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Changes in arctic plant communities along an altitudinal
and temporal gradient in Northern Sweden

BACHELOR THESIS

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List of abbreviations and definitions

Approx.	approximately
m a.s.l.	meters above sea level
e.g.	exempli gratia, for example
n.e.	not existing
ANS	Abisko Naturvetenskapliga Station (Abisko Scientific Research Station)
CIRC	Climate Impacts Research Centre

Alpine community: A plant association without trees and shrubs is defined as an alpine community and characterised by either heath (*Dryas octopetala*-heath) or meadow communities (forb-rich meadow).

Dwarf shrub: Every woody multi-stemmed individual smaller than 0.8 m in height is considered a dwarf shrub.

Forest community: A forest community is a plant association with tree-forming individuals, such as moss birch forests, forb-rich meadow birch forests, as well as meadow willow thickets. In this study, stand-forming species could be *Betula* as well as *Salix*.

Forest line: The forest line is defined as the continuous line between the uppermost pieces of closed forest, in this case formed by *Betula pubescens* (Fries, 1913; Sandberg, 1952b; Körner, 1999).

Growing season: The number of consecutive weeks with an average temperature above 0 °C form the length of the growing season, where plant life is possible (Körner, 2012).

Plant association: A plant association is a vegetation type with more or less homogenous physiognomic and floristic composition. One species can be part of several associations and can even form the basis for several associations. The species composition within one and the same association can alternate strongly (Fries, 1913).

Physiognomy: This term refers to the life form or external appearance of an individual plant, e.g. if it is a tree, shrub or herb (Fries, 1913)

Segmented transect: A segmented transect is a profile line with several monitored sections along an ecological, mostly altitudinal gradient (Elzinga, Salzer, & Willoughby, n.d.). In this study the sections were labelled with poles.

Shrub: A shrub is defined as a multi-stemmed woody plant with a growing height between 0.8 m and 2 m (Fries, 1913).

Shrub community: Every association with shrub-forming individuals is classified as a shrub community, for example meadow willow thickets.

Tree: A tree is a woody, mostly one-stemmed individual with a minimum growing height of 2 m (Fries, 1913; Kullman, 1979).

Tree limit: The tree limit or tree line is specified as the connecting line between the altitudinally uppermost tree-forming individuals (Fries, 1913; Sandberg, 1952b; Kullman, 2015).

1. Abstract

Global warming has led to profound changes in arctic ecosystems over the last century. Impacts of warming in the Arctic include shrubification, where trees and shrubs invade formerly alpine or tundra regions. To see if this phenomenon can be documented using historical surveys, two vegetation community data sets from 1917 and 1952 were examined in this study. Along an altitudinal gradient on Mt. Nuolja (390 – 1164 m a.s.l.) in Abisko, northern Sweden, the past state of arctic plant communities was compared with the current to assess potential impacts of warming. Over the last century, shrub and forest communities have expanded markedly upslope. Shrub communities especially between 1917 and 1952, forest ones mainly between 1952 and 2018. Alpine heath and meadow communities were invaded by small willow patches and thereby reduced in extent as they changed into shrub communities. The tree limit shifted to higher elevations from 624 m a.s.l. (1917) to 795 m a.s.l. (2018), while the birch forest line moved from 624 m a.s.l. (1917) to 645 m a.s.l. (1952) and 648 m a.s.l. (2018). Factors influencing these forest-alpine ecotone dynamics and related plant communities depend not only on overall temperature changes and resulting longer growing seasons, but also decreasing grazing pressure from reindeer and existing favourable slope conditions on mountains (e.g. depressions with snow protection). In addition, human impacts, related to the development of ski tourism infrastructure from 1966 to present has led to the suppression of tree and shrub expansion. Investigations in microclimatic habitat research compiling different factors (e.g. temperature, snow depth, wind, precipitation patterns & nutrient availability) could be addressed in future research to get a better understanding of the complexity of these ecotone dynamics.

2. Introduction

Over the last century, mean surface air temperature increased globally by approximate 1 °C (IPCC, 2018). Warming has accelerated over the last decades (Callaghan et al., 2010; Serreze & Barry, 2011; Wipf, Stöckli, Herz, & Rixen, 2013) and is twice as fast in the Arctic as the global average (Walsh, 2014; Overland et al., 2018). For example in Abisko, Sweden, the temperature has risen by + 1.7 °C between 1913 and 2018 (ANS, 2019; unpublished data). Temperature increases can lead to particular consequences for Arctic ecosystems, where the survival of plant species is determined by the length of the growing season (Callaghan et al., 2011). Longer growing seasons induced by higher air temperatures consequently lead to a greening of the Arctic (Myers-Smith et al., 2011). To examine changes in vegetation patterns especially on mountains, long term observation data becomes more and more important to keep pace with climate changes and changes in human activities in a warming world.

For decades, botanists have used plant populations characterised by certain species to differentiate among various plant associations. An association is determined by a fairly uniform physiognomy, known as life form or external appearance, and developed under the same conditions (Frey & Lössch, 2010, p. 64). As Alexander von Humboldt already showed 1817 in “Lines of Geography of Plants”, the first study in biogeography, mountains are, relating to vegetation, always structured in the following way, no matter if it is the Andes, the Alps or the Scandinavian mountains (see Appendix 1). Going upslope, a forest zone is first, followed by a shrub zone and finally an alpine zone (von Humboldt, Bonpland, Jackson, & Romanowski, 2008). Each one has unique plant communities. Consequently, plant communities change with increasing elevation. In his studies, Humboldt showed sharp lines between the different zones. In fact, there is a transition zone between each one, called ecotone (Körner, 2012, p. 13). Depending on the “strength” of the environmental gradient and the spatial resolution of the research topic, an ecotone can approximate a sharp line or a gradual change (Körner, 2012). In most cases, especially in forest-alpine ecotones, a gradual change represents the disturbances and limitations influencing an ecotone. Disturbances, such as avalanches or herbivory, and environmental limitations, for example extreme temperatures or fluctuating water availability, exist in every ecosystem, but particularly in mountainous ones and „prevent tree growth beyond certain elevations“ (Körner, 2012, p.1). If those limiting constraints loose “strength”, due to e.g. increasing temperatures, tree and shrub growth can occur higher up (Myers-Smith et al., 2011).

Forest tundra ecotones are especially sensitive to changes (Hinzman et al., 2005; Körner, 2012) and the predicted warming might favour further upward movements of plant communities, as more and more suitable habitats emerge (Hinzman et al., 2005). One possible approach for testing this process is using historical surveys. In this study, a well-preserved vegetation data set from a 100 years ago, was compared to the vegetation state in 1952 and the current state in 2018. The overall goal of this project was to continue the long-term data series and to assess vegetation changes in plant communities on a spatial and temporal scale. Rapid environmental change brought about by global warming necessitates understanding how changes, that have taken place in the last century can be used to predict future changes. For this reason, scientific research will be increasingly important.

To determine changes in arctic plant communities, the study from 1917 and 1952 was repeated using the same altitudinal gradient in northern Sweden. Additionally, historical pictures were closely examined to answer two questions: (I) How has temperature and growing season length changed in the last century and (II) how have the plant communities on Mt. Nuolja (Abisko, northern Sweden) responded to temperature and growing season changes in the last century?

I hypothesize, that with the observed increase in temperature and growing season length from 1917 to 2018 there will be an upslope shift in the forest-alpine ecotone. Specifically, a shift in the respective forest and shrub plant communities along the mountain slope, which will lead to a reduction in areal extent of alpine communities. With this “shrubification” (Myers-Smith et al., 2011), I predict that the tree-limit, defined as the connecting line between the altitudinally uppermost individuals of a tree forming species taller than 2 m (Fries, 1913; Sandberg, 1952b) has shifted upslope. On the studied transect those tree forming species were *Betula pubescens* ssp. *czerepanovii* (N. I. Orlova) Hämet-Ahti, *Salix myrsinifolia* Salisb., *Salix lanata* L and *Salix phylicifolia* L.. Nonetheless, these species can also be found on the transect as shrub forming multi-stemmed individuals smaller than 2 m.

3. Methods

3.1. Study site

The study site is located in the Arctic of northern Sweden in the Abisko National Park on the north-eastern slope of Mt. Nuolja (1164 m a.s.l., 68°22'20.1"N 18°41'49.4"E, Figure 1).

The landscape is shaped by different types of land use. A major factor in the Scandes and also on Mt. Nuolja were the Sámi communities and their grazing reindeer herds (Emanuelsson, 1987). Nowadays, due to the great reputation of the Abisko National Park and a chairlift plus ski offpist on the slope of Mt. Nuolja, summer and winter tourism plays an important social and economic role in the region (Reinius & Fredman, 2007; Lundmark, Fredman, & Sandell, 2010).

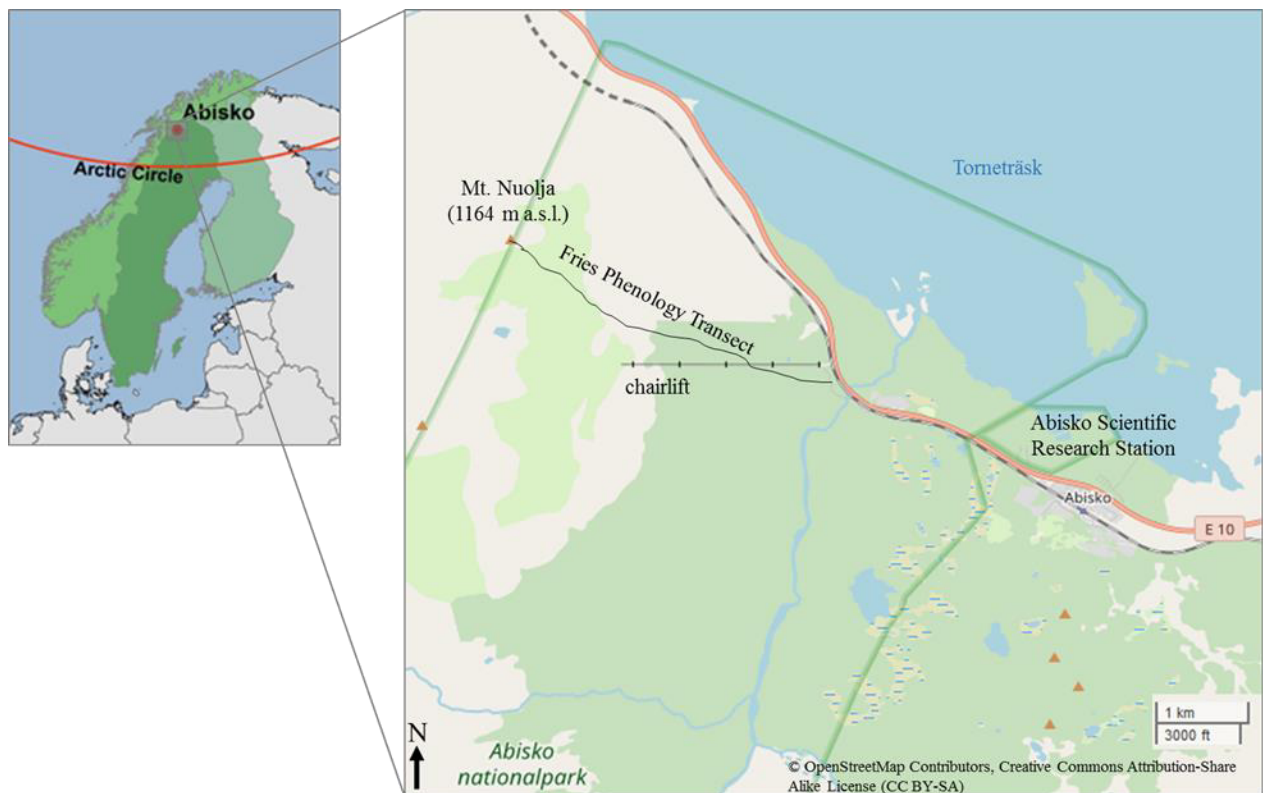


Figure 1 Location of the plant phenology transect (black line) in Abisko, northern Sweden established by Thore Fries in 1917 spanning from the Abisko Valley to the summit of Mt. Nuolja (1164 m a.s.l.; Landmäteriet / National Land Survey, 2019).

3.2. Climate changes in the last century

The 30-year mean annual temperature for Abisko changed over the last century from $-2.43\text{ }^{\circ}\text{C}$ (1917) to $+0.25\text{ }^{\circ}\text{C}$ (2018; Figure 2), while most of the warming occurred during the second half of the 20th century (Figure 3; ANS, 2019).

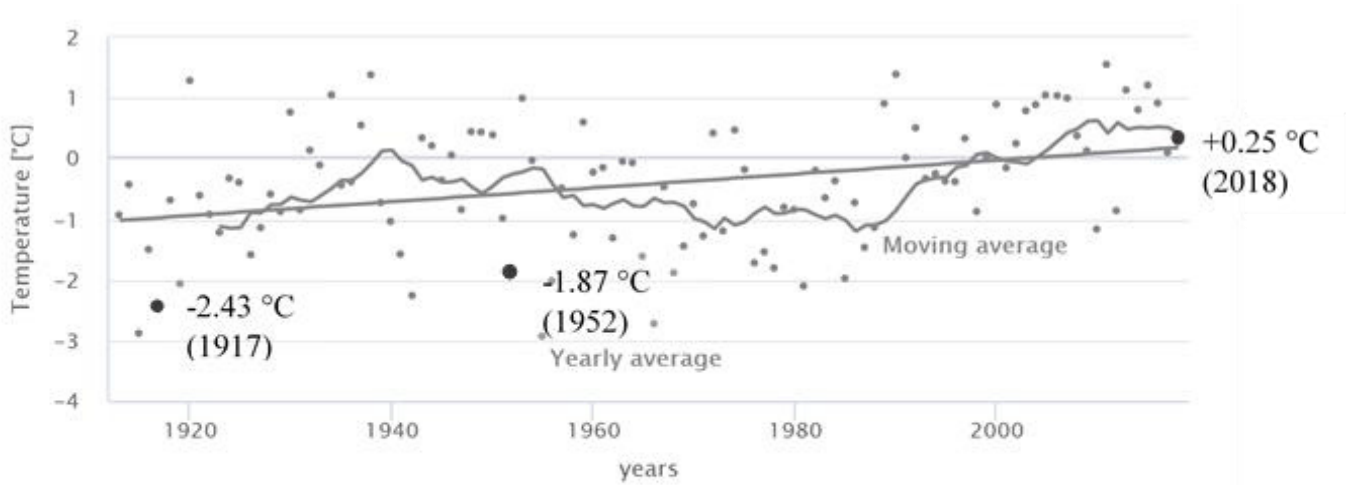


Figure 2 Mean annual temperatures (in $^{\circ}\text{C}$) recorded at the Abisko Scientific Research Station (ANS) from 1913-2018. Every dot represents an average of hourly measurements across each year, the solid line indicates the 10-year moving average (unpublished data from ANS, 2019; graphs created by CIRC). The years with investigations on the transect, are labelled separately.

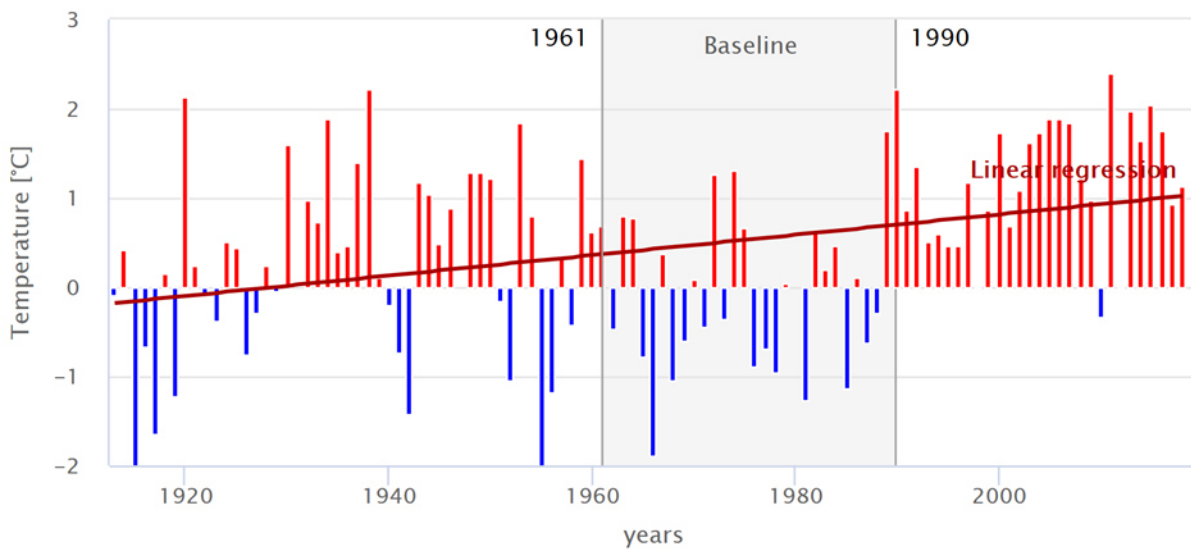


Figure 3 Temperature differences (1913 – 2019) measured at the Abisko Scientific Research Station. Yearly average is compared to a baseline formed by standardised averaged years 1961 - 1990. Red bars indicate warmer years, Blue bars colder ones. Solid red line shows a warming trend (ANS, 2019; unpublished data).

The growing season in the Abisko area, defined as the consecutive weeks with an average temperature above 0 °C, has expanded by four weeks over the same period (Figure 4).

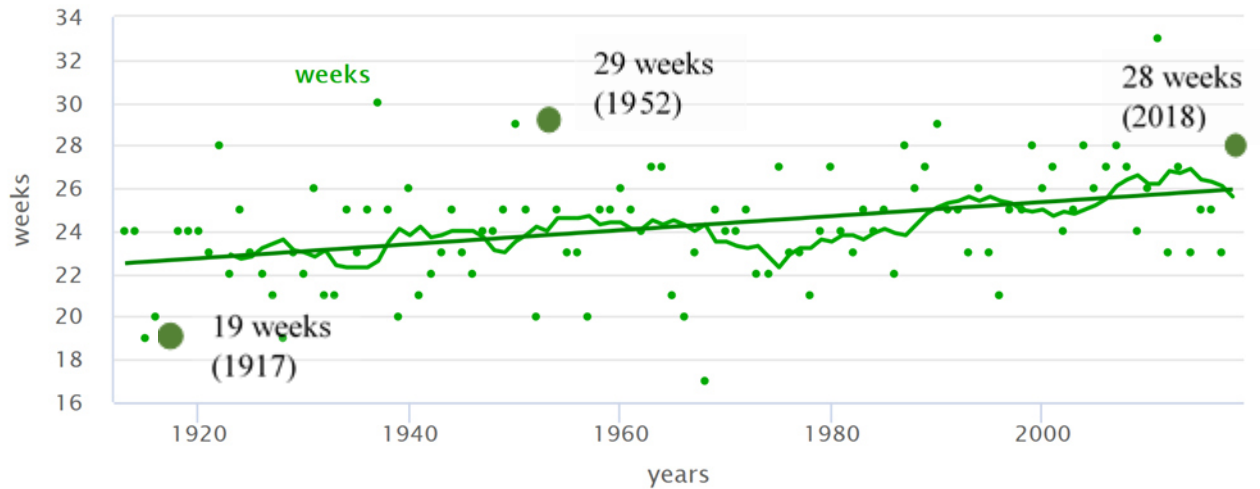


Figure 4 Length of the growing season in Abisko defined by the number of consecutive weeks with an average temperature above 0 °C. Measurements taken at the Abisko Scientific Research Centre between 1913 and 2019, the solid line shows a linear trend, whereas the other one indicates the 10-year moving average. The years with investigations on the transect, are labelled separately (ANS, 2019; unpublished data).

3.3. Gradient study: a segmented transect

The method used in this study is a segmented transect, a profile line with several monitored sections along an altitudinal gradient. The sampling unit is a line, giving this approach the name line-intercept method. This study used an approximately 3.5 km long transect established by Thore C.E. Fries completely randomly on the north eastern slope of Mt. Nuolja, as the whole area was covered in snow in May 1917 (Fries, 1925). The original purpose of the investigation line was to study the relation between timing of snowmelt and the presence of plant communities as well as the phenological development of the vegetation (Appendix 2). In 2017, we re-established the study site with the specific intent of repeating the original study. The gradient starts in the birch forest in the Abisko Valley (390 m a.s.l.), dominated by *Betula pubescens*, and extends through the shrub and alpine areas to the summit of Mt. Nuolja (Picture 1; Fries, 1925).



Picture 1 Mt. Nuolja seen from the Abisko Scientific Research Station with the approximate route of the transect (dashed line). Photo: 5th September 2017 (© A. Schäfer).

3.4. Classification of plant communities

Fries plant community concept was based on the characteristic vegetation and classified regarding its physiognomy (Fries, 1913). For each northern Swedish plant association and its variants, he defined a German name indicating as good as possible the characteristics of the plant communities regarding their composition (Fries, 1913).

In summer 1917, Fries measured the location and extension of each plant community, meter-by-meter, along the transect on Mt. Nuolja using a layer classification system for Fennoscandian alpine plant communities (Fries, 1925). He proposed a generally applicable formula consisting of several parts indicating the floristic composition of the vegetation (Table 1). The first part of the formula described the highest dominant life form with capital letters from “A” to “E”, although evergreen

needle trees (A) were not found in the study area. The second part consisted of the vegetation type with Roman numbers I to IV. The understory or field layer was specified by small letters “a” or “b” according to the given vegetation type. The series of open water was not considered in his work, as this vegetation type was not present on the transect (Fries, 1925).

Table 1 Formula for classifying Fennoscandian alpine plant communities with the respective description of each code (Fries, 1925).

Community rank	Description	Code
Highest dominant rank life form	Needle-leaf trees (evergreen)	A
	Deciduous-leaf trees	B
	Shrubs	C
	Dwarf shrubs	D
	Graminoids and forbs	E
Vegetation type (series)	Heath	I
	Meadow	II
	Mire	III
	Open water	IV
Understory or field layer	Heath lichen-rich	a
	Heath moss-rich	b
	Meadow, tall growing, graminoid and forb-rich	a
	Meadow, low growing, forb-rich	b
	Mire (in mire series)	a
	Swamp (in mire series)	b

3.5. Vegetation layer classification and frequency codes

The different layers in the vegetation and frequencies of the plant species were classified according to the following scheme invented by Fries (Table 2 & Table 3; Fries, 1913).

Table 2 Layer classification system established by Fries (1913) with the respective description of each layer and growing heights.

Layer code	Layer description	Height (in m)
a	Highest forest layer	> 6
b	Lowest forest layer	2 – 6
c	Shrub layer	0.8 – 2
d	Highest field layer	0.3 – 0.8
e	Middle field layer	0.1 – 0.3
f	Lowest field layer	0.03 – 0.1
g	Ground layer	< 0.03

Table 3 Frequency codes for classifying plant communities, described by Fries (1913). For each plant species a code from 1 (rare) to 5 (widespread) was applied.

Frequency code	Frequency description
1	rare, occasional
2	sparse, sporadic
3	dispersed, scattered
4	abundant
5	widespread

3.6. Plant community resurveys in 1952 and 2018

In 1952, Gustaf Sandberg resurveyed the plant communities on Mt. Nuolja along the same transect but only the sections encompassing the forest-alpine ecotone from the birch forest line to the lower borders of the alpine zone (Figure 5; Sandberg, 1952a).

On the 4th and 5th of August 2018, the plant communities on the transect were examined again (Figure 5). Once more, the section around the forest line built the basis and was studied in three teams to avoid subjective observations. Additionally, the resurvey area was extended upslope in order to measure a possible immigration of willow and birch shrubs. To compare the historical data from Fries and Sandberg, this study was conducted following exactly the same formula including the same layer and frequency classifications. The highest forest layer (above 6 m height) was not applied in 2018. The majority of the birch trees and willow shrubs on the transect was smaller than six meters. A differential Global Positioning System (Trimble R8s receiver with GNSS System and trimble tablet T10) was used to record accurate distance and elevation measurements. Additionally, pictures were taken to give visual examples of the different plant communities and to compare the recent pictures with historical ones. Microsoft Excel was used for data comparison and analysis.

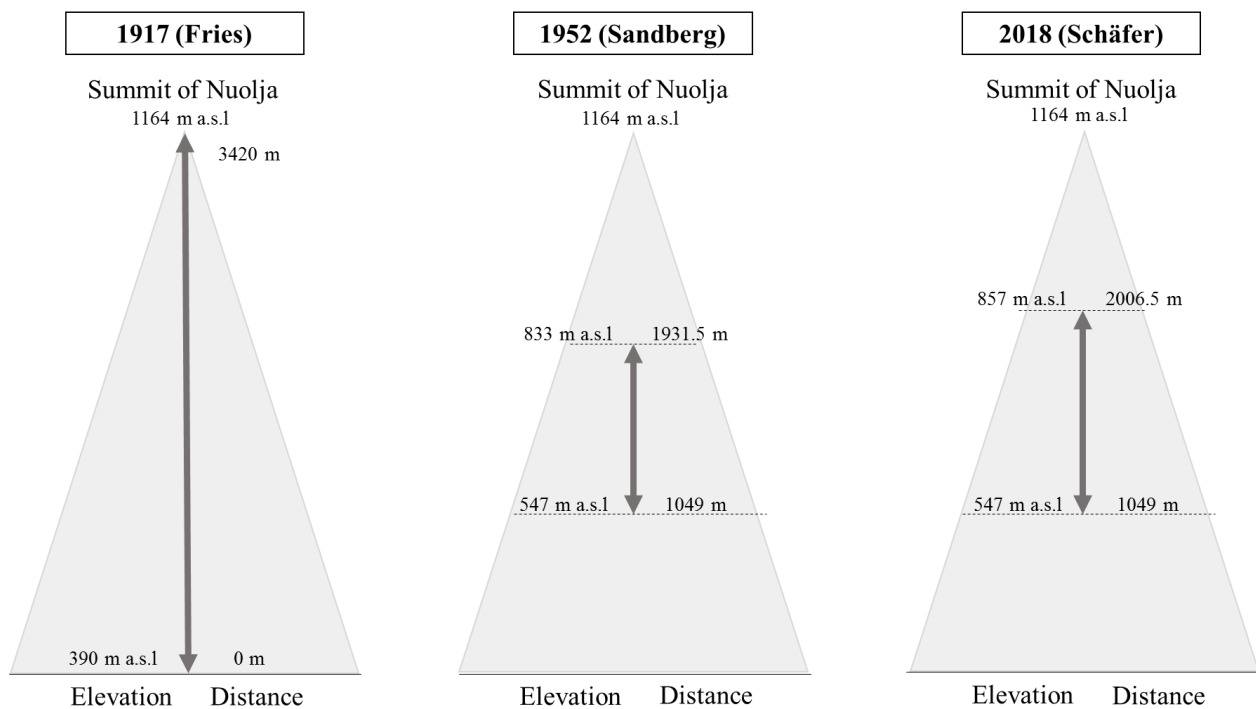





Figure 5 Extension of the three investigation areas on the plant phenology transect on Mt. Nuolja including elevation and distance starting in the Abisko Valley (390 m a.s.l.). Fries (1913) studied the whole transect along the mountain, whereas Sandberg (1952) and this study (2018) only surveyed the illustrated section in the forest – alpine ecotone.



3.7. Plant communities


The occurring plant communities on Mt. Nuolja, in reference to Fries classification system for Fennoscandian alpine plant communities, were generally divided into forest, shrub and alpine communities shown in Table 4.


Table 4 The occurring plant communities on the studied transect with the original German wording as well as characterising species and illustrative pictures of each community divided into three community types: forest, shrub and alpine. This is a selection of several described plant communities for northern Sweden written by Fries (1913). The moss-rich willow thicket was originally not described by Thore Fries, but the formula was realised the same way.

Type	Name	Original German wording	Fries code	Characterising species	Illustrative pictures
FOREST	Moss birch forest	Moosbirkenwald Fries (1913) p. 85	B I b	<i>Betula pubescens</i> <i>Deschampsia flexuosa</i> <i>Empetrum nigrum</i> <i>Linnaea borealis</i> <i>Melampyrum sylvaticum</i> <i>Pedicularis lapponica</i> <i>Solidago virgaurea</i> <i>Vaccinium myrtillus</i> <i>Vaccinium uliginosum</i> <i>Vaccinium vitis-idaea</i>	 <p>Photo: 7th August 2018 © A. Schäfer</p>

FOREST	Forb-rich meadow birch forest	kräuterreicher Wiesenbirkenwald Fries (1913) p. 98	B II a/b	<i>Deschampsia flexuosa</i> <i>Epilobium angustifolium</i> <i>Geranium sylvaticum</i> <i>Milium effusum</i> <i>Rumex acetosa</i> <i>Stellaria nemorum</i> <i>Trollius europaeus</i> <i>Viola biflora</i>	 <p>Photo: 7th August 2018 © A. Schäfer</p>
SHRUB	Forb-rich meadow willow thicket	kräuterreiches Wiesenweidengebüsch Fries (1913) p. 106	C II a	<i>Alchemilla glomerulans</i> <i>Epilobium angustifolium</i> <i>Geranium sylvaticum</i> <i>Salix glauca</i> <i>Salix lanata</i> <i>Salix myrsinifolia</i> <i>Salix phylicifolia</i> <i>Solidago virgaurea</i> <i>Trollius europaeus</i>	 <p>Photo: 7th August 2018 © A. Schäfer</p>

SHRUB	<i>Betula nana</i> thicket	Moosreiche <i>Betula nana</i> - Gebüschassozi- ation Fries (1913) p. 88	C I b	<i>Betula nana</i> <i>Calamagrostis lapponica</i> <i>Empetrum nigrum</i> <i>Vaccinium uliginosum</i>	 <p>Photo: 5th August 2018 © A. Schäfer</p>
SHRUB	Moss-rich willow thicket	n.e.	C I b	<i>Astragalus alpinus</i> <i>Bartsia alpina</i> <i>Salix hastata</i> <i>Salix lanata</i> <i>Saussurea alpina</i> <i>Solidago virgaurea</i>	 <p>Photo: 5th August 2018 © A. Schäfer</p>

ALPINE	Forb-rich meadow	Wiesen Fries (1913) p. 110	E II b	<i>Anthoxanthum alpinum</i> <i>Astragalus alpinus</i> <i>Bistorta vivipara</i> <i>Oxyria digyna</i> <i>Poa alpina</i> <i>Rumex acetosa</i> <i>Salix hastata</i> , <i>Salix herbacea</i> , <i>Saussurea alpina</i> <i>Sibbaldia procumbens</i> <i>Solidago virgaurea</i> <i>Thalictrum alpinum</i>	 <p data-bbox="1209 667 1690 704">Photo: 5th August 2018 © A. Schäfer</p>
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ALPINE	<i>Dryas octopetala</i> - heath	Moosreiche <i>Dryas octopetala</i> Assoziation Fries (1913) p. 91	D I b	<i>Betula nana</i> <i>Carex bigelowii</i> <i>Dryas octopetala</i> <i>Empetrum nigrum</i> <i>Silene acaulis</i> <i>Vaccinium uliginosum</i>	 <p data-bbox="1209 675 1915 742">Photo: 5th August 2018 © A. Schäfer</p>
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4. Results

4.1. Plant communities on Mt. Nuolja in 2018

On Mt. Nuolja, the following plant communities formed the essential element of the forest-alpine ecotone. The forest community in the lower part of the closed forest was described as a moss birch forest (B I b) with the dominant species shown in Table 4. With increasing elevation and after walking 1094.5 m on the transect, the moss birch forest was replaced by a forb-rich meadow birch forest (B II a/b) with characteristically tall growing forbs. In between those two most abundant forest communities, an approximately 15 m transition zone from moss birch forest to forb-rich meadow birch forest with species from both communities, for instance *Vaccinium myrtillus* and *Linnaea borealis*, but also *Epilobium angustifolium* and *Geranium sylvaticum* was distinguished.

The forb-rich meadow birch forest was continuous until a distance of 1416 m from the start of the transect. There the forest line, formed by stand-forming *Betula pubescens* was positioned at an elevation of 648 m a.s.l. The next community, a forb-rich meadow willow thicket (C II a) with an extent of approx. 20 m was dominated by different willow species in the shrub layer and tall-growing forbs in the field layer (frequency codes 3 and higher). This forb-rich meadow willow thicket, in most parts taller than 2 m, was continuous until a distance of 1722 m from the starting of the transect. The canopy structure in this part was very heterogeneous, partly open (Picture 2), partly completely closed (Picture 3) both in the communities dominated by *Betula pubescens* and in the ones with dominating *Salix lanata*, *S. phylicifolia*, *S. glauca* and *S. myrsinifolia*.



Picture 2 Part in the forb-rich meadow willow thicket in the forest-alpine ecotone with a heterogeneous, open canopy structure. Photo: 5th August 2019 © A. Schäfer.



Picture 3 Perspective orientated downslope into the Abisko Valley from “inside” the forest community forb-rich meadow willow thicket (C II a) with an almost closed canopy. Photo: 5th August 2019 © A. Schäfer.

After 1722 m on the transect, a small moss-rich *Betula nana*-thicket (C I b; 25.5 m extent) with *Betula nana*, *Vaccinium uliginosum*, *Empetrum nigrum* and *Calamagrostis lapponica* occurred. *Salix lanata* and *Salix glauca* grew abundantly as small shrubs (< 1 m, in layer c and d, frequency 4) in between this heath-like community.

The consecutive part on the transect above the *Betula nana*-thicket consisted again of forb-rich meadow willow thickets (C II a) with partly open, shrub-less meadow patches. With increasing elevation, the willow thicket became patchier and the abundance of tall *Salix* species in the lower forest layer (b) decreased. The tree limit, formed by *Salix myrsinifolia* at an elevation of 795 m a.s.l. (distance: 1835 m from the start of the transect) distinguished the end of the forest communities (minimum height of 2 m) and the beginning of the shrub communities (maximum height of 2 m, Picture 4).



Picture 4 The tree limit forming *Salix myrsinifolia* found on the transect at 795 m a.s.l.. Perspective orientated downslope. Photo: 24th August 2019 © A. Schäfer.

A moss-rich willow thicket (0.8-2 m tall), originally not described and classified by Thore Fries, formed the upper shrub limit and the transition to the forb-rich and treeless alpine meadows and heaths. A forb-rich meadow (E II b) and the following moss-rich *Dryas octopetala* heath (D I b) represented the lower border of the alpine communities.

4.2. Changes in plant communities from 1917 to 1952 and 2018

Overall, the forest and shrub communities extended in the last century, while the alpine communities diminished (Figure 6). In the first period from 1917 to 1952, the extent of forest

communities did not change (+ 0.2 %). The shrub communities extended in area by 13.2 % due to immigration of willow shrubs and occasionally young birch trees (maximum height: 0.9 m) into forb-rich meadow communities (E II b), with the result of shrinking alpine communities (Figure 7), exemplified by the change from a forb-rich meadow into a meadow willow thicket (C II a) at a distance of 1173 m – 1200.5 m. on the transect.

In the second time span from 1952 to 2018, forest communities increased from 40.8 to 53.2 % driven by the newly established willows (mostly *Salix glauca*, *S. phylicifolia*, *S. myrsinifolia*) and birch trees (*Betula pubescens*), which increased in height and moved further upslope. The shrub communities' extent decreased as former shrub communities developed into forest communities due to vertical growth (Figure 7). In 2018, the uppermost individual birch tree taller than 2 m, was observed at approximately 765 m a.s.l. Smaller individuals were found at even higher elevations in the alpine zone (Figure 9).

There is a general trend over time and along the studied part of the transect from meadow into shrub and afterwards into forest communities. For example, in 1917 there was a forb-rich meadow (E II b), starting at a distance of 1328 m and extending 27 m upslope as one of several open patches in the birch forest, which was replaced by a forb-rich meadow willow thicket (C II a) with scattered young birch trees in 1952. In 2018 it was described as a forb-rich meadow birch forest (B II a/b; Picture 5).



Picture 5 A forb-rich meadow birch forest (B II a/b) on the transect at a distance of 1328 m from the start. In 1917, Thore Fries found here a forb-rich meadow (E II b), while Sandberg (1952) described it as a meadow willow thicket (C II a). Photo: 7th August 2018 © Anne Schäfer.

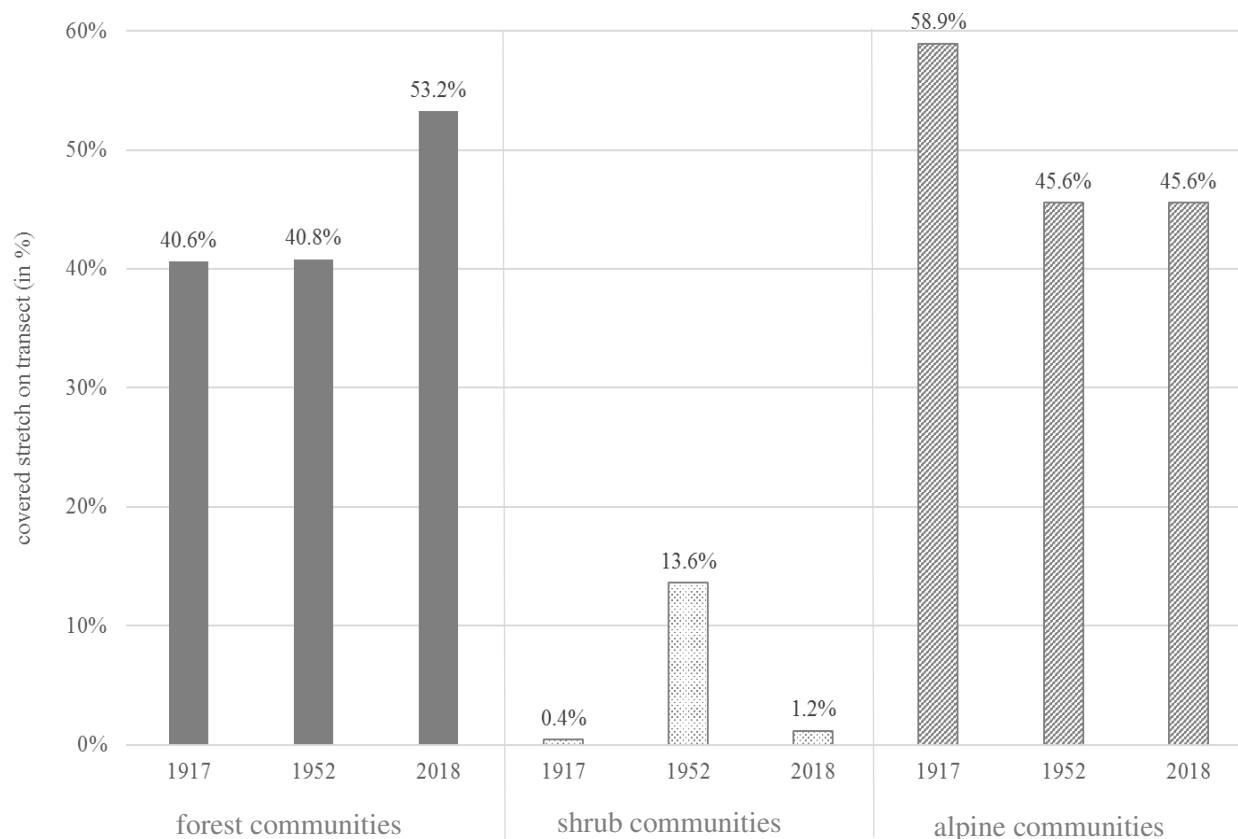


Figure 6 Expansion of the different plant community types on Mt. Nuolja in 1917, 1952 and 2018. Occurring plant community types include forest (grey), shrub (dotted) and alpine (light grey dashed) communities. Calculated as the respectively covered stretch on the whole transect from Abisko Valley to the summit (in %).

The period with strong temperature change in the second half of the century, corresponds to the period with extension in forest communities (Figure 3 and Figure 7). The general trend of a longer growing season (Figure 4) over the whole century supports the extension of the shrub communities (1917-1952) and forest communities (1952-2018).

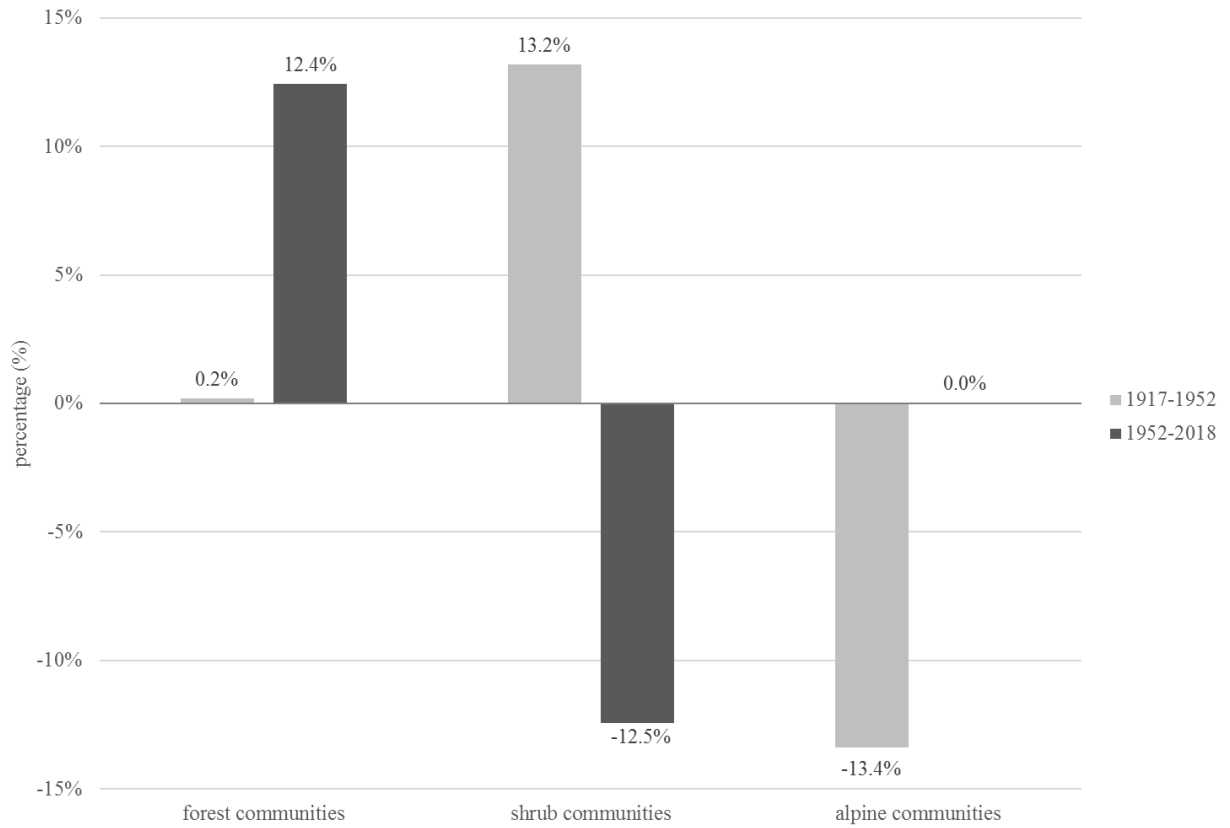


Figure 7 percentage increase or decrease for the forest, shrub and alpine communities on Mt. Nuolja comparing 1917 to 1952 and 2018. Note: Although alpine communities did not change between 1952 and 2018, dwarf willow shrubs invaded those communities.

4.3. Changes in forest line and tree limit

In the last century, the birch forest line shifted in elevation from approximately 624 m a.s.l. (1917) to 645 m a.s.l. (1952) and 648 m a.s.l. (2018; Figure 8; Picture 6) or approximately 47 meters upslope over the entire period. Whereas the tree limit, the altitudinally uppermost tree individual taller than 2 m, moved from approx. 624 m a.s.l. (1917) to 795 m a.s.l. formed by *Salix myrsinifolia* (2018) or approx. 464 meters upslope. Thus, forest line and tree limit currently do not match, in contrast to 1917 and 1952, where both were located at respectively 624 m and 645 m a.s.l. (Figure 8).

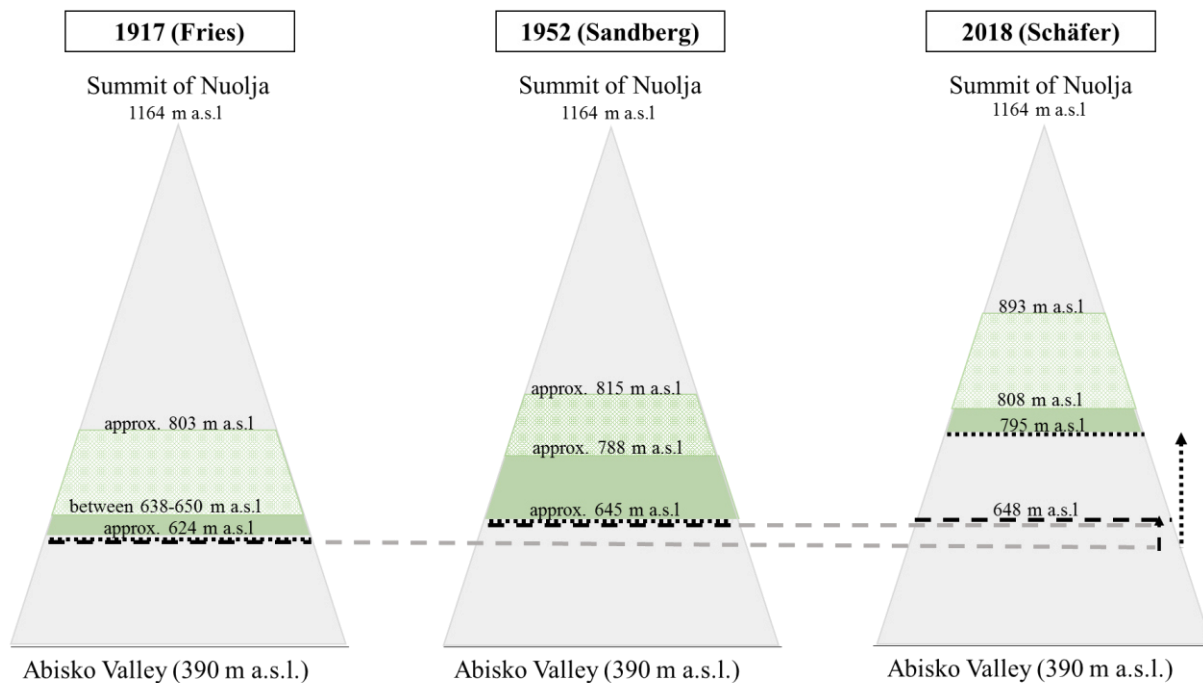


Figure 8 Schematic diagram of forest-alpine ecotone with birch forest line (dashed line) and tree limit (dotted line) on the plant phenology transect on Mt. Nuolja in 1917, 1952 and 2018. Green coloured area indicates the shrub communities (0.80-2 m) with approximate elevations of upper shrub limits. Green dotted area shows the dwarf shrub (< 0.80 m) expansion with approximate elevations. The value from 1917 for the „dwarf shrub line“ derives from the phenological recordings, not the community data (Fries, 1925). All noted elevational values refer to the line below them.

In 1952, immigrating birch trees above the tree limit were observed on both sides at a certain distance from the transect. The forest communities' expansion with tall *Salix* and *Betula* species was clearly visible in 2017 (Picture 7). Individual outpost birch trees, taller than 2 m, were found all the way up on the transect until 765 m a.s.l. (birch tree limit). Birch individuals, smaller than 0.8 m were observed close to the summit of Mt. Nuolja at 1132 m a.s.l., while the uppermost willow species grew at 1112 m a.s.l. (Figure 9, Appendix 3).

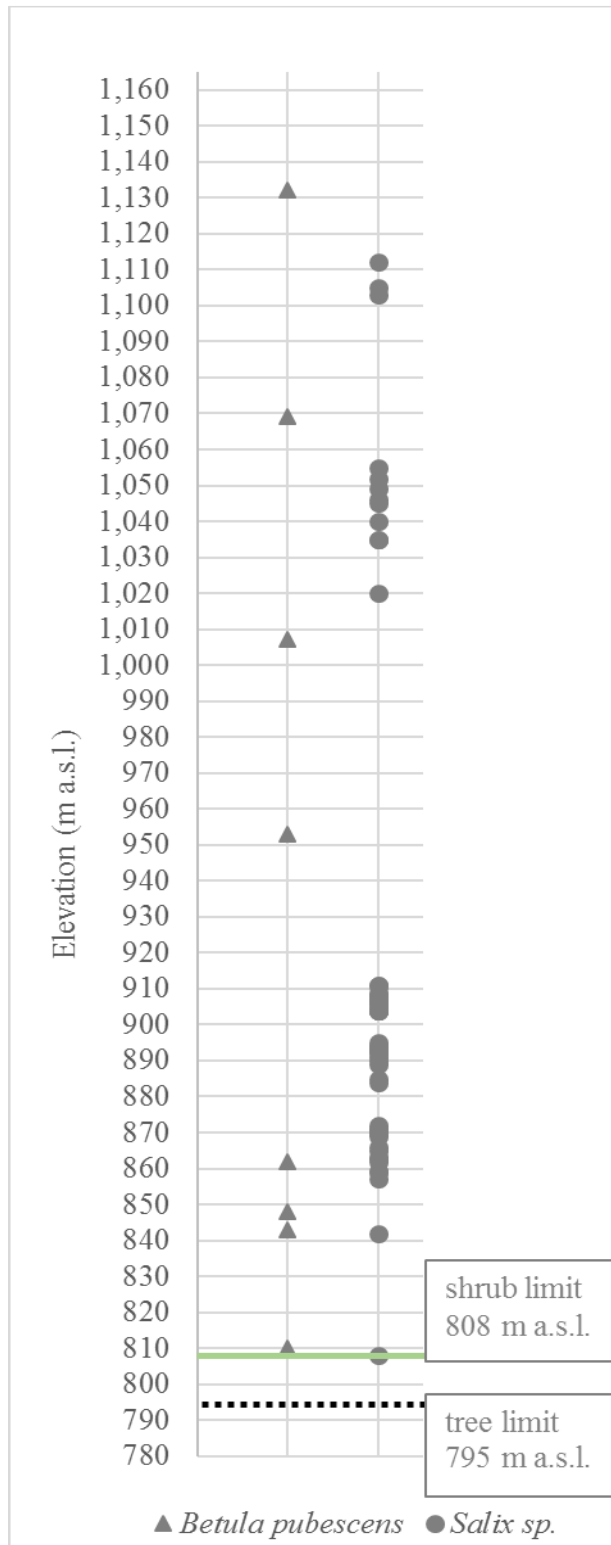
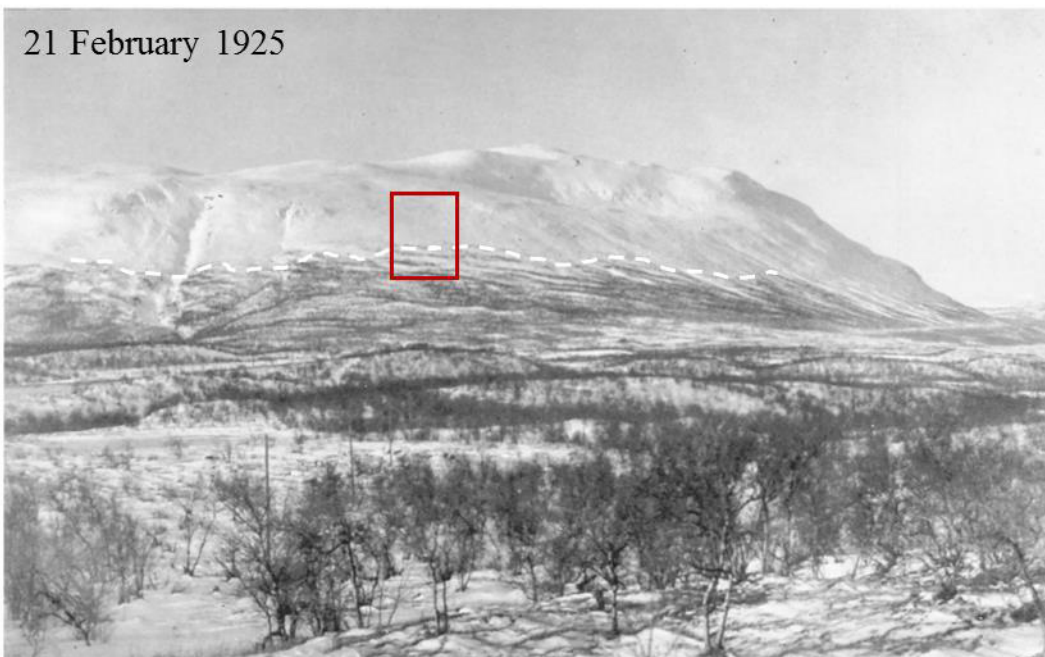


Figure 9 Visualisation of found outpost individuals of *Betula pubescens* and *Salix* species in 2018 above the tree limit (795 m a.s.l.) along the transect. Shrub limit is formed by the uppermost *Salix* individual (*Salix lanata*) taller than 0.8 m. Every willow and birch individual above the shrub limit grew smaller than 0.8 m.



Picture 6 Nuolja's north-eastern slope in February 1921 (taken by CG Alm) and 2017 (© Oliver Wright). Dashed white lines present the approximate location of the birch forest line with an illustrative picture section (red square). Due to a lot of snow in this winter, the upslope migrating willow shrubs were mostly covered in snow.

Summer 1920



Summer 2017



Picture 7 Nuolja in summer 1920 (taken by CG Alm) and 2017 (© Anne Schäfer). The upslope movement of tree and shrub species is shown in the red square. Note that the pictures are taken from slightly different perspectives (upper: at the Abisko Canyon, lower: Abisko Scientific Research Station).

5. Discussion

5.1. Thematical discussion

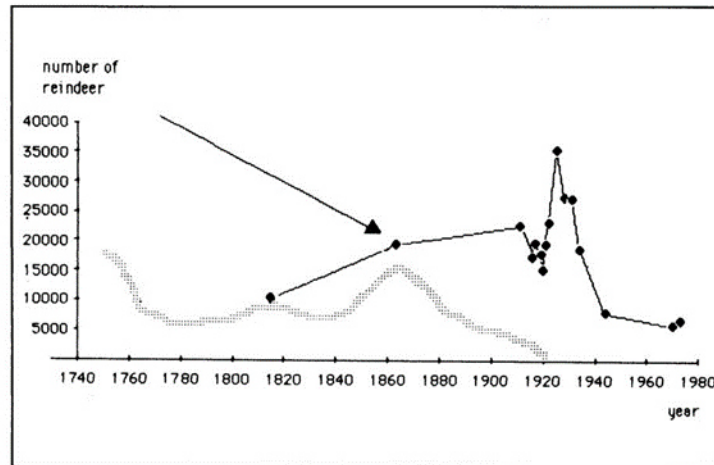
The visible changes in the plant communities confirm previous research conducted on Mt. Nuolja (Rundqvist et al., 2011; Kullman, 2015). The fact that there was practically no elevational shift in birch forest line between 1952 and 2018 is likely related to the building of the chairlift in 1966 and associated cutting of taller trees and shrubs for the ski slope. The ski run crosses the transect right at the forest line.

The expansion of shrub communities and reduction of alpine ones between 1917 and 1952, might be mainly driven by alterations in reindeer grazing intensity and not solely by a warming climate, as most warming occurred in the second half of the 20th century. Reindeer herbivory, in general, is having a great impact on tree line positions in northern Sweden (Olofsson et al., 2009; Myers-Smith et al., 2011; Vowles et al., 2017), especially the area around the forest line, where previously Sámi herders grazed their reindeer most intensively during the summer months. This was clearly shown in a description written by Israel Ruong (1975) and translated by Urban Emanuelsson (1987):

“The role of the timberline in reindeer husbandry can be inferred from the location of the [...] camps immediately below the timberline. Here the camp was protected against strong winds and firewood was at hand. There was also a good view of the grazing grounds from here and it was a short way to the treeless mountain where the reindeer herds grazed during the warm days in the autumn and from which they retreated down into the birchforest during rainy weather. Earlier, when the saami people milked the reindeer cows regularly, the location of the camp at the timberline was important as the herds were collected on the mountain and taken to the area around the camp to be milked.” (Emanuelsson, 1987, p. 99).

The described old, intensive way of reindeer herding with a regular milking process, shifted to a modern, extensive way of free-roaming herds. This shift in herding management at the end of the 19th century, led to a decrease in reindeer numbers (Figure 10; Emanuelsson, 1987). By the time Fries did his investigation on the plant communities, almost all reindeer in the area were managed

extensively. As a result of these reindeer management changes, the grazing pressure on the vegetation declined in the following decades and the occurring plant communities could recover resulting in upslope moving shrubs (Emanuelsson, 1987). Sandberg (1952a) already observed young birches and, in some places, young forest on meadows and heathland, which were birch-free in the past, on both sides of the transect close to the birch forest line (Picture 8).





 Estimated number of intensively managed reindeer in Talma, Rautasvuoma and Laevas according to Ruong (1937).
 Total number of reindeer in these villages. The arrow marks the date of the introduction of extensive reindeer husbandry into the investigation area.

Figure 10 The number of reindeer in the Saami villages of Talma, Rautasvuorna and Laevas (Emanuelsson, 1987)



Picture 8 Forest line on Nuolja's north-eastern slope showing vegetation changes. upper picture: 30th August 1937, beginning invasion of willow shrubs (*Salix glauca*, *S. lanata*, *S. phylicifolia*) into the open meadows. lower picture: 2nd August 1959, the open meadow changed into a willow thicket, Birch trees were moving upslope, older birch trees got more abundant. pictures taken by Gustaf Sandberg (1963a).

Additionally, strong and cold winters from the beginning of the 20th century until the 1970s (see Figure 3), diminished reindeer herds in size. Consequently, the grazing pressure declined even more, favouring a recruitment of trees and shrubs further upslope (Emanuelsson, 1987; van Bogaert et al., 2011). That means, although average temperatures were then lower than in the first half of the 20th century, shrubs could establish due to release from grazing pressure. Thus, grazing pressure most likely inhibited the upslope movement more than the cooler temperatures. After the 1960s, the grazing pressure increased again, but by then the new trees and shrubs had probably grown making grazing less attractive (Emanuelsson, 1987). In places with suitable habitats, established shrub communities tend to stay, such as the forb-rich meadow thicket in between surrounding forest communities (1366 m – 1389 m distance from the transect start, Picture 9). This community was found on the same area on the transect in all three investigation years.



Picture 9 Transitional form between a forb-rich meadow birch forest and moss birch forest. Photo: 7th August 2018 © A. Schäfer.

A main driver for the expansion of forest communities between 1952 and 2018 might not be grazing pressure but higher temperatures and a longer growing season, both reasons supporting shrub establishment and growth (Picture 10; Myers-Smith et al., 2011). More favourable climatic conditions were already indicated in several scientific papers in the 1970s and 1980s as reasons for an upslope shift of the forest line and tree limit in the Scandinavian mountains (Kullman, 1979; Sonesson, 1980; Emanuelsson, 1987).

Today's impact on the forest line mostly derives from continued human disturbance related to slope management for skiing, rather than reindeer grazing (Emanuelsson, 1987). Reasons why especially *Salix myrsinifolia* expanded so intensively was not obvious.

It is predicted that Arctic shrub expansion or greening will accelerate in the next decades due to increasing temperatures resulting in a longer growing season (see Figure 3 & Figure 4; Hallinger, Manthey, & Wilmking, 2010; Myers-Smith et al., 2011). It is likely, that some of the early expansion of shrubs throughout the region occurred as temperatures rose naturally at the end of the Little Ice Age, thus leading to a slow "re-colonisation process" along mountain slopes, which is still going on (Kammer, Schöb, & Choler, 2007).

Additionally, future increases in shrub growth might relate to increasing snow depth. Kohler, Brandt, Johansson, and Callaghan (2006) showed an increase in snow depth for the Abisko area, which might lead to a positive feedback effect as shrubs trap snow. Furthermore, due to the colonization of *Salix* thickets between 1917 and 1952 snow could accumulate more intensively. Consequently, a higher insulation capacity in winter and a higher water and nutrient availability in early summer would favour shrub growth and tall growing meadow communities instead of heath communities, latter ones adapted to a thin snow cover and cold temperatures (Emanuelsson, 1987). Thus, a reduction in alpine heath communities can be expected in the future, especially as they show the greatest changes due to climate change compared to other community types (Maliniemi, Kapfer, Saccone, Skog, & Virtanen, 2018). Nevertheless, more snow in alpine regions could lead to more long-lasting snow beds, where an establishment of shrubs might be difficult. Sandberg already discussed in 1952, that due to long-lasting snow beds above the forest line, birches and willows could not establish easily in such habitats (Sandberg, 1952a). Additionally, the direction of change, e.g. from a lichen rich tundra into an ericoid-moss tundra, might be crucial for further shrub establishments, as ericaceous plant litter tend to inhibit seedling establishment (Vuorinen et al., 2017).

With a sample size of one, the results from this study cannot be extrapolated to bigger scales without considering a higher sample size and several investigation sites on the same mountain. Even on Mt. Nuolja the forest line and tree limit vary strongly between, for example, north- and south-facing slopes. Avalanches and landslides suppress shrub and tree movements along steep edges on the northern slopes. Maliniemi et al. (2018) suggest, that several investigation sites are necessary to understand the complex interactions. However, shrubification of the Arctic has been topic in several research projects all over the northern hemisphere with noticeable increases in shrub cover and biomass (Myers-Smith et al., 2011), which alters plant communities and their distribution.



Picture 10 clearly visible establishment of willow patches (smaller than 0.8 m) along the transect in alpine heath communities. Photo: 24th August 2019 © A. Schäfer

5.2. Methodological discussion

The existing historical data sets from 1917 and 1952 have an exceptional value as they give a rather exhaustive picture of the historical, floristic composition of the vegetation, even though coverage data for the different communities were not recorded and elevational data might be inaccurate, as Fries used barograms with an accuracy of several meters (Fries, 1925). Fries' research and his

classification system provides a good basis for future investigations. Classification systems, in general, are helpful man-made inventions with a certain purpose: making comprehension easier. This has certain advantages, though single named plant communities cannot be understood by the name itself and classification systems in plant sociology tend to be applicable only by experts having the necessary knowledge. In a strict, scientific sense this is not a reproducible feature and thus non-scientific.

Fries community concept is based on the characteristic vegetation and its physiognomy. According to Fries, plant associations can be classified regarding their location or their life form (Fries, 1913). He preferred the latter one, as the life form and different vegetation types are directly visible and discoverable features, whereas the location is determined by many unknown edaphic and climatic factors. Fries put an emphasis on not mixing or combining those two principles when plant communities are classified. In the proposed formula, dominant life forms were recorded with capital letter (Fries, 1925), causing difficulties in the practical implementation. In the open, patchy arctic birch forest the dominant life form in the highest layer would be recorded as a “B” (deciduous tree). Although, the dominant life form in terms of abundance, independently seen from the highest layer, might be an “E” (graminoids and forbs) or “D” (dwarf shrubs). Conclusions could then be drawn into different directions.

Fries’ approach of transect is a common tool in vegetation surveys although it is a quite undefined method concerning the spatial limitations. In this study, I defined the study area to be 2.5 m wide on each side of the transect line. In practice, this distance is hard to keep while evaluating all the given plant species concerning their frequency. When vegetation surveys are done, different factors such as the season, weather, competence and knowledge of the observers play an important variable. The tall growing forbs *Geranium sylvaticum* and *Trollius europaeus* in the forb-rich meadows (E II b), could be observed with a higher frequency in early July, due to clearly visible flowers, than in early August, when most of the plant individuals already finished flowering.

Surveys including vegetation borders, such as the Arctic forest-alpine ecotone, with very heterogeneous conditions, highly complicate the analysis, as a clear assignment of the found vegetation type to a certain plant community is rarely possible. A more useful and applicable proposal would still be a transect survey but instead of a continuous area, distributing several

squared plots with a fixed size in a certain distance could help objectify the results. However, the data sets would no longer be comparable anymore.

6. Conclusion

This study highlighted, that over the last century, shrub and forest communities on Mt. Nuolja moved upslope, a process known as Arctic shrubification. Shrub communities moved especially between 1917 and 1952, forest communities mainly between 1952 and 2018. Alpine heath and meadow communities were invaded by small willow patches and thereby reduced in extent as they changed into shrub communities. The tree limit shifted to higher elevations, while movement of the forest line was comparatively small across the entire period. Reasons for the upslope shift might be decreasing grazing pressure and improving growing conditions, such as increased temperature and growing season length, which both have appeared in the last century.

The current trend of global warming will most certainly continue for the future. This warming will create more favourable growing conditions for plant life in the Arctic and alpine regions, allowing more shrub and tree expansion (Myers-Smith et al., 2011). Future changes will also likely be limited by microclimatic conditions (e.g. temperature, snow depth, wind, precipitation patterns and nutrient availability; Myers-Smith et al., 2011). Microclimatic habitat research combined with historical vegetation surveys, which offer a time machine approach, allow a comparison of past and current conditions. This might help us to understand current changes and predict future changes. Factors influencing the complex and multi-dimensional forest-alpine ecotone dynamics and related plant communities are likely not dependent solely on climatic changes but also on other factors such as the intensity of mainly reindeer herbivory (Olofsson et al., 2009) and land-use changes (Hinzman et al., 2005; Rundqvist et al., 2011). Addressing the interaction between a warming climate and land-use changes in future research is vital to understand patterns in tree and shrub establishment in the Scandinavian mountains.

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9. Supplementary appendices

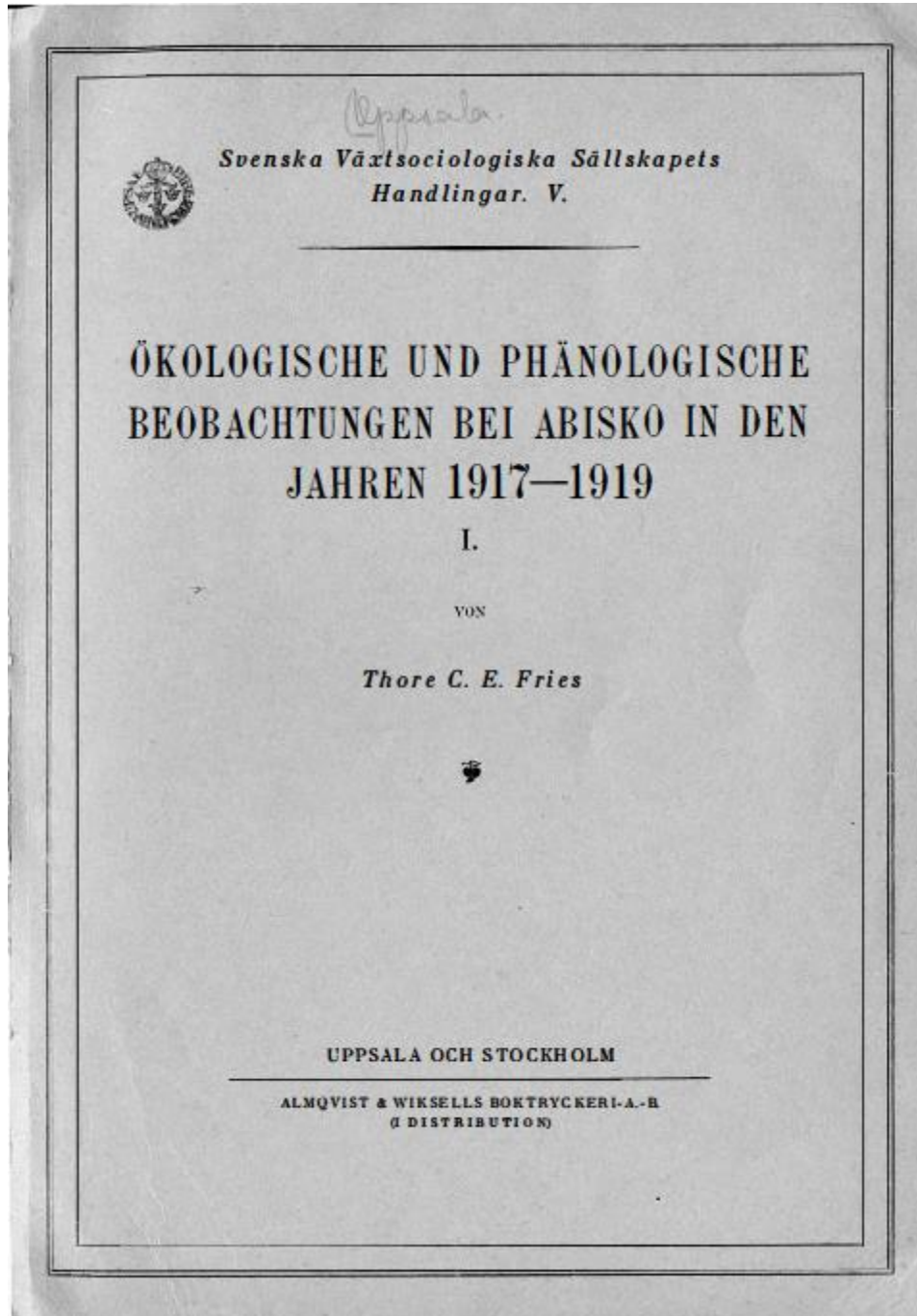
Appendix 1

Alexander von Humboldt’s study “Lines of Geography of Plants”, Original title: "Geographica plantarum lineamenta" 1817. It shows the Andes on the left, the Alps in the middle and the Scandinavian mountains on the right with distinct borders between each vegetation zone.



Appendix 2

Section of the original manuscript written by Thore Fries in 1925 dealing with the plant communities (p. 1 – 18).



Tab. 1. *Höhe der verschiedenen Abschnitte und Unterabschnitte über dem Meere. Die Höhenziffern beziehen sich auf die Pfähle.*

Pfahl	m ü. d. M.	Pfahl	m ü. d. M.	Pfahl	m ü. d. M.
I	390	VIII	604	XV	981
a	390	a	623	a	999
b	396	b	636	b	1 020
c	406	c	645	c	1 033
II	408	IX	665	XVI	1 051
a	410	a	678	a	1 053
b	414	b	708	b	1 055
c	417	c	726	c	1 060
III	425	X	742	XVII	1 060
a	432	a	761	a	1 060
b	439	b	776	b	1 060
c	442	c	789	c	1 061
IV	443	XI	806	XVIII	1 066
a	462	a	822	a	1 085
b	469	b	831	b	1 098
c	480	c	855	c	1 124
V	494	XII	869	XIX	1 129
a	499	a	871	a	—
b	504	b	876	b	1 136
c	511	c	822	c	—
VI	518	XIII	896	XX	1 153
a	523	a	—	a	1 159
b	534	b	924	b	1 168
c	546	c	928		
VII	559	XIV	939		
a	564	a	951		
b	578	b	965		
c	596	c	977		

Tab. 2. *Lagen und Längen der Pflanzengesellschaften längs des Nuolja-Profiles.*

Abschnitt I—II.

- I—a: 0—47 m=BI b 2 (*Empetrum* reichlich).
 a—b: 0—46/5 m=BI b 2 (*Empetrum* reichlich).
 b—c: 0—46/5 m=BI b 2 (*Empetrum* reichlich).
 c—II: 0—40 m=BI b 2 (*Empetrum* reichlich).

Abschnitt II—III.

- II—a*: 0—46 m=BI b 2 (*Empetrum* reichlich).
a—b: 0—46/5 m=BI b 2 (*Empetrum* reichlich).
b—c: 0—46/5 m=BI b 2 (0—18/5 m *Empetrum* reichlich).
c—III: 0—43 m=BI b 2 (26—43 m *Empetrum* reichlich).

Abschnitt III—IV.

- III—a*: 0—47 m=BI b 2 (0—5 m *Empetrum* reichlich; 37—47 m *Empetrum* reichlich).
a—b: 0—46/5 m=BI b 2 (*Empetrum* reichlich).
b—c: 0—47 m=BI b 2 (*Empetrum* reichlich).
c—IV: 0—40/5 m=BI b 2 (*Empetrum* reichlich).

Abschnitt IV—V.

- IV—a*: 0—46 m=BI b 2 (0—23 m *Empetrum* reichlich).
a—b: 0—2/5 m BI b 2—2/5—5 m=BII a 1. — 5—41/5 m=BI b 2. — 41/5—46/5 m BII a 1.
b—c: 0—45 m=BI b 2.
c—V: 0—44=BI b 2 (17—24 m *Empetrum* reichlich).

Abschnitt V—VI.

- V—a*: 0—25 m=BI b 2 (13/5 m — 19 m *Empetrum* reichlich). — 25—45/5 m=BII a 1.
a—b: 0—6/5 m=BII a 1. — 6/5—18 m=BI b 2. — 18—29 m=BII a 1. — 29—46 m=BI b 2
 (37—46 m *Empetrum* reichlich).
b—c: 0—47 m=BI b 2 (0—5 m *Empetrum* reichlich; 42—47 m *Empetrum* reichlich).
c—IV: 0—46/5 m=BI b 2 (0—2/5 m *Empetrum* reichlich).

Abschnitt VI—VII.

- VI—a*: 0—29/5 m=BI b 2. — 29/5—37/5 m=BI b 1 (*Vaccinium vitis idea* reichlich). —
 37/5—46/5 m=BI b 2.
a—b: 0—46/5 m=BI b 2.
b—c: 0—46/5 m=BI b 2.
c—VII: 0—44/5 m=BI b 2.

Abschnitt VII—VIII.

- VII—a*: 0—14 m=BI b 2. — 14—21 m=BII a 1. — 21—46 m=BII b 2.
a—b: 0—26/5 m=BI b 2. — 26/5—33/5 m=CII a 2. — 33/5—42 m=EII a 4. — 42—46/5 m
 =EII a 1.
b—c: 0—14/5 m=EII a 1. — (6 m—11 m=EII b 1). — 11—14/5 m=EII a 1. — 14/5—35 m
 =BII a 1. — 35—46/5 m=EII a 1.
c—VIII: 0—26 m=CII a 1. — 26—33/5 m=EII a 1. — 33/5—44 m=EII b 1. — 44—46 m
 =EII a 1.

Abschnitt VIII—IX.

- VIII—a*: 0—6 m=EIII a 1. — 6—46 m=BII a 1.
a—b: 0—41/5 m=EII a 1 (0—14 m=CII 1, aber *Salices* abgestorben). — 41/5—46/5 m=BII a 1 (—BI b 2; die Birken verkümmert).
b—c: 0—18 m=BII a 1 (—BI b 2; die Birken verkümmert). — 18—43 m=CII a 1. (33—43 m *Salices* abgestorben). — 43—47 m=EII a 1.
c—IX: P—47 m= EII a 1 (44—47 m EII a 1—EII b 1).

Abschnitt IX—X.

- IX—a*: 0—33 m=EII b 1. — 33—46 m=EII a 1.
a—b: 0—22 m=EII a 1. — 22—47 m=EII b 2 (34—47 m zwergstrauchheidenartig).
b—c: 0—46/5 m=EII b 2 (0—5 m zwergstrauchheidenartig).
c—X: 0—46/5 m=EII b 2.

Abschnitt X—XI.

- X—a*: 0—46/5 m=EII b 2 (42/5—46/5 m zwergstrauchheidenartig).
a—b: 0—46/5 m=EII b 2.
b(—c)—XI: 0—93 m=EII b 2.

Abschnitt XI—XII.

- XI—a*: 0—25 m=EII b 2. — 25—47 m=Kolonievegetation (wiesenartig).
a—b: 0—10 m=sehr lichte Kolonievegetation. — 10 m—47/5 m=Schneeboden (fast) phanerogamenfrei.
b—c: 0—21 m=Schneeboden, (fast) phanerogamenfrei. — 21—28 m=Schneeboden mit *Epilobium anagallidifolium* und *Veronica alpina* reichlich. — 28—34 m=EII b 1 (*Phleum alpinum* reichlich). — 34—46 m=EII b 3 (36—40 m mit *Cassiope hypnoides* und *Bryanthus coeruleus* sparsam).
c—XII: 0—35/5 m=DI b 7.

Abschnitt XII—XIII.

- XII—a*: 0—32 m=DI b 7 (*Empetrum* sparsam). — 32—46/5 m=EII b 2.
a—b: 0—3/5 m=EII b 2. — 3/5—8/5 m=Rutscherde. — 8/5—16/5 m=DI a 8. — 16/5—26/5 m=EII b 1. — 26/5—47/5=EI 7 (26/5—37/5 mit Annäherung an EII b 1).
b—c: 0—6 m=Rutscherde. — 6—14 m=EII b 1. — 14—32 m=DI a 8. — 32—46/5=EII b 2.
c—XIII: 0—10 m=DI a 8. — 10—25 m=EII b 1 (—EI). — 25—47 m=EI 6.

Abschnitt XIII—XIV.

- XIII(—a)—b*: 0—17/5 m=EI 6. — 17/5—47/5 m=EII b 1. — 47/5—89 m=kolonienartige Wiesenvegetation.
b—c: =Schneeboden (einzelne Phanerogamen am nächsten C).
c—XIV: =Schneeboden (Phanerogamen 0).

Abschnitt XIV—XV.

- XIV—a*: =Schneeboden (Phanerogamen 0).
a—b: 0—8 m=Schneeboden (einzelne Phanerogamen). — 8—13 m=EI 7. — 13—25 m=
Luzula confusa—L. Wahlenbergii-Zone. — 25—38 m=DI b 1.
b—c: 0—11 m=DI b 1. — 11—19/5 m=*Luzula confusa*-Zone. — 19/5—28 m=EI 7. —
 28—36 m=Sn 1. — 36—45/5 m=EI 8. — 45/5—47 m DI b 1.
c—XV: 0—1 m=DI b 1. — 1—19 m=DI b 5. — 19—34 m=DI a 8. — 34—47 m=Sn.
 (einzelne Phanerogamen).

Abschnitt XV—XVI.

- XV—a*: 0—44/5 m=Schneeboden (0—25 m phanerogamenfrei; 34/4—44/5 m=Schneeboden 1).
 — 44/5—45/5 m=DI a 7.
a—b: 0—2/5 m=DI a 7. — 2/5—12/5 m=DI b 3 (*Cassiope hypnoides* reichlich am unteren
 Rande, *Empetrum* und *Loiseleuria procumbens* sparsam am oberen). — 12/5—47/5 m
 =DI b 1.
b—c: 0—47 m=DI b 1.
c—XVI: 0—35 m=DI b 1.

Abschnitt XVI—XVII.

- XVI—a*: 0—47 m=DI b 1.
a—b: 0—47 m=DI b 1.
b—c: 0—47 m=DI b 1.
c—XVII: 0—47 m=DI b 1.

Abschnitt XVII—XVIII.

- XVII—a*: 0—47 m=DI b 1.
a—b: 0—27 m=DI b 1. — 27—34 m=III b. — 34—47 m=DI b 1.
b—c: 0—47 m=DI b 1.
c—XVIII: 0—12 m=DI b 1. — 12—20 m=DI b 5. — 20—24 m=DI a 8. — 24—35 m=EI
 (*Luzula confusa* reichlich). — 35—47 m=Schneeboden (einzelne Phanerogamen).

Abschnitt XVIII—XIX.

- XVIII—a*: 0—33 m=Sn. (0—17/5 m phanerogamenfrei; 17/5—27 m Phanerogamen einzeln —
 spärlich; 27—33 m=Schneeboden auf Rutscherde). — 33—34/5 m=DI a 8. — 34/5—
 37/5 m=DI b 3 (zu unterst reichlich *Cassiope hypnoides*, zu oberst sparsam *Empetrum*).
 — 37/5—46/5 m=DI b 1.
a—b: 0—20 m=DI b 1. — 20—46/5 m=DI a 8.
b—c: 0—3/5 m=DI a 8. — 3/5—10/5 m=DI b 3 (zu unterst reichlich *Cassiope hypnoides*, zu
 oberst *Cassiope tetragona*). — 10/5—47/5 m=DI b 1.
c—XIX: 0—36 m=DI b 1.

Abschnitt XIX—XX.

XIX—*a*: 0—47 m=DI b 1 (—EI).

a—*b*: 0—41 m=DI b 1 (—EI). — 41—47 m=DI b 5.

b—*c*: 0—9 m=DI b 5. — 9—18 m=EI. — 18—43 m=DI a 8. — 43—46 m=DI b 5. —
46—47 m=DI b 1 (*Cassiope tetragona sparsam*).

c—XX: 0—38 m=DI b 1.

Abschnitt XX—B.

XX—*a*: 0—47 m=DI b 1.

a—*b*: 0—45 m=DI b 1.

sichere Anhaltspunkte für die phänologische Beschaffenheit des Jahres im Verhältnis zu den vorhergehenden zwei Jahren gewinnen.

Leider bin ich gegenwärtig nicht in der Lage, einige meteorologische Beobachtungen auf dem Profil mitzuteilen. Anstatt ihrer gebe ich in einer Tabelle die mittleren Temperaturen während der Zeitabschnitte zwischen den phänologischen Beobachtungen bei der Naturwissenschaftlichen Station Abisko (393 m ü. d. M), kaum 2 km von dem unteren Ende des Profils an. Diese mittleren Temperaturen sind aus den Angaben der »*Observations météorologiques à Abisko 1917—1919*», Uppsala & Stockholm 1920—1924, berechnet.

Tab. 3. *Mittlere Temperaturen bei Abisko (Thermograph 393 m ü. d. M.) während der Zeitabschnitte zwischen den Beobachtungen.*

1917.

$26/5 - 30/5 + 3,7^{\circ}$	$10/7 - 14/7 + 6,1^{\circ}$	$25/8 - 29/8 + 11,1^{\circ}$
$31/5 - 7/6 + 4,4^{\circ}$	$15/7 - 19/7 + 13,7^{\circ}$	$30/8 - 3/9 + 8,1^{\circ}$
$8/6 - 11/6 + 7,7^{\circ}$	$20/7 - 24/7 + 7,4^{\circ}$	$4/9 - 8/9 + 5,7^{\circ}$
$12/6 - 15/6 + 9,5^{\circ}$	$25/7 - 29/7 + 11,0^{\circ}$	$9/9 - 13/9 + 5,5^{\circ}$
$16/6 - 20/6 + 7,9^{\circ}$	$30/7 - 4/8 + 11,4^{\circ}$	$14/9 - 18/9 + 2,9^{\circ}$
$21/6 - 24/6 + 11,1^{\circ}$	$5/8 - 9/8 + 15,8^{\circ}$	$19/9 - 23/9 + 1,9^{\circ}$
$25/6 - 30/6 + 9,1^{\circ}$	$10/8 - 14/8 + 11,8^{\circ}$	$24/9 - 28/9 + 3,0^{\circ}$
$1/7 - 4/7 + 5,0^{\circ}$	$15/8 - 19/8 + 14,9^{\circ}$	$29/9 - 3/10 + 0,7^{\circ}$
$5/7 - 9/7 + 4,9^{\circ}$	$20/8 - 24/8 + 10,3^{\circ}$	$4/10 - 9/10 - 2,5^{\circ}$

Max. + 26,9° (16/7), Min. — 8,5° (9/10).

1918.

$^{25}/_5 - ^{30}/_5 + 5,1^\circ$	$^{30}/_6 - ^4/_7 + 12,4^\circ$	$^5/_8 - ^9/_8 + 9,0^\circ$
$^{31}/_5 - ^4/_6 + 2,1^\circ$	$^5/_7 - ^9/_7 + 14,0^\circ$	$^{10}/_8 - ^{14}/_8 + 10,7^\circ$
$^5/_6 - ^{10}/_6 + 6,7^\circ$	$^{10}/_7 - ^{14}/_7 + 14,7^\circ$	$^{15}/_8 - ^{19}/_8 + 8,0^\circ$
$^{11}/_6 - ^{16}/_6 + 7,5^\circ$	$^{15}/_7 - ^{20}/_7 + 11,1^\circ$	$^{20}/_8 - ^{30}/_8 + 7,5^\circ$
$^{17}/_6 - ^{20}/_6 + 7,4^\circ$	$^{21}/_7 - ^{24}/_7 + 15,1^\circ$	$^{31}/_8 - ^9/_9 + 5,3^\circ$
$^{21}/_6 - ^{25}/_6 + 10,1^\circ$	$^{25}/_7 - ^{29}/_7 + 14,1^\circ$	$^{10}/_9 - ^{15}/_9 + 7,1^\circ$
$^{20}/_6 - ^{29}/_6 + 10,9^\circ$	$^{30}/_7 - ^4/_8 + 13,6^\circ$	

Max. +25,6° ($^4/_7$), *Min.* -2,4° ($^2/_6$).

1919.

$^{28}/_5 - ^3/_6 + 5,5^\circ$	$^4/_6 - ^{10}/_6 + 10,1^\circ$	$^{11}/_6 - ^{15}/_6 + 9,3^\circ$	$^{16}/_6 - ^{20}/_6 + 11,1^\circ$
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Max. +23,0° ($^8/_6$), *Min.* -2,1 ($^{28}/_5$).

Appendix 3

Exact position of each outpost birch or willow individual and extent of some willow patches along the transect on Mt. Nuolja above the tree limit at 795 m a.s.l. GPS coordinates (WGS 84) taken with a differential Global Positioning System (Trimble R8s receiver with GNSS System and trimble tablet T10) in 2018 and 2019.

Abbreviations:

SALlan = *Salix lanata*

SALgla = *Salix glauca*

Species	Latitude (N)	Longitude (E)	Elevation (m)	Height (m)	Notes
<i>Betula pubescens</i>	68.37167086	18.70153159	1132.098	< 0.80	uppermost outpost birch individual
<i>Salix glauca</i>	68.37075661	18.70459912	1111.971	< 0.80	uppermost outpost willow individual
<i>Salix glauca</i>	68.37067701	18.70496606	1105.273	< 0.80	
<i>Salix glauca</i>	68.37060910	18.70495075	1102.551	< 0.80	
<i>Betula pubescens</i>	68.37015497	18.70693256	1069.010	< 0.80	
<i>Salix glauca</i>	68.36913623	18.71026357	1054.921	< 0.80	
<i>Salix glauca</i>	68.36861348	18.71227190	1052.341	< 0.80	
<i>Salix glauca</i>	68.36845570	18.71275714	1049.082	< 0.80	
<i>Salix glauca</i>	68.36838660	18.71305534	1045.695	< 0.80	
<i>Salix glauca</i>	68.36837986	18.71312942	1044.905	< 0.80	
<i>Salix phylicifolia</i>	68.36828498	18.71341053	1039.762	< 0.80	
<i>Salix glauca</i>	68.36819919	18.71368099	1035.200	< 0.80	
<i>Salix glauca</i>	68.36814256	18.71362134	1035.460	< 0.80	
<i>Salix glauca</i>	68.36794773	18.71460417	1020.027	< 0.80	
<i>Betula pubescens</i>	68.36777236	18.71530009	1007.122	< 0.80	
<i>Betula pubescens</i>	68.36673411	18.71859042	952.683	< 0.80	
<i>Salix lanata</i>	68.36582883	18.72189636	911.487	< 0.80	
<i>Salix lanata</i>	68.36582751	18.72194379	910.635	< 0.80	
<i>Salix glauca</i>	68.36584097	18.72214731	908.269	< 0.80	
<i>Salix glauca</i>	68.36576158	18.72229498	908.046	< 0.80	
<i>Salix lanata</i>	68.36572648	18.72237396	908.616	< 0.80	
<i>Salix lanata</i>	68.36572285	18.72241323	908.257	< 0.80	
<i>Salix glauca</i>	68.36570300	18.72243078	908.351	< 0.80	
<i>Salix glauca</i>	68.36570746	18.72248707	907.370	< 0.80	
<i>Salix glauca</i>	68.36570658	18.72253420	906.972	< 0.80	
<i>Salix glauca</i>	68.36568642	18.72255315	907.186	< 0.80	
<i>Salix glauca</i>	68.36566193	18.72269348	905.904	< 0.80	
<i>Salix glauca</i>	68.36565789	18.72273901	905.603	< 0.80	
<i>Salix sp.</i>	68.36566629	18.72278152	904.879	< 0.80	
<i>Salix lanata</i>	68.36566759	18.72290746	904.110	< 0.80	

<i>Salix lanata</i>	68.36563806	18.72296094	904.290	< 0.80	
<i>Salix lanata</i>	68.36562129	18.72296413	904.400	< 0.80	
<i>Salix hastata</i>	68.36562735	18.72297578	904.115	< 0.80	
<i>Salix hastata</i>	68.36543268	18.72380664	895.174	< 0.80	
<i>Salix lanata</i>	68.36540679	18.72401798	894.178	< 0.80	
<i>Salix lanata</i>	68.36533206	18.72413203	893.501	< 0.80	
<i>Salix lanata</i>	68.36534546	18.72421768	893.097	< 0.80	
patch1_SALlan_start	68.36532749	18.72424597	892.878	< 0.80	<i>Salix lanata</i> up to 40cm tall
patch1_SALlan_end	68.36532890	18.72428509	892.575	< 0.80	<i>Salix lanata</i> up to 40cm tall
patch2_SALlan_start	68.36529828	18.72432356	892.617	< 0.80	<i>Salix lanata</i> up to 40cm tall
patch2_SALlan_end	68.36528659	18.72439377	892.220	< 0.80	<i>Salix lanata</i> up to 40cm tall
patch3_SALlan_start	68.36527692	18.72441856	892.006	< 0.80	<i>Salix lanata</i> up to 40cm tall
patch3_SALlan_end	68.36526346	18.72447221	891.437	< 0.80	<i>Salix lanata</i> up to 40cm tall
patch4_SALlan_start	68.36524506	18.72454484	890.940	< 0.80	<i>Salix lanata</i> up to 40cm tall
patch4_SALlan_end	68.36523840	18.72456626	890.812	< 0.80	<i>Salix lanata</i> up to 40cm tall
patch5_SALlan_start	68.36523286	18.72467704	889.604	< 0.80	<i>Salix lanata</i> up to 40cm tall
patch5_SALlan_end	68.36521758	18.72470288	889.207	< 0.80	<i>Salix lanata</i> up to 40cm tall
patch6_SALlan_start	68.36521101	18.72473959	888.499	< 0.80	<i>Salix lanata</i> up to 40cm tall
patch6_SALlan_end	68.36517672	18.72488572	886.616	< 0.80	<i>Salix lanata</i> up to 40cm tall
patch7_SALlan_start	68.36515383	18.72502502	884.937	< 0.80	<i>Salix lanata</i> up to 40cm tall
patch7_SALlan_end	68.36514888	18.72507789	884.198	< 0.80	<i>Salix lanata</i> up to 40cm tall
patch8_SALlan_start	68.36514245	18.72510114	884.085	< 0.80	<i>Salix lanata</i> up to 40cm tall
patch8_SALlan_end	68.36513718	18.72513535	883.511	< 0.80	<i>Salix lanata</i> up to 40cm tall
patch9_SALlan_start	68.36492878	18.72609321	871.960	< 0.80	<i>Salix lanata</i> 30-50 cm tall
patch9_SALlan_end	68.36492635	18.72610533	871.899	< 0.80	<i>Salix lanata</i> 30-50 cm tall
patch10_SALlan_start	68.36490154	18.72619947	871.141	< 0.80	<i>Salix lanata</i> 30-50 cm tall
patch10_SALlan_end	68.36490048	18.72620470	871.034	< 0.80	<i>Salix lanata</i> 30-50 cm tall
patch11_SALgla_start	68.36488605	18.72619693	870.998	< 0.80	<i>Salix glauca</i> 50cm tall
patch11_SALgla_end	68.36488400	18.72621394	870.655	< 0.80	<i>Salix glauca</i> 50cm tall
patch12_SALlan_start	68.36488761	18.72624821	870.419	< 0.80	<i>Salix lanata</i> 30-50 cm tall
patch12_SALlan_end	68.36488683	18.72626732	870.305	< 0.80	<i>Salix lanata</i> 30-50 cm tall
patch13_SALlan_start	68.36487852	18.72628713	870.307	< 0.80	<i>Salix lanata</i> 30-50 cm tall
patch13_SALlan_end	68.36488885	18.72636812	869.911	< 0.80	<i>Salix lanata</i> 30-50 cm tall
patch14_SALlan_start	68.36489157	18.72628043	870.201	< 0.80	<i>Salix lanata</i> 30-50 cm tall
patch14_SALlan_end	68.36492803	18.72637650	869.553	< 0.80	<i>Salix lanata</i> 30-50 cm tall
patch15_SALlan_start	68.36486720	18.72647483	869.195	< 0.80	<i>S. glauca</i> + <i>S. lanata</i>
patch15_SALlan_end	68.36480815	18.72678194	866.314	< 0.80	<i>S. glauca</i> + <i>S. lanata</i>
patch16_SALlan_start	68.36481663	18.72684240	865.559	< 0.80	<i>Salix</i> sp. ca. 30 cm tall
patch16_SALlan_end	68.36481539	18.72693621	864.820	< 0.80	<i>Salix</i> sp. ca. 30 cm tall
patch17_SALgla_start	68.36478681	18.72694516	864.964	< 0.80	<i>Salix</i> sp. ca. 30 cm tall

patch17_SaLgla_end	68.36478427	18.72697139	864.811	< 0.80	<i>Salix</i> sp. ca. 30 cm tall
patch18_SALgla_start	68.36477813	18.72717125	862.886	< 0.80	<i>Salix</i> sp. ca. 30 cm tall
patch18_SALgla_end	68.36477419	18.72717819	862.693	< 0.80	<i>Salix</i> sp. ca. 30 cm tall
patch19_SALgla_start	68.36476401	18.72720240	862.626	< 0.80	<i>Salix</i> sp. ca. 30 cm tall
patch19_SALgla_end	68.36475634	18.72723501	862.166	< 0.80	<i>Salix</i> sp. ca. 30 cm tall
patch20_SALgla_start	68.36476172	18.72726719	861.989	< 0.80	<i>Salix</i> sp. ca. 30 cm tall
patch20_SALgla_end	68.36475707	18.72728342	861.616	< 0.80	<i>Salix</i> sp. ca. 30 cm tall
<i>Betula pubescens</i>	68.36472448	18.72730824	861.683	< 0.80	
patch21_SALgla_start	68.36467784	18.72755566	859.211	< 0.80	<i>Salix</i> sp. ca. 30 cm tall
patch21_SALgla_end	68.36467065	18.72757248	858.949	< 0.80	<i>Salix</i> sp. ca. 30 cm tall
patch22_SALlan_start	68.36465105	18.72759317	858.545	< 0.80	<i>Salix</i> sp. ca. 30 cm tall
patch22_SALlan_end	68.36464847	18.72760932	858.491	< 0.80	<i>Salix</i> sp. ca. 30 cm tall
patch23_SALgla_start	68.36464517	18.72773439	857.304	< 0.80	<i>Salix</i> sp. smaller than 20cm
patch23_SALgla_end	68.36462340	18.72775759	857.200	< 0.80	<i>Salix</i> sp. smaller than 20cm
<i>Betula pubescens</i>	68.36455665	18.72818652	847.752	< 0.80	
<i>Betula pubescens</i>	68.36452222	18.72831597	843.205	< 0.80	
patch24_SALlan_start	68.36450355	18.72834868	842.027	< 0.80	<i>Salix</i> sp. smaller than 20cm
patch24_SALlan_end	68.36450996	18.72833246	842.299	< 0.80	<i>Salix</i> sp. smaller than 20cm
<i>Salix arbuscula</i>	68.36458343	18.72787407	854.911	< 0.80	
upper end continuous shrub area	68.36423387	18.72991111	813.117	0.50 - 0.80	<i>Salix lanata</i> , <i>S. glauca</i>
<i>Betula pubescens</i>	68.36424953	18.73022515	809.535	< 0.80	
upper shrub limit	68.36421931	18.73029877	807.806	> 0.80	uppermost shrub forming individual (<i>Salix glauca</i>)
tree limit	68.36413680	18.73120931	794.826	> 2	uppermost tree forming species (<i>Salix myrsinifolia</i>)
<i>Betula pubescens</i>	68.36387414	18.73316385	767.869	> 0.80	
<i>Betula pubescens</i>	68.36385311	18.73319803	767.837	> 0.80	
<i>Betula pubescens</i>	68.36383583	18.73323122	767.390	> 0.80	
<i>Betula pubescens</i>	68.36384539	18.73326935	766.571	> 0.80	
<i>Betula pubescens</i>	68.36385148	18.73340031	764.697	> 2	
<i>Betula pubescens</i>	68.36378298	18.73388299	756.916	> 2	
<i>Betula pubescens</i>	68.36379569	18.73388550	756.910	> 2	
<i>Betula pubescens</i>	68.36393687	18.73401194	753.878	> 2	
<i>Betula pubescens</i>	68.36380809	18.73415234	752.450	> 0.80	
<i>Betula pubescens</i>	68.36378325	18.73423245	751.427	> 2	
<i>Betula pubescens</i>	68.36373953	18.73423043	751.373	> 2	
<i>Betula pubescens</i>	68.36372068	18.73445803	747.851	> 2	
<i>Betula pubescens</i>	68.36374517	18.73501972	738.249	> 2	
<i>Betula pubescens</i>	68.36366951	18.73531649	733.862	> 2	
<i>Betula pubescens</i>	68.36364231	18.73537461	733.465	> 2	
<i>Betula pubescens</i>	68.36366059	18.73538161	732.858	> 2	

<i>Betula pubescens</i>	68.36366522	18.73548363	730.287	> 0.80	
<i>Betula pubescens</i>	68.36371308	18.73570912	725.130	> 0.80	
<i>Betula pubescens</i>	68.36373959	18.73572598	724.851	> 2	
<i>Betula pubescens</i>	68.36373848	18.73585317	722.474	> 0.80	
<i>Betula pubescens</i>	68.36370422	18.73594372	720.943	> 0.80	
<i>Betula pubescens</i>	68.36366197	18.73596688	720.744	> 0.80	
<i>Betula pubescens</i>	68.36347204	18.73657524	711.011	> 0.80	
<i>Betula pubescens</i>	68.36346633	18.73656641	711.126	> 0.80	
<i>Betula pubescens</i>	68.36347301	18.73662449	710.360	> 0.80	
<i>Betula pubescens</i>	68.36349629	18.73679238	707.623	> 2	
<i>Betula pubescens</i>	68.36354993	18.73728542	698.693	> 2	
<i>Betula pubescens</i>	68.36338906	18.73737627	696.443	> 0.80	
<i>Betula pubescens</i>	68.36342741	18.73740323	695.727	> 2	
<i>Betula pubescens</i>	68.36337147	18.73752209	694.140	> 2	
<i>Betula pubescens</i>	68.36338038	18.73760335	692.630	> 2	
<i>Betula pubescens</i>	68.36332327	18.73802026	683.806	> 2	
<i>Betula pubescens</i>	68.36335948	18.73829436	676.555	> 0.80	
<i>Betula pubescens</i>	68.36335836	18.73847848	673.281	> 0.80	
<i>Betula pubescens</i>	68.36328400	18.73934007	657.207	> 0.80	
<i>Betula pubescens</i>	68.36329455	18.73936111	656.919	> 0.80	
<i>Betula pubescens</i>	68.36327343	18.73936467	656.792	> 0.80	
<i>Betula pubescens</i>	68.36327068	18.73941148	656.182	> 0.80	
<i>Betula pubescens</i>	68.36326100	18.73943091	655.799	> 0.80	
<i>Betula pubescens</i>	68.36327212	18.73944266	655.686	> 0.80	
<i>Betula pubescens</i>	68.36322390	18.73959550	652.875	> 0.80	
<i>Betula pubescens</i>	68.36322159	18.73958796	653.127	> 0.80	
<i>Betula pubescens</i>	68.36318945	18.73971261	651.161	> 0.80	
forest line	68.36321681	18.73984755	648.708	> 2	forest line formed by <i>Betula pubescens</i>