach which statistically combined the biological attributes with our on-site micro-environmental drivers. Furthermore, we looked closely into growth responses of deciduous and evergreen species to long-term micro-environmental constraints, and for the first time, we made use of high-precision dendrometers to monitor radial growth of dwarf shrubs at unprecedented temporal resolution, bridging the gap between classical dendroecology and the underlying growth physiology of a species (e.g. Dobbert et al. 2021a, b). Using statistical methods on a five-year dataset, including a relative importance analysis based on partial least squares regression, linear mixed modelling, and correlation analysis, we identified distinct growth mechanisms for both evergreen (*Empetrum hermaphroditum*) and deciduous (*Betula nana*) species. We found those mechanisms in accordance with the species respective physiological requirements and the exclusive micro-environmental conditions, suggesting high phenotypical plasticity in both focal species (Dobbert et al. 2021a).

All in all, our long-term alpine ecosystem research program contributes to the ongoing scientific debate on future ecosystem responses to global change (Löffler et al. 2011). Our novel dataset, published here, as such offers meaningful interpretations of biological phenomena driven by near-ground air and soil temperatures and soil moisture. The theoretical concept of the underlying geographical ecosystem research was developed in Leser and Löffler (2017).

The dataset supplement is available online via: https://doi.org/10.3112/erdkunde.2021.ds.01

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