Faculty of Science

Mapping state and change of the Scots pine population in Abisko in subarctic Sweden

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Degree of Bachelor of Science
with a major in Earth Sciences
15 hec

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2020 B-1103

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ISSN 1400-3821

B1103
Bachelor of Science thesis
Göteborg 2020

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Preface

This is a Bachelor's thesis in Earth Sciences with a specialisation in Physical Geography. The project was carried out in the spring of 2020.

First and foremost, I would like to thank my supervisor Associate Professor Heather Reese for guidance and support through the process. I would also like to give thanks to the course leader Associate Professor Mark Johnson, and to my fellow classmates for valuable feedback and inspiration on the long and winding road of thesis writing. In a time of global crisis, the corona epidemic, all of you made the long days of working from home seem shorter.

Abstract

In the face of accelerating climate change, poleward and elevational range expansion have been recorded in many species of the subarctic. In recent decades Scots pine *(Pinus Sylvestris)* has become more abundant in the mountain-birch dominated forests of subarctic Sweden. Monitoring this shift is vital to understanding the effects of climate change on the subarctic ecosystem. Finding a cost effective and time efficient method for mapping and monitoring the Scots pine population over larger areas would improve our knowledge of the Scots pines response to climate change. This study evaluates the feasibility of mapping the state and change of the local Scots pine population in Abisko national park in subarctic Sweden using three different remote sensing techniques. The aim is both to evaluate the methods and to analyse eventual changes in the local Scots pine population.

The first task, mapping of the current Scots pine population, was successfully performed utilizing a Sentinel-2 image and a method of estimating the Scots pine crown coverage of each pixel using a natural difference water index (NDWI). The second task, the change analyses were done in two parts, the first one being a repeat aerial photograph analysis, done by comparing an aerial photo from 1959 with an aerial photo from 2018. The second part measured changes in height and was done by calculating the height of 20 trees from measurements of tree-shadows in an aerial photo from 1959. The measurements were compared to LIDAR data from 2015. The results of the first part show an 9-34% increase in Scots pine abundancy in two 1km^2 large study areas. Most of the increase was however confined to already existing stands and no significant range expansion could be detected. The height comparison showed no increase in height between 1959 and 2015.

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1. Introduction

1.1. Background

Compared to pre-industrial levels, by 2018 the global mean temperature had increased by 1 degree Celsius (IPCC, 2019). In arctic regions, the increase has been two to three times greater than the global average (ACIA, 2005). The polar regions are of great importance for the global climate, due to several feedback mechanisms such as changes in albedo of melting glaciers and ice caps. This accelerated warming effect is referred to as polar amplification (ACIA, 2005). Because of polar amplification, arctic ecosystem changes have become a vital aspect in climate change research. Forest range and tree line expansion as well as changes in species composition has been studied extensively in the last decade. In the Swedish Scandes, research suggests that a climate induced advance of the forest tundra ecotone has taken place in the last decades and that this trend will continue as climate change accelerates (Hedenås, Christensen, & Svensson, 2016; Rundqvist et al., 2011; Sturm, Racine, & Tape, 2001; ACIA, 2005). The forest tundra ecotone is expected to advance to higher elevations and to more northerly latitudes (ACIA, 2005).

In the mountain forests of subarctic Sweden, the dominant tree species are mountain birch (*Betula pubescens subsp. tortuosa (Ledeb.) Nyman)* and Scots pine (*Pinus sylvestris*). Mapping of these species is important for understanding how climate change can impact the subarctic vegetation. Several vegetation maps over the Swedish Scandes have been created in the past, from Lantmäteriets "vegetationskartan" created in the 1970s to the Nationell markdatatäckedata (NMD) from 2017. However, these maps do not have a spatial resolution high enough to find individual or small patches of trees. In the subalpine zone, on the boundary of its climatic habitat, Scots pine grows in small patches or as individual trees in the surrounding birch forest. To map an eventual change in the Scots pine population, it is therefore vital to find a method that can identify small stands of pine trees.

Scots pine, being a thermophilic species, is expected to increase in quantity and spatial extent in a future warmer climate (Grudd, 2008; Kullman & Kjällgren, 2006). Research of fossils also shows a correlation between warmer Holocene periods and a higher Scots pine tree line (Kullman & Kjällgren, 2006; Kultti, Mikkola, Virtanenj, Timonen, & Eronen, 2006). Previous research has also suggested a range expansion of the Scots pine population in the last half century (Bryn, 2008; Kullman, 2014). However, in recent years the notion of a forest-climate disequilibrium (Rees et al., 2020) has emerged, indicating that forest range expansion in subarctic regions does not have a linear response to increasing temperatures, at least not in the short term. Climate change induced range expansion has also been shown to differ greatly between regions, indicating that temperature is one factor amongst many influencing range expansion (Rees et al., 2020). Increasing temperature leads to feedback mechanisms which influences species in different ways. Furthermore, precipitation patterns are expected to shift in a warmer climate (ACIA, 2005), and since subarctic Scots pine populations is only competitive on dry soils, higher precipitation levels may affect the populations range extent negatively (Kullman, 2007). Studies of the forest tundra ecotone has also been shown to correlate more closely to precipitation than to temperature (Rees et al., 2020). Studies of limiting factors for Scots pine range expansion has shown that even thou Scots pine grows slower at higher altitudes, it can still sprout at altitudes well above the tree line if planted there (Wahlberg, 2009). This shows that seed dispersion is important as a limiting factor. Another aspect is that Scots pine in subarctic regions is slow-growing and a range expansion should therefore not be expected to follow climate change velocities directly (Kullman & Öberg, 2018).

Previous studies of Scots pine distribution in subalpine regions have been conducted mostly through field studies, limiting the size of their study area (Barnekow, 1999; Kullman, 2007, 2014; Kultti et al., 2006; Magnusson, Fransson, & Holmgren, 2007). This makes a remote sensing approach an important supplement to existing research, where a key strength of remote sensing is that it can map large areas more time-efficiently than field inventory. Furthermore, to the author's knowledge, there have been no previous publications regarding mapping change of the Scots pine population in Abisko using remote sensing data that spanned decades.

Sentinel-2 earth observation satellites

The two Sentinel-2 satellites Sentinel-2A and Sentinel-2B, are part of the European Space Agency's Copernicus program. They were launched in 2015 and 2017, respectively. Their purpose is to provide global geospatial information with high temporal resolution, similar to the capacity of the Landsat and Spot satellite programs (Drusch et al., 2012). The satellites have a lifespan of 7.5 years and with launches planned for additional satellites, the program plans to be in operation for 15 years (Immitzer, Vuolo, & Atzberger, 2016; Persson, 2018). They are medium spatial resolution (between 10 and 60 meters) optical earth observation satellites with passive sensors. Their sensor is equipped with 13 spectral bands and they have a revisit time of 5 days at the equator and 3 days closer to the poles (Immitzer et al., 2016). Sentinel data is open and free to use for anyone.

1.2. Study aims and objectives

This study aims to evaluate the feasibility of mapping the state and change of the local Scots pine population in Abisko national park in subarctic Sweden using different remote sensing techniques.

The objectives are the following:

1) To investigate the utility of the vegetation index known as the Normalized Difference Water Index (NDWI) derived from medium spatial resolution Sentinel-2 satellite images for mapping Scots pine in the Abisko valley.
2) To examine the local population of Scots pine in a repeat aerial photo analysis using historical aerial photos to detect a possible range expansion of the local Scots pine habitat in the last half century.
3) To estimate growth in height of the local Scots pine population in the last half century using historical aerial photos and LIDAR data.

2. Materials and methods

2.1. Study area and local ecology

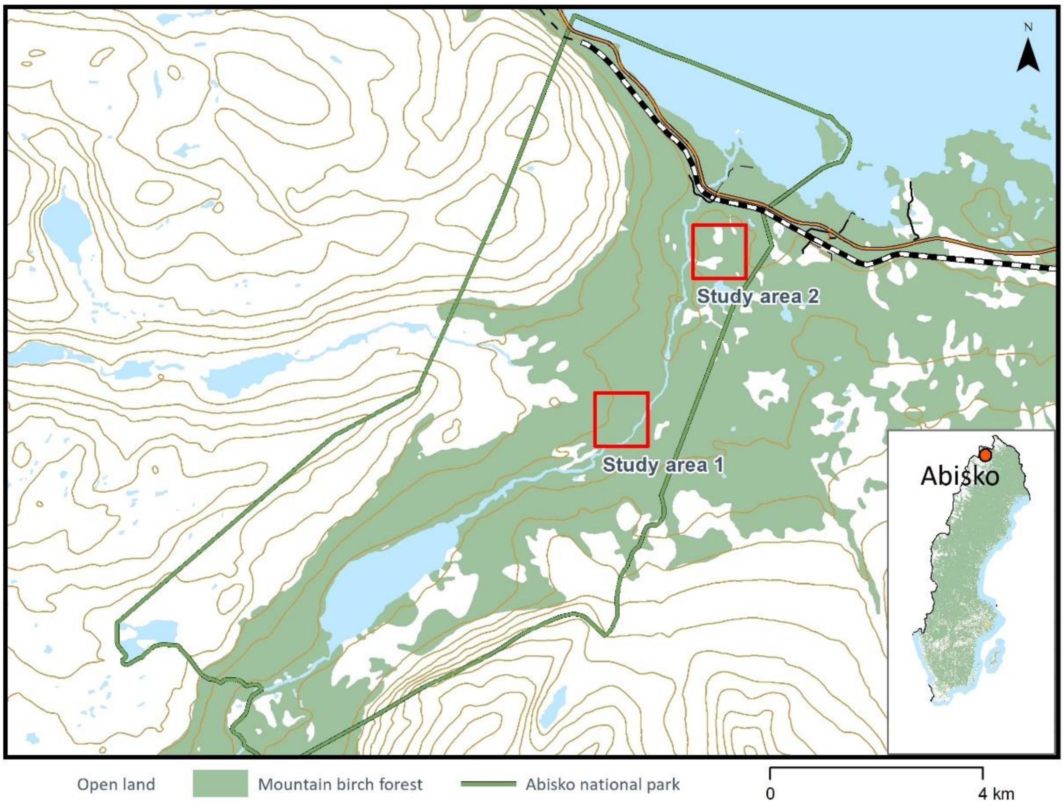


Figure 1 *Map of Abisko national park with Study areas; Background data © (Lantmäteriet, 2019)*

Abisko is located in a mountainous region of Lapland, in northern Sweden. It was designated a national park in 1909 and with the construction of the railroad in the early 2000th century it became popular for tourism and scientific research. Even so, the mountains of northern Lapland are arguably amongst the least exploited areas in the country, making it suitable for climate change related ecology research. The Abisko valley is surrounded by several high mountain peaks which creates rain shadow, making Abisko's climate relatively dry (Barnekow, 1999). The yearly mean temperature is 3°C and the yearly precipitation is ca. 450 mm (SMHI, 2020a).

The ecosystems of the subarctic is categorized into belts based on types on vegetation. This is dependent mainly on elevation and latitudinal position. The alpine zone starts where the boreal forest ends, in northern Lapland at about 400-500 meters of elevation. The lowest part of this zone is the subalpine zone consisting mainly of birch forest. The birch forest line in northern Lapland is at about 600 meters a.s.l. Above this the low alpine zone starts where no trees can grow (Rafstedt, 1984).

The subalpine zone in Abisko consists of mountain birch forest, open wetlands, heaths and meadows. The density and composition of vegetation varies greatly depending on a number of factors such as local micro climate and nutrient and water supply (Rafstedt, 1984). Other than mountain birch a few other tree species exists. These includes Aspen (*Populus tremula*) and Scots pine (*Pinus sylvestris*), both of which grows as individual trees or in small stands in the surrounding birch forest (Rafstedt, 1984; Van Bogaert, Jonasson, De Dapper, & Callaghan, 2010). These species exist mostly in the lower parts of the zone. The ground cover of the subalpine zone consists of rich meadows on nutritious and wet ground and heaths with blueberry (*Vaccinium myrtillus*) and heather (*Calluna vulgaris*) on dryer and less nutritious ground. Scots pine grows mainly on dry ground where it can compete with the more hydrophilic mountain birch (Rafstedt, 1984).

2.2. Data

Doing remote sensing change analysis over half a century is challenging. Remote sensing technology is constantly developing, and older data can be scarce. To study larger time spans at high spatial resolution, aerial photography is one of few data sources. In this project several methods and types of data have been used, including Sentinel-2 satellite data, LIDAR data, aerial photos, and historical research data.

The following data were used

Sentinel-2 satellite data

A Sentinel-2 image (tile number T33WXR) from 2019-06-27 was acquired from earthexplorer.usgs.gov. Sentinel-2 data have a spatial resolution of 10 to 60 meters depending on spectral band. It was corrected to the L1C level. A single tile is 10 000km^2 in size and was projected to the UTM/WGS84 coordinate system. In this study band 8 and band 11 were used. Band 8 is a near infrared (NIR) band with a resolution of 10 meters and band 11 is a short-wave infrared (SWIR) band with a resolution of 20 meters.

Light detection and ranging (LIDAR) imagery

LIDAR point cloud data with sensing date 2015-09-08 were acquired from Lantmäteriet using the Swedish agricultural university’s geodata extraction tool (maps.slu.se). Its coverage includes all of Sweden and it can be used to measure vegetation height and density with great accuracy.

LIDAR is an active sensing system sending out laser pulses and then recording the time of travel for the returned pulse. Aircraft based LIDAR systems have become a common means for mapping topography as well as objects on the Earth´s surface. Because of its ability to create both digital terrain models as well as information about vegetation height and density, it is now also a vital component in forestry and ecosystem studies. Its high spatial accuracy makes it a good instrument for determining spatial coordinates for individual tree-canopies (Koukoulas & Blackburn, 2005; Pascual, García-Abril, Cohen, & Martín-Fernández, 2010; Reese, Nyström, Nordkvist, & Olsson, 2014).

Nationella marktäckedata (NMD) from 2017

NMD is a raster dataset with information about vegetation type and is produced by Naturvårdsverket. It is produced from among other sources Sentinel-2 data from ca 2017 and the national LIDAR data. The ungeneralised version was used which has a spatial resolution of 10 meters and this version was projected to the UTM/WGS84 coordinate system.

Aerial photography

To investigate changes in the pine population, an aerial photograph from 1959 was compared with one from 2018. These photos are produced by Lantmäteriet and were downloaded from Swedish agricultural university (SLU's) data extraction tool. They were both orthorectified and the spatial distortion between them was determined to be insignificant for this purpose.

Table 1 Photographs used for analysis of repeat aerial photography

	Sensing date	Resolution (m)	Bands
Aerial Photo 1	September 9, 2018	0.5*0.5	RGB and NIR
Aerial Photo 2	September 23, 1959	0.5*0.5	Grey scale

2.3. Mapping of Scots pine population using Sentinel-2 derived NDWI

Finding and classifying single trees with remote sensing is challenging. To differentiate tree species a sensor with high spectral resolution is needed. Therefore, satellite data are generally better suited than aerial photography. Satellite data is also available for most parts of the world with a high temporal resolution. The Sentinel-2 satellite data offer these advantages. However, with a spatial resolution of 10 to 60 meters it is not ideal for finding single tree canopies. With Sentinel-2 data it is however possible to estimate the fraction of different vegetation types per pixel (Karlson et al., 2015).

2.3.1. Data pre-processing

Normalized difference water index (NDWI)

The normalized difference water index (NDWI) is a remote sensing index that indicates the water content in vegetation. The NDWI has values ranging from -1 to 1, where -1 represents no water content and 1 represents a water content close to 100 percent, for example a lake or a snow patch. It uses the near infrared (NIR) and shortwave infrared (SWIR) spectral bands. Both bands are situated in a wavelength area where vegetation leaf reflectance is high. Therefore, differences between vegetation with a high water content and vegetation with a low water content will be accentuated (Gao, 1996). NDWI was introduced in 1996 and is used in a variety of applications where estimating water content is important. This can be everything from irrigation monitoring to forest fire hazard evaluation. NDWI can also be used for estimating above ground biomass and canopy coverage (Karlson et al., 2015). NDWI can also be used to differentiate between tree species since their canopies have different water contents and fluctuates to varying degree depending on species (Gao, 1996). Since Scots pine and the surrounding birch forest have very different water content, the NDWI value can be expected to be affected by the presence of Scots pine. This is true even if a pixel contains both Scots pine and other species.

An NDWI index was calculated from the Sentinel-2 dataset using the raster calculator in Arc map. First, the SWIR band had to be resampled from 20 to 10 meters spatial resolution and then NDWI calculated with the near infrared (NIR) and the short-wave infrared (SWIR) bands as seen in Equation 1.

$$NDWI = \frac{NIR - SWIR}{NIR + SWIR} \quad (1)$$

In the NDWI dataset, pixels containing other groundcover than forest were clipped. Clipping was done using NMD as a mask with the Arc map tool clip by mask. Since NMD is produced partly from

Sentinel-2 data it has the same resolution and pixel alignment as Sentinel-2 data. Deleting all pixels except the ones containing forest meant that potential sources of false readings were removed.

LIDAR data processing

The LIDAR data were processed in ArcMap into two datasets, a canopy height model (CHM) and a canopy density model (CDM). The CHM was processed to result in a raster dataset with a spatial resolution of $1m^2$ that describes the maximum vegetation height per pixel in meters. The CDM was processed to result in a raster dataset with a spatial resolution of $10m^2$ and had the same geolocational alignment as the NDWI dataset (i.e., so that pixels were spatially aligned). The CDM describes the vegetation density with pixel values ranging from 0 to 1, where 0 represents the lowest vegetation density of the dataset, in this case bare rock and bodies of water, and 1 represents the highest vegetation density of the dataset.

2.3.2. Delineating of canopies

Reference data regarding the percent of Scots pine present per Sentinel pixel was needed as training data for the regression model. For obtaining this information, and for identifying the Scots pine canopies, the LIDAR-derived CHM was used. Since fully grown Scots pines are taller than mountain birch forest, the pine trees could be spotted with great accuracy (Figure 2). Another reason for choosing a CHM over a high-resolution aerial photo was that the CHM has less spatial distortion (Magnusson et al., 2007; Okeke, 2010). The contours of the pine canopies were manually delineated in ArcMap, resulting in a polygon dataset.

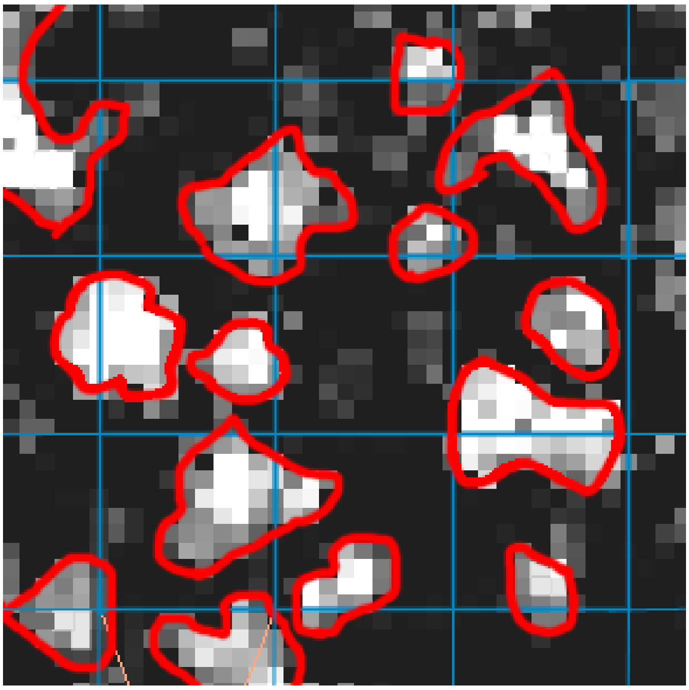


Figure 2 Grayscale CHM raster with delineated Scots pine canopies in red. $10m^2$ Sentinel-2 pixel-outlines in blue.

To create a training data set as input to the regression, it was then calculated how much pine-canopy cover occurred within each Sentinel-2 pixel it overlapped with. Two sets of training data were defined, one made with pixels containing only pine trees and bare ground, and another containing a mix of pine trees and birch. This division into two sets was necessary since pixels containing a mix of birch and pine tended to have a dominant spectral signal from birch and therefore the NDWI values will be different from pixels containing Scots pine only.

A training data set was created with each point representing a Sentinel-2 pixel. Each point held information about the NDWI value as well as the pixel's pine and birch canopy coverage. Points that had a pine tree crown coverage less than 10 percent were excluded since other vegetation types than Scots pine will dominate the NDWI value in these pixels. The attribute tables of these two layers were then imported to Microsoft Excel.

2.3.3. Regression analysis

Two regression analyses were done. One that describes the relationship between Scots pine coverage and NDWI value when the pixel also contains birch, and one equation that describes the relationship between Scots pine and NDWI value when the pixel contained no birch.

Once a regression equation was obtained, it was applied to the entire NDWI raster (which had been masked to only have pixels representing forest) using Arc map raster calculator. By analysing the regression equation, it was estimated that pixels with a NDWI value lower than 0.25 should contain Scots pine. By masking away every pixel with NDWI > 0.25, a map of the Scots pine population was created. The value 0.25 was chosen since my estimation was that this gave the best balance between including false pine tree identifications and excluding actual pine trees.

This raster was then generalized with a majority filter tool to eliminate single pine tree pixels since these often were false readings. The resulting raster was then compared with the CDM. Using the CDM, pixels with a vegetation density value lower than 0.3 were masked away since these pixels often give low NDWI values but do not contain Scots pine. Scots pine however, gives low NDWI values while having high vegetation density. The final map (Figure 7) was compared to aerial photographs to evaluate the method accuracy used here for mapping Scots pine.

2.4. Repeat aerial photography (1959 – 2018) change analysis of Scots pine habitat

Two 1 km^2 square study areas were identified in areas where the NDWI analysis predicted the presence of Scots pines. Square 1 was placed far inside the national park on the frontier of the Scots pine habitat (Figure 1). This location was chosen to investigate whether pine might be advancing to higher elevations. Square 2 was placed in lower terrain where it could be studied if the Scots pine population were advancing on this lower elevation and supposedly warmer climate.

Aerial Photo 1 from 2018 (see Table 1) was used to manually identify all individual pine trees inside the study areas. The dark colour of the pine trees was easy to spot against the lighter birch forest. The CHM made from LIDAR data was also useful in unclear cases, and LIDAR point clouds were also used.

To obtain a variety of tree sizes, all trees were considered, and none excluded on the basis of tree height. Every clearly detectable pine tree was marked with a red symbol. The geographic data layer with pine tree locations was then placed on top of aerial Photo 2 (1959). The tree locations were examined to determine if the pine trees could be spotted in Photo 2. Pine trees that could not be spotted on Photo 2 were marked with a different colour than the others (Figure 3).

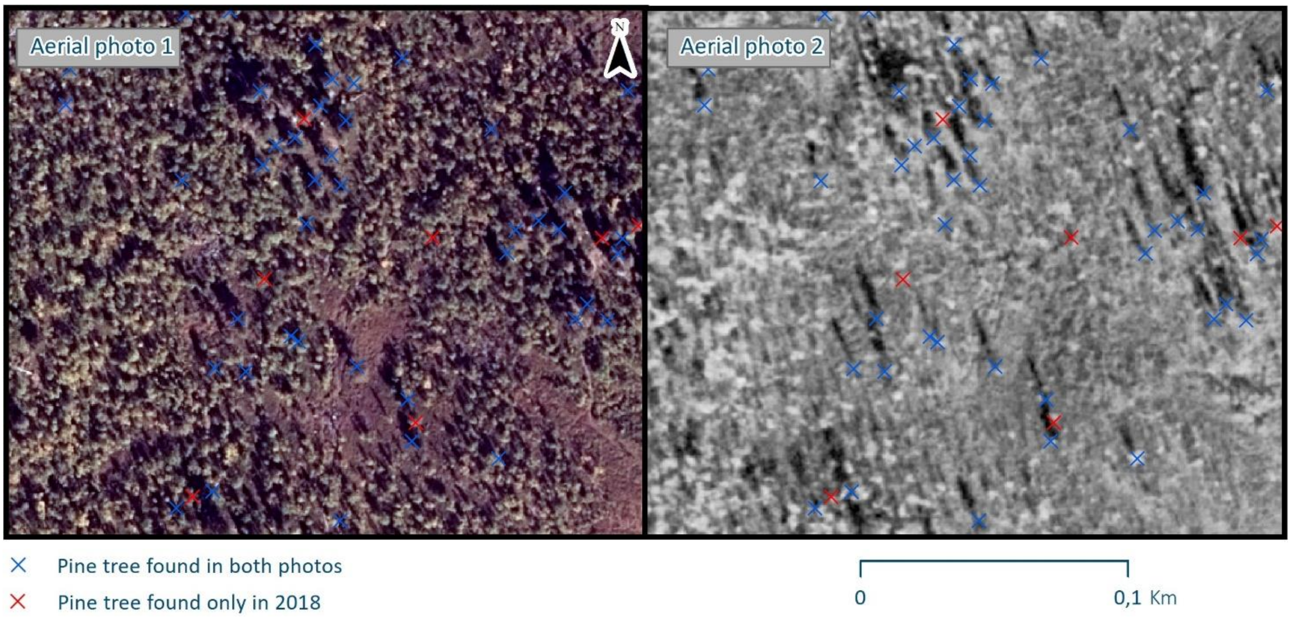


Figure 3 *Cut out from study area 1*
a) Aerial photo 1 (2018) as background
b) Aerial photo 2 (1959) as background

2.5. Estimation of growth in height between 1959 and 2015 of the local Scots pine population using historical aerial photos and LIDAR

With the help of a digital elevation model (DEM) combined with orthophotos, twenty pine trees that were located on flat ground and that had no tall vegetation growing around them were selected. Their shadows were measured in Photo 2 (1959) from approximately the centre of the tree's canopy to the end of the shadow cast by the tree (Figure 4), using ArcMap.

The time and date of the photograph was needed in order to determine the sun elevation angle, and was obtained from the photograph's metadata. The sun elevation angle was calculated with a sun angle and azimuth calculator (Agafonkin, 2009). With the sun elevation information, the tree height could be calculated (Eq. 2).

$$Tree\ height = \left(Tan(sun\ elevation\ angle°)\right) * length\ of\ shadow \qquad (2)$$

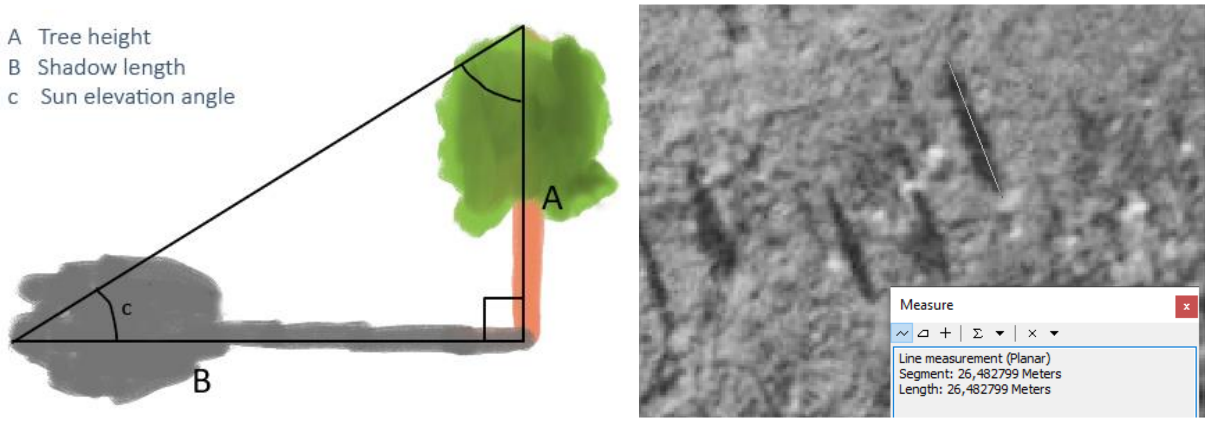


Figure 4 *a) Description of how tree height is calculated from shadow length*
b) Screen shot of measurement of Pine tree-shadow in Photo 2 (from 1959) in ArcMap.

The tree heights were then compared to LIDAR point cloud data from 2015 to determine if the trees had grown taller in the 56year period (1959-2015). Measurements in the LIDAR point cloud were conducted with the ArcMap LAS dataset profile view tool (Figure 5).

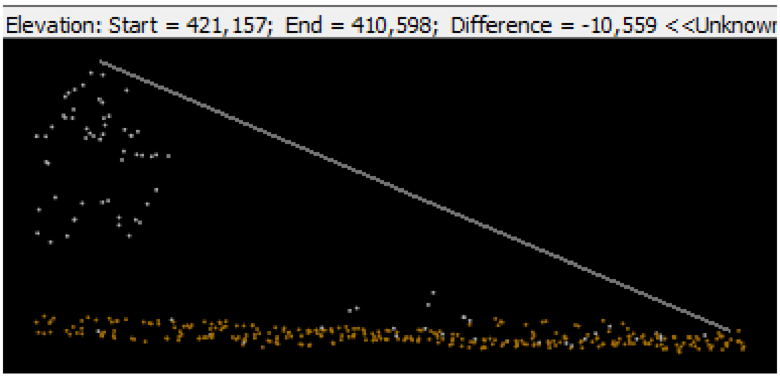
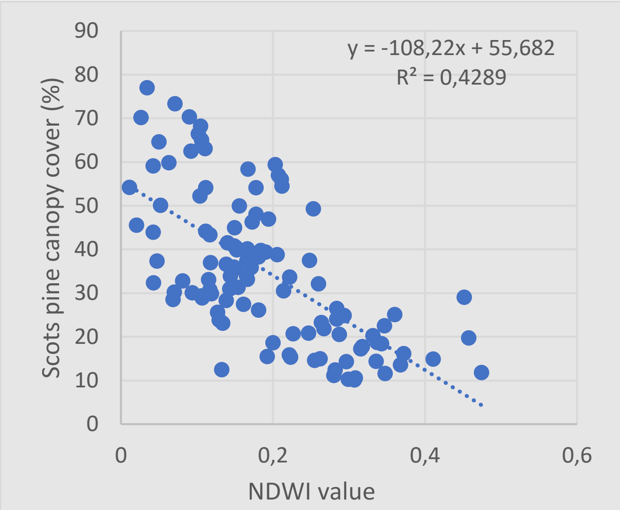


Figure 5 *Screen shot of pine tree height measurement using LIDAR point cloud data in ArcMap LAS dataset profile view*

3. Results

3.1. Mapping of Scots pine population using Sentinel-2 derived NDWI

The regression analysis of the NDWI shows a marked difference between pixels containing Scots pine and pixels consisting of only birch forest (Figure 6a). A significant correlation (r=0.65, p=1.26*10^{-14}) between pixel-wise values of NDWI and percent of Scots pine canopy per pixel was found. A significant correlation (r=0.65, p=0.83*10^{-8}) was also discovered between NDWI and pixels containing both pine and birch forest and pixels containing only birch forest (Figure 6b). A comparison of the two regression analyses shows that the average NDWI value for pixels containing pine and birch generally is higher than for pixels containing only pine. The correlation between pine tree crown coverage and NDWI value is however very similar regardless of whether birch is present or not.



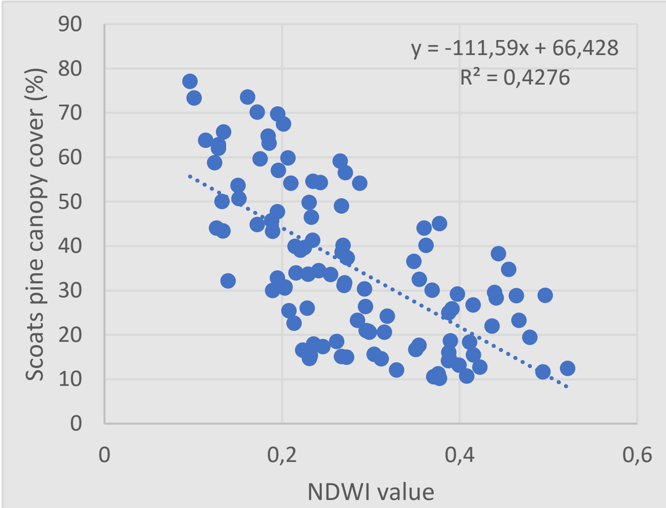


Figure 6 *Regression analysis between NDWI value and Scots pine canopy cover*
a) Pixels containing only Scots pine
b) Pixels containing Pine and Birch

The result of applying the regression equation for percent Scots pine only, to the whole NDWI raster, is a map of the Scots pine population in Abisko national park (Figure 7a). The comparison of the result to the high-resolution aerial photo (Fig 7b-c) gives an indication that the mapping of the Scots pine stands is accurate.

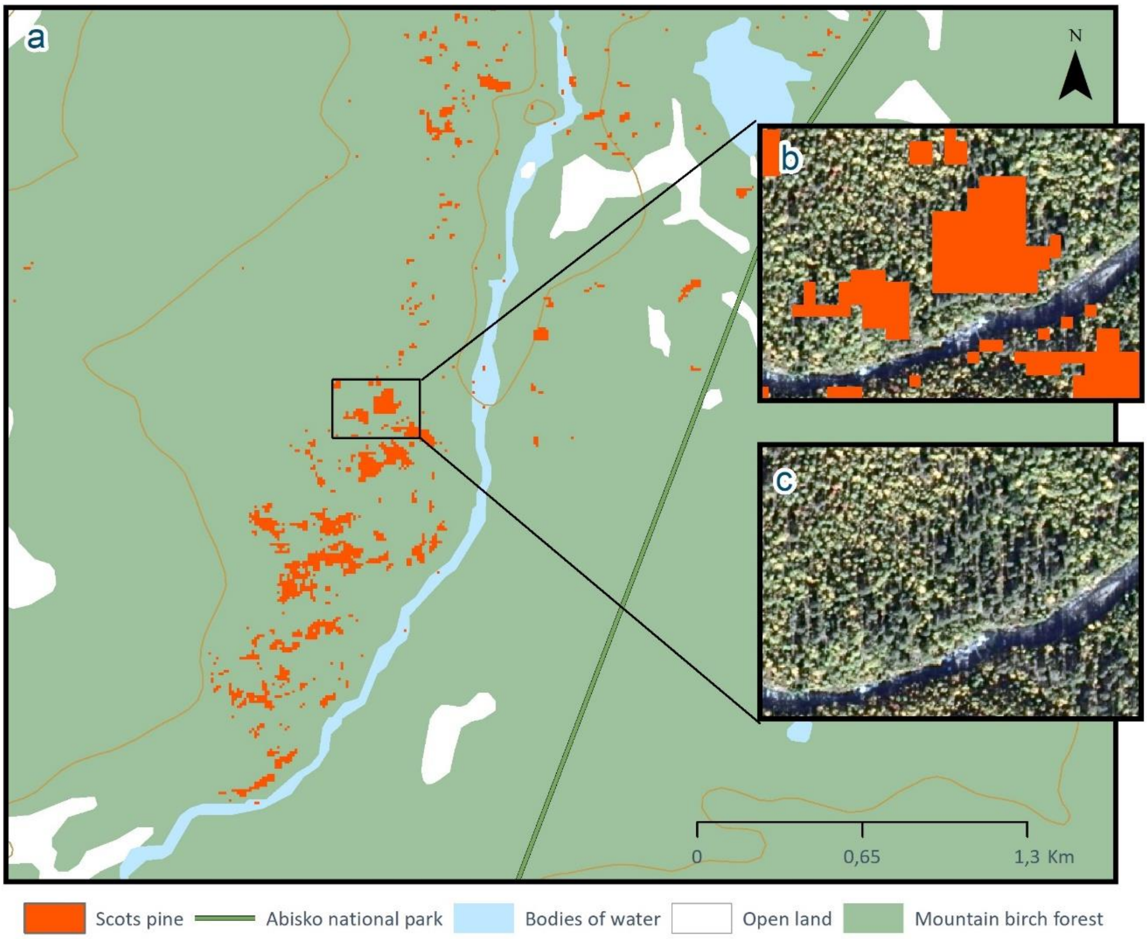


Figure 7. a) Map of the Scots pine population in Abisko national park created from NDWI index
b & c) Comparison between NDWI based mapping (b) and aerial photo of Scots pine stand (c)
Background © (Lantmäteriet)

3.2. Repeat aerial photography (1959 – 2018) change analysis of Scots pine habitat

The repeat aerial photography analysis found an increase in the quantity of Scots pine in both study area 1 and study area 2 (Table 2). In area 1 the total tree count in photo 1 (2018) was 240 while it was 221 in photo 2 (1959). In area 2, 41 trees were marked in Photo 1 and 31 were found in Photo 2. The increase is mostly confined to already established Scots pine stands (Figure 8; 9)

Table 2 Result of tree count in the two study areas

	Photo 1 (2018)	Photo 2 (1959)	Change	Change (%)
Study area 1	240	221	+19	+8.6
Study area 2	41	31	+10	+31

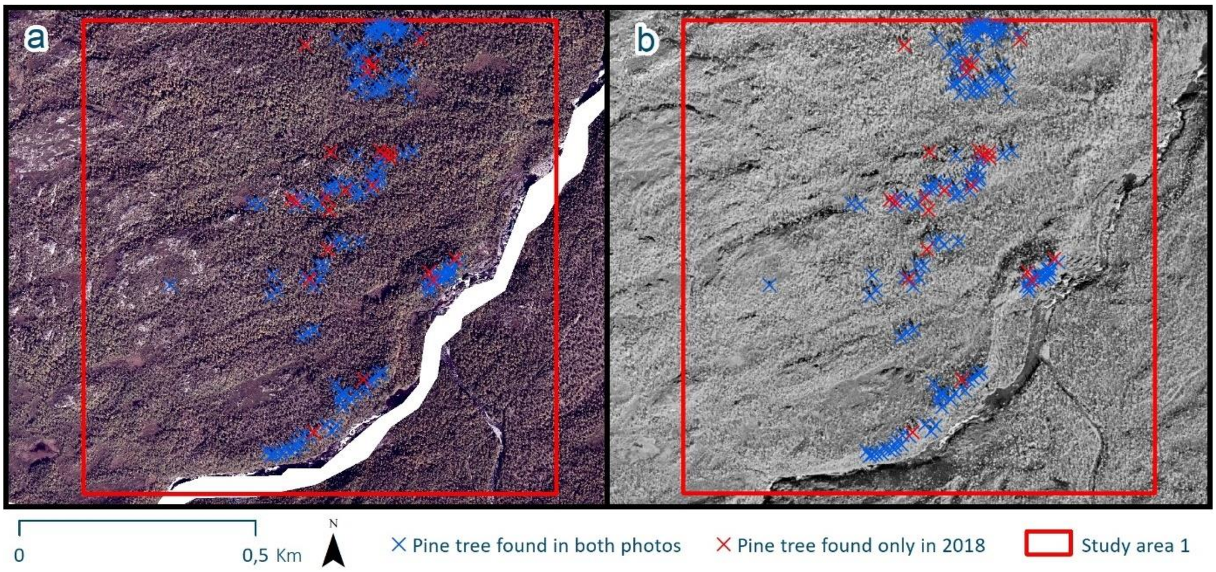


Figure 8 *Pine tree distribution in study area 1 with aerial photo 1 (a) and aerial photo 2 (b) as background. Background © (Lantmäteriet)*

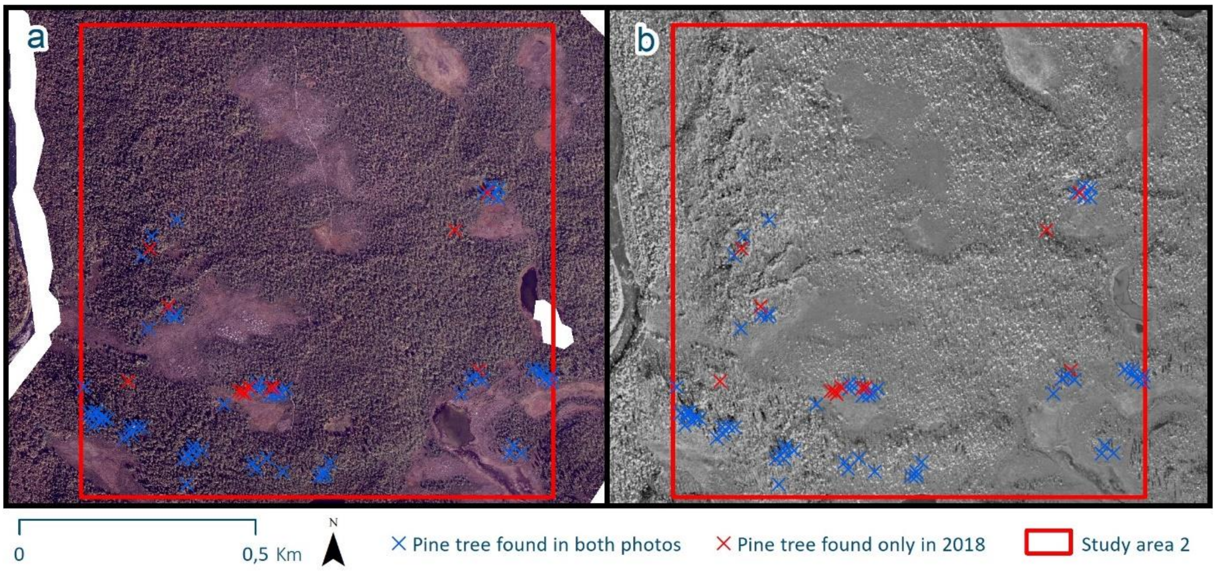


Figure 9 *Pine tree distribution in study area 2 with aerial photo 1 (a) and aerial photo 2 (b) as background. Background © (Lantmäteriet)*

3.3. Estimation of growth in height between 1959 and 2015 of the local Scots pine population using historical aerial photos and LIDAR

The mean measured height difference between 1959 and 2015 is 0.825 meters and the standard deviation is 1.85 meters (Table 3). The median tree height difference is 0.17 meters or 2.03%. The biggest height difference was measured for tree number 4 which is 5.75 meters taller according to the 2015 measurement. The biggest difference in percent is seen in tree nr. 6 which according to the measurements is 37% taller. Tree nr. 11 measured 1.12 meters lower in 2015 than in 1959 and four of the other trees also show a slightly lower height in 2015 than in 1959.

Table 3 Results of tree height comparison between 1959 and 2015

Tree number	Height 1959 (m)	Height 2015 (m)	Change (m)	Change (%)
1	11.21	11.54	0.33	3.7
2	10.32	10.48	0.16	1.7
3	9.87	10.15	0.28	2.8
4	6.31	12.06	5.75	36.3
5	10.01	9.41	-0.6	-6.0
6	8.33	12.72	4.39	36.6
7	12.82	13.02	0.2	2.6
8	12.54	12.76	0.22	2.8
9	13.2	13.38	0.18	2.4
10	13.14	13.01	-0.13	-1.7
11	12.42	11.3	-1.12	-13.9
12	11.22	11.12	-0.1	-1.1
13	10.23	10.36	0.13	1.3
14	5.32	9.19	3.87	20.6
15	12.32	12.44	0.12	1.5
16	12.89	12.36	-0.53	-6.8
17	9.73	9.19	-0.54	-5.3
18	11.59	11.84	0.25	2.9
19	11.53	11.67	0.14	1.6
20	5.32	8.82	3.5	18.6
Mean	**10.52**	**11.34**	**0.83**	**5.0**
Median	**11.22**	**11.61**	**0.17**	**2.01**
Std. dev.			**1.85**	**12.8**

4. Discussion

A significant correlation between Scots pine presence and NDWI value from Sentinel-2 data was shown. This implies that Sentinel-2 NDWI data can be used for estimating Scots pine range extent in Abisko as well as in other regions. The repeat aerial photo analysis showed an increase in quantity in the Scots pine population. The increase was largely confined to already existing stands. (Table 1). The tree height comparison showed no meaningful changes in tree height.

4.1. Mapping of Scots pine population using Sentinel-2 derived NDWI

The coefficient of determination (R^2=0.429) for the relationship between NDWI and Scots pine canopy cover shows that there is a fairly good relationship that can be used to estimate Scots pine occurrence. The relationship was determined to be significant ($p=1.26*10^{-14}$). When using medium resolution satellite data, other types of vegetation interfering with the signal is typical (Persson, 2018). The mixed spectral reflectance coming from birch forest together with pine in the individual pixels was the main reason for needing two different regression equations, and for the difference between them. The correlation between pine+birch and NDWI ($p=0.83*10^{-8}$), shows that the NDWI value can be used to separate between pine and birch even if birch is present in the pixels.

One possible source of error is if the canopy coverage per pixel in the training data is inaccurate. If the Sentinel-2 data is misaligned with the CHM or if the delineation of the canopies is not accurate, then that would impact the canopy coverage fraction per pixel. A better result could possibly be obtained if the canopy coverage percentage were grouped into several thematic levels. For example, 0% pine, 1-20% pine, 21-50% pine and greater than 50% pine.

The outliers in figure 6 can mainly be attributed to two factors. A high NDWI value can be obtained even with a high pine tree crown cover if the pixel also includes other vegetation. This is especially true in figure 6 b where all pixels contained birch. The low-valued NDWI outliers can mainly be attributed to a sparse total vegetation in the pixel. In these cases, a low pine crown cover may not affect much since the ground around the pine has an equally low NDWI value. This however might not be a big factor in mountain ecosystems since pine trees here tend to grow on open ground where birch forest can't be established (Kullman, 2014). Due to this, the best results might be obtained in dense and homogeneous forests with pine trees scattered within it rather than open forests with mixed in wetlands and open heaths.

With an adequate methodology for excluding sparse birch forest, such as a LIDAR derived canopy density raster can provide, the NDWI analysis can be applied with greater accuracy also in an open and diverse forest. There are also possible methods for improving the accuracy of the results using only Sentinel-2 data. One of the strengths with Sentinel-2 images is the high temporal resolution. This study used a single date image. However, multiple images from different seasons (e.g., late spring, summer and fall) could be utilized to create a regression equation, resulting in a more distinct NDWI profile for Scots pine.

The correlation between pine canopy cover and NDWI value also means that NDWI index should be included if a more extensive mapping of the forest were to be attempted with, for example, a random forest algorithm. The combination of the NDWI raster dataset and other Sentinel-2 spectral bands and multi-temporal image combinations could eliminate the need for LIDAR data for separating between sparce and dense forest(Karlson et al., 2015). This would make the method far more usable since Sentinel-2 data have global coverage and a high temporal resolution (Drusch et al., 2012).

An important part of the results is the validation of the crown cover measurement. Not only NDWI value, but all medium resolution satellite data will be sensitive to containing mixed vegetation types when mapping objects smaller than the pixel size. It is therefore of great significance that the correlation between NDWI pixel value and crown coverage could be established. This has also been successful in other studies where more bands than only the NDWI ratio have been used (Karlson et al., 2015).

After post-processing (generalization and cleaning of false readings using the CDM), the map of Scots pine appeared to be accurate (Figure 7). The comparison with aerial photographs in Figure 7b and c suggests that the mapping corresponds well with the actual Scots pine population. False indications of Scots pine are present in the map in several locations but the large clusters of Scots pine pixels in Figure 7 corresponds well to the pine tree stands.

This method is sensitive to the satellite image dates used. The difference in NDWI value between coniferous and deciduous forest occurs only in the middle of the summer. In this study the method is only applied in a small area and the regression equations developed are, of course, particular for this area. This limits its use somewhat since the regression equation is only applicable to the conditions specific to this Sentinel-2 tile (e.g., image date and sensor settings on this date). But it is worth noting that each full Sentinel-2 image covers an area of 290 x 290 km, consisting of nine 100 x 100 km tiles which are all imaged for the same date. This means it should be possible to apply the regression equation to the larger image area (290 x 290 km) with the same small training data size as in this study.

4.2. Repeat aerial photography (1959 – 2018) change analysis of Scots pine habitat

An increase in Scots pine quantity was found (Table 2). This suggests that some large pine trees have either sprouted between 1959 and 2018 or they had sprouted earlier but have grown enough in height between 1959 and 2018 to only be detected in the latter photo. Kullman (2014) states that in his study, young pine trees grew on average 4 meters over a nearly 40 year period between 1973 and 2012. A tree of that size should be possible to detect by the method used in this study and therefore the time span of 59 years should be enough to detect changes in the population.

The method did not allow for an investigation of the number of trees that had disappeared between 1959 and 2018, because counting trees over large areas without knowing approximately where they should be, is impractical in the lower spatial resolution photo 2 from 1959. However, the disappearance of a pine tree is by no means a sudden event. If a pine tree would have died between 1959 and 2018, it is likely that it would stand as a dead tree for many decades or even centuries, and thereafter lie visible on the ground for many years before the decay is complete (Kullman & Öberg, 2018). Only two dead pine trees were detected in photo 1 and their light grey colour contrasted well to the green surroundings making them easy to detect. This suggests that few pine trees have died in the 59-year time span of the study. Therefore, this aspect was not considered in the result.

As seen in figure 8 and 9, most pine trees detected in Photo 1 (2018) only, are located in close proximity to older existing stands. This is consistent with Kullman's (2014) research, which shows that increase in Scots pine abundancy in mountain forests occurs mostly through infilling in existing stands. Other research such as Bryn (2008) have found a significant increase in Scots pine range extent in recent years in a similar biome in Norway. However, Kullman's study is probably the most extensive one on this topic.

The increase in Scots pine is greater in study area 2 (34%) than in study area 1 (9%). One possible contributing factor to this is that study area 2 is located at lower elevation and therefore supposedly has a warmer climate. As mentioned in the introduction Scots pine have however been shown to be able to sprout and grow to trees at elevations above the forest tundra ecotone if planted there, although to a lesser extent than at lower elevations (Wahlberg, 2009). It is also noteworthy that although Abisko is a national park, protected from human exploitation, many different anthropogenic activities have taken place here during the last centuries. From the 18th century and onwards to the founding of the national park in 1909, the Scots pine population was diminished as a consequence of cutting, both for fire wood and for construction material (Emanuelsson, 1987; Van Bogaert et al., 2011). The large reindeer herds of the early twentieth century probably also had a negative effect on the pine tree population, both through grazing of pine sprouts, and also by rubbing their antlers against young pine tree individuals causing mechanical damage (Kullman, 2014). Therefore, the increase in the number of Scots pine trees might not only be a consequence of a warmer climate, but also a consequence of a decrease in anthropogenic disturbances in the last hundred years.

If there has been an expansion of the Scots pine habitat, it is not great enough to be detected in this study. The Scots pine have become a more prominent species in in the landscape close to the forest limit through infilling, but no significant range expansion has taken place. Since this is in line with the recent notion of a disequilibrium between forest range extent and climate change (Kullman, 2014; Rees et al., 2020), the conclusion should be that although new trees have sprouted in proximity to established Scots pine stands in Abisko, this study is probably accurate in stating that expansion of the habitat in the past half century has been small.

4.3. Estimation of growth in height between 1959 and 2015 of the local Scots pine population using historical aerial photos and LIDAR

The results shows an increase in mean tree growth by 0.83 meters between 1959 and 2015 (Table 3). The median growth is however only 0.17 meters, suggesting that outliers have a big effect on the mean. According to the results trees number 4 and 6 have grown 5.75 and 4.39 meters respectively, while most other trees have grown less than one meter. Five trees showed a lower height reading in 2015 than in 1959.

These results are not surprising since Scots pine grows rapidly the first decades of their lives after which the growth in height stagnates (Kultti et al., 2006). Many of the pine trees in the Abisko region are over 300 years old (Emanuelsson, 1987), and they have therefore ceased to grow in height.

The aerial photo from 1959 is produced with older equipment and the grain size of the film is unknown. It has thereafter been digitalized with a pixel size of 0.5 meters. This process can distort the photo somewhat making measurements of shadows less accurate (Avery, 1978). The LIDAR measurements, although very accurate in theory, also have some weaknesses. The mean point spacing in Lantmäteriets LIDAR data is one meter and in mountainous areas often greater since the sensing altitude must be increased. This means that the pulse can miss the highest point of the canopies (Magnusson et al., 2007). The negative readings could be explained by any of the errors mentioned above. It could also be that some trees have had their tops broken. Most had however only minor negative readings, which could be inside the margin of error for this method. The probability that most trees had about the same height in 2015 as in 1959 is high. In the results only tree nr 11 showed a markedly shorter height measurement in 2015 compared to 1959. This tree has a greater probability of having had its top broken.

The results of this part of the study were not unexpected considering the Scots pines' life cycle of rapid initial growth that later in life stagnates. Trees that shows a small height difference are probably old, while the once that showed a greater height difference probably are younger. The overall similarities between the results from the old and new measurements does however indicate that this method of comparison is valid and accurate.

5. Conclusion

NDWI analysis of Sentinel-2 images proved to be a valid method for estimating the spatial extent of the Scots pine population in Abisko. The successful mapping is, according to the author, the main achievement of the study. It is also fairly easy to validate its accuracy and the precision is higher than for the other parts of the study. To apply the method to a full-size Sentinel-2 image would create a map a large portion of the Scots pine population in subarctic Lapland. The map could be used in future studies, possibly together with dendrochronology for investigating past range expansion in the Abisko valley. Applying the method to other species such as Aspen is also a possible subject for future research.

The Scots pine habitat have not increased much in extent. However, Scots pine have become more abundant in the region through infilling in already existing stands. The change analysis of aerial photos proved to be a useful methodology. 59 years is however a short time in the life of a pine tree and the 1959 aerial photos will be available for future research over a longer time span.

The comparison of tree height showed that in general the trees had similar height in 1959 as in 2015, indicating that most of them are at least half a century old. This was not surprising, given the Scots pines' long lifetime. The methodology is however useful for future research.

6. References

Agafonkin, V. (2009). Suncalc online sun-angle calculator. Retrieved from https://www.suncalc.org/

Avery, T. E. (1978). *Forester´s guide to aerial photo interpretation*. Washington D.C.: US Department of Agriculture.

Barnekow, L. (1999). Holocene tree-line dynamics and inferred climatic changes in the Abisko area, northern Sweden, based on macrofossil and pollen records. *The Holocene, 9*(3), 253-265. doi:10.1191/095968399676322637

Bryn, A. (2008). Recent forest limit changes in south-east Norway: Effects of climate change or regrowth after abandoned utilisation? *Norsk Geografisk Tidsskrift - Norwegian Journal of Geography, 62*(4), 251-270. doi:10.1080/00291950802517551

Drusch, M., Del Bello, U., Carlier, S., Colin, O., Fernandez, V., Gascon, F., . . . Bargellini, P. (2012). Sentinel-2: ESA's Optical High-Resolution Mission for GMES Operational Services. *Remote Sensing of Environment, 120*, 25-36. doi:10.1016/j.rse.2011.11.026

Emanuelsson, U. (1987). Human influence on vegetation in the Torneträsk area during the last three centuries. *Ecological Bulletins, 38*, 95-111. Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:polar:diva-7330

Grudd, H. (2008). Torneträsk tree-ring width and density ad 500–2004: a test of climatic sensitivity and a new 1500-year reconstruction of north Fennoscandian summers. *Climate Dynamics, 31*(7-8), 843-857. doi:10.1007/s00382-007-0358-2

Hedenås, H., Christensen, P., & Svensson, J. (2016). Changes in vegetation cover and composition in the Swedish mountain region. *Environmental Monitoring and Assessment, 188*(8), 1-15. doi:10.1007/s10661-016-5457-2

Immitzer, M., Vuolo, F., & Atzberger, C. (2016). First Experience with Sentinel-2 Data for Crop and Tree Species Classifications in Central Europe. *Remote Sensing, 8*(3), 166. doi:10.3390/rs8030166

IPCC. (2019). *Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. Retrieved from

Karlson, M., Ostwald, M., Reese, H., Sanou, J., Tankoano, B., & Mattsson, E. (2015). Mapping Tree Canopy Cover and Aboveground Biomass in Sudano-Sahelian Woodlands Using Landsat 8 and Random Forest. *Remote Sensing, 2015, Vol. 7, Iss. 8, pp. 10017-.10041, 7*(8), 10017-10041.

Koukoulas, S., & Blackburn, G. A. (2005). Mapping individual tree location, height and species in broadleaved deciduous forest using airborne LIDAR and multi-spectral remotely sensed data. *International Journal of Remote Sensing, 26*(3), 431-455. doi:10.1080/0143116042000298289

Kullman, L. (2007). Tree line population monitoring of Pinus sylvestris in the Swedish Scandes, 1973-2005: implications for tree line theory and climate change ecology.(Author abstract). *The Journal of Ecology, 95*(1), 41. doi:10.1111/j.1365-2745.2006.01190.x

Kullman, L. (2014). Treeline (Pinus sylvestris) landscape evolution in the Swedish Scandes - a 40-year demographic effort viewed in a broader temporal context. *Norsk Geografisk Tidsskrift - Norwegian Journal of Geography, 68*(3), 155-167. doi:10.1080/00291951.2014.904402

Kullman, L., & Kjällgren, L. (2006). Holocene pine tree-line evolution in the Swedish Scandes: Recent tree-line rise and climate change in a long-term perspective. *Boreas, 35*(1), 159-168. doi:10.1111/j.1502-3885.2006.tb01119.x

Kullman, L., & Öberg, L. (2018). *Fjällens tallar : och klimatet under 10 000 år*. Stockholm: BoD - Books on Demand.

Kultti, S., Mikkola, K., Virtanenj, T., Timonen, M., & Eronen, M. (2006). Past changes in the Scots pine forest line and climate in Finnish Lapland: a study based on megafossils, lake sediments, and GIS-based vegetation and climate data. *The Holocene, 16*(3), 381-391. doi:10.1191/0959683606hl934rp

Lantmäteriet (Cartographer). (2019). Vägkartan

Magnusson, M., Fransson, J. E. S., & Holmgren, J. (2007). Effects on estimation accuracy of forest variables using different pulse density of laser data. *Forest Science, 53*(6), pp. 619-626. doi:10.1093/forestscience/53.6.619

Okeke, F. (2010). Review of Digital Image Orthorectification Techniques. *Geospatial world*(7 -2010).

Pascual, C., García-Abril, A., Cohen, W. B., & Martín-Fernández, S. (2010). Relationship between LiDAR-derived forest canopy height and Landsat images. *International Journal of Remote Sensing: SilviLaser 2008, 31*(5), 1261-1280. doi:10.1080/01431160903380656

Persson, M. (2018). *Tree species classification using multi-temporal Sentinel-2 data.* (Master Master thesis). Swedish university of agricultural sciences, Umeå.

Rafstedt, T. (1984). *Fjällens vegetation = Vegetation of the Swedish mountain area*. Solna : Stockholm: Solna : Statens naturvårdsverk

Stockholm : Naturgeografiska inst., Univ. : Liber distribution.

Rees, G., Hofgaard, A., Boudreau, S., Cairns, D., Harper, K., Mamet, S., . . . Tutubalina, O. (2020). Is subarctic forest advance able to keep pace with climate change? *Global Change Biology*. doi:10.1111/gcb.15113

Reese, H., Nyström, M., Nordkvist, K., & Olsson, H. (2014). Combining airborne laser scanning data and optical satellite data for classification of alpine vegetation. *International Journal Of Applied Earth Observation And Geoinformation, 27*(Special issue, part A), 81-90. doi:10.1016/j.jag.2013.05.003

Rundqvist, S., Hedenås, H., Sandström, A., Emanuelsson, U., Eriksson, H., Jonasson, C., & Callaghan, T. (2011). Tree and Shrub Expansion Over the Past 34 Years at the Tree-Line Near Abisko, Sweden. *AMBIO, 40*(6), 683-692. doi:10.1007/s13280-011-0174-0

SMHI. (2020a). Normal uppmätt årsnederbörd, medelvärde 1961-1990. Retrieved from http://www.smhi.se/data/meteorologi/nederbord/normal-uppmatt-arsnederbord-medelvarde-1961-1990-1.4160

SMHI. (2020b). Sveriges klimat. Retrieved from https://www.smhi.se/kunskapsbanken/klimat/sveriges-klimat-1.6867

Sturm, M., Racine, C., & Tape, K. (2001). Climate change: Increasing shrub abundance in the Arctic. *Nature, 411*(6837), 546. doi:10.1038/35079180

Symon, C., Arris, L., Heal, B., International Arctic Science, C., & Arctic, C. (2005). *Arctic climate impact assessment : ACIA*. Cambridge: Cambridge : Cambridge University Press.

Wahlberg, S. (2009). *Kan herbivorer begränsa fröetablering av fjällbjörk, tall, gran och sibirisk lärk i norra Fennoskandien? .* (Master). Umeå university, Umeå.

Van Bogaert, R., Haneca, K., Hoogesteger, J., Jonasson, C., De Dapper, M., & Callaghan, T. V. (2011). A century of tree line changes in sub-Arctic Sweden shows local and regional variability and only a minor influence of 20th century climate warming.(Report). *Journal of Biogeography, 38*(5), 907.

Van Bogaert, R., Jonasson, C., De Dapper, M., & Callaghan, T. V. (2010). Range Expansion of Thermophilic Aspen (Populus tremula L.) in the Swedish Subarctic. *Arctic, Antarctic, and Alpine Research, 42*(3), 362-375. doi:10.1657/1938-4246-42.3.362

Appendix

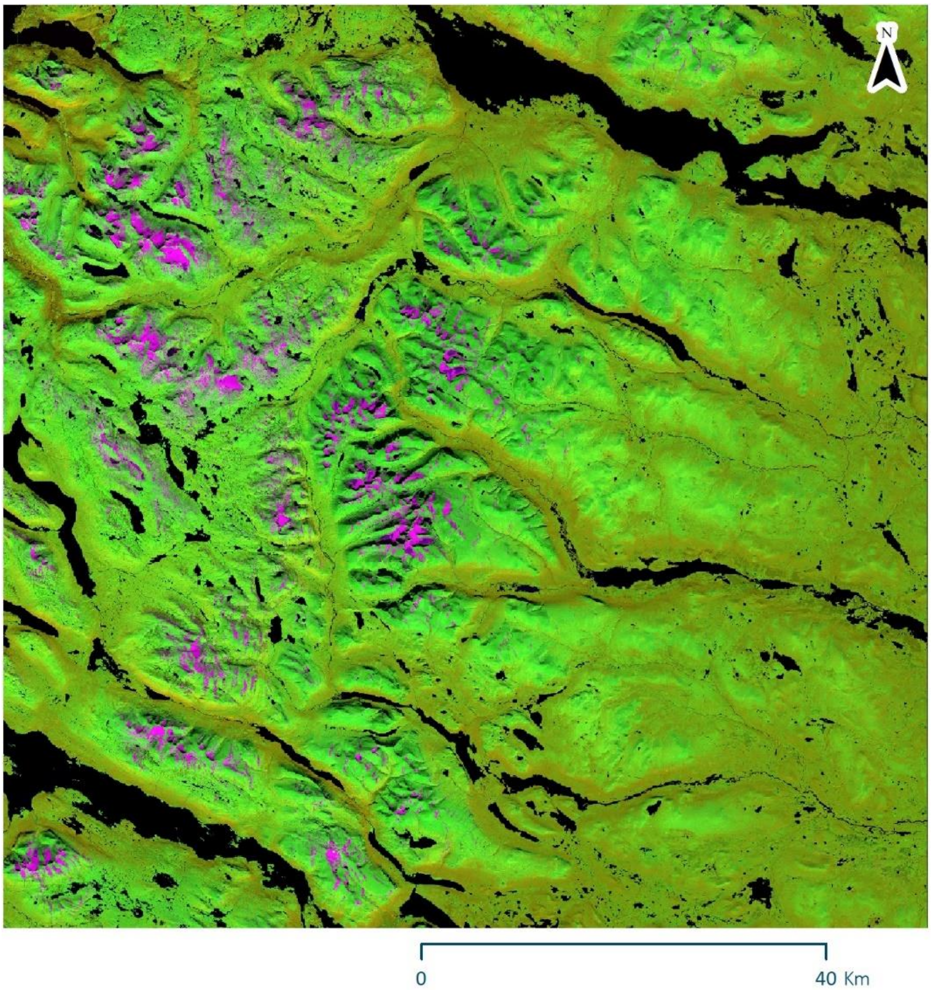


Figure 1 Sentinel-2 tile number T33WXR, NIR, SWIR and RED bands, showed as RGB

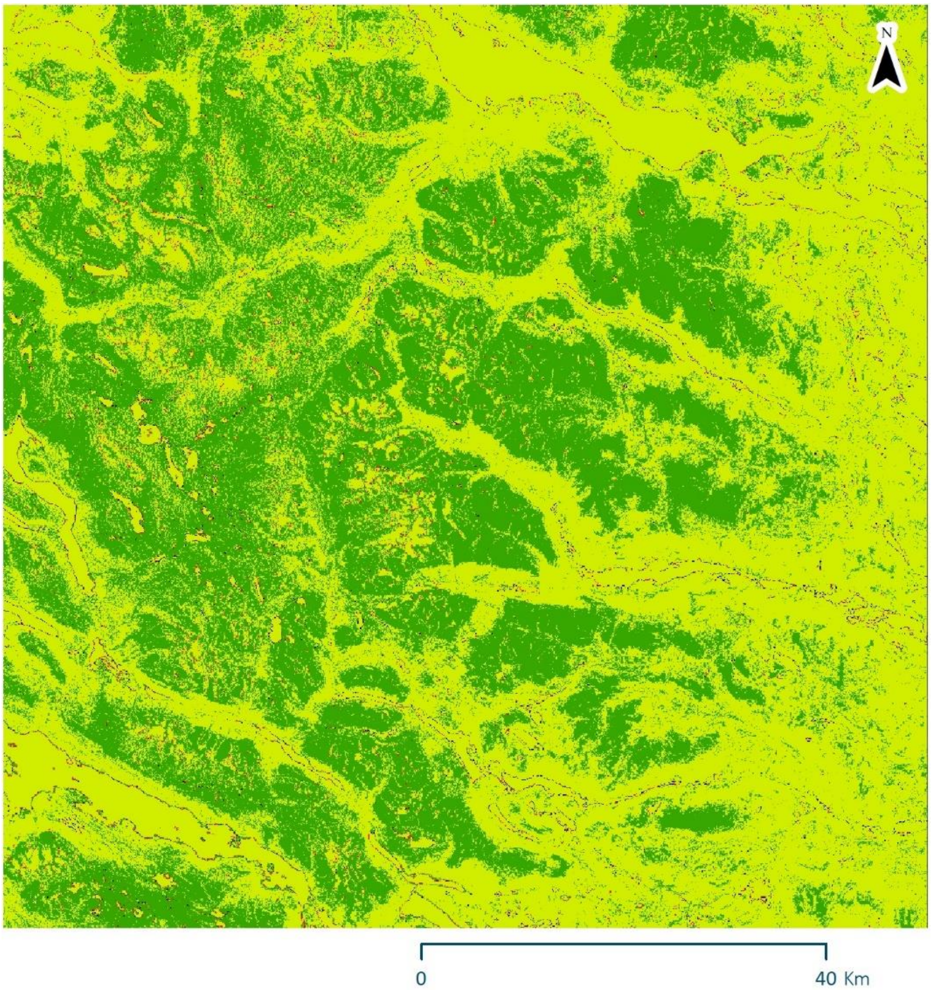


Figure 2 NDWI image of Sentinel-2 tile T33WXR