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Vegetation cover change on Tindfjöll mountains, Iceland, assessed by aerial photographs, topography, and climate

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Master thesis, 30 credits, in *environmental changes at higher latitudes (EnCHiL)*

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Abstract

Climate change is having a great impact on the fragile High Latitude environment where warming is occurring at a rate at least double the global average. It is urgent to understand the relationship between climate and vegetation cover, which is playing an important role, as a carbon sink, for biodiversity, and for protecting against natural hazards. Less studied but equally important is to understand how mountain areas are responding to climate warming and how topography; elevation, aspect, and slope are affecting vegetation distribution and dynamics. This study focuses on Tindfjöll mountain, Iceland, and compares two transects representing two different aspects (one south facing and one west facing) between the years 2004 and 2019. The results show that vegetation coverage has increased in both areas while for the same period climate warming has been approximately 1°C. This is especially significant for the vegetation class moss heath. The classes glacier and sand/gravel have on the other hand retreated. The south facing transect has shown more significant increase and the vegetation line in the same area has ascended about 150 m during the study period. These results indicate that not only climate is having a significant impact on vegetation production but also topography; elevation, aspect, and slope is creating a microclimate which highly affects vegetation growth. The most important factor is temperature with higher summer temperature and prolonged growing season while warmer winters lead to less protecting snow cover. Aspect and incoming solar radiation are also a strong influencing factor as south facing slopes (more incoming solar radiation) are showing much stronger vegetation responses than west facing slopes. The findings indicate that similar changes might be occurring in other arctic areas which requires further investigation.

***Keywords**: Environmental changes, High Latitudes, vegetation cover, vegetation change, climate change, topography, GIS.*

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1. Introduction

The Arctic is warming at a rate two times the global average, and the warming in Iceland during the period 1980 – 2015 has been reported 0.47°C per decade (Björnsson et al., 2018). Consequently, changes in the natural environment emerge in loss of ice cover and changes in vegetation (IPCC, 2013; AMAP, 2017; Bring et al., 2016; Björnsson et al., 2018). Climate is one of the major factors affecting the temporal vegetation development in the Arctic, where the range of maximum and minimum temperatures is the most prominent factor and delimitating the growing season, yet prolonged growing seasons are the largest contribution to increased biomass production (Hatfield and Prueger, 2015; Kreyling et el., 2019). Topoclimate is controlled by the topographic elements; elevation, slope angle and aspect, where temperature decreases with altitude and south facing slopes receive more solar radiation than north facing slopes. As a result, there are spatial variations in climate with uneven length of growing seasons (Böhner and Antonić, 2009).

Vegetation cover in mountain environments is an important component of the ecosystem and plays a vital role in preventing erosion as well as protection against natural hazards such as landslides, rockfall and surface water flow (Brang et al., 2001; Arnalds, 1987). Vegetation is also an important carbon sink and thus essential in mitigating against climate warming and is an important conservation element for biodiversity (Gitelson et al., 2002). Understanding how vegetation is spatially distributed, its phenology and process is urgent and the relationship with topographic elements plays a significant role in mountain environments. The impact of climate change on vegetation dynamics has been vastly studied while the effect of topographic variables on vegetation production and distribution has been minimally explored.

Remote sensing and geographical information systems (GIS) is a widely used and efficient tool to study and assess spatial vegetation distribution for which satellite images and aerial photography are highly useful data sources. Changes in vegetation cover and vegetation growth have been to some extent examined in Iceland the last decades (Raynolds et al., 2015; Olafsson and Rousta, 2021). These studies mostly cover large areas assessed by satellite data while limited studies have been carried out at high spatial resolution. Changes in vegetation cover have further been minimally studied in relation to topography, whereas changes in land cover, in the proximity of retreating glaciers, and erosion, which has been a severe problem in Iceland, have been thoroughly examined (Gísladóttir et al., 2005; Halldórsson et al., 2009). It is of vital importance to study the relationship between environmental factors and vegetation development in mountain environments in Iceland for effective planning and management of the fragile ecosystem (Runnström et al., 2019).

1.1. Research aim

This study aims at exploring vegetation cover change of Tindfjöll mountain area. The goal is to examine how vegetation cover of the fragile arctic mountain environment is developing by examining the relationship to temperature trend, along a gradient in elevation, aspect, and slope (IPCC, 2013; AMAP, 2017). It is important to illuminate temporal and spatial patterns as well as developments of the vegetation cover, to assess natural processes and dynamics. The knowledge gained is a contribution to future assessment of ecological resilience of the mountain environment and the aim is to produce and map data which illuminates and assesses the development of the fragile vegetation cover. It is of an utmost importance to gain knowledge about the dynamics of such sparsely vegetated areas, which are highly susceptible towards external factors and disturbances such as climatic factors, human activities, grazing, and volcanic eruptions (Pickett, 1980; Laska, 2001).

The following questions are considered:

1. How is vegetation cover in the mountain area of Tindfjöll responding to current climate warming?
2. Does topography; elevation, aspect and slope have an impact on vegetation dynamics?

The following hypothesis are put forward:

1. Vegetation is responding to climate change with increased vegetation cover due to warmer climate and longer growing seasons.
2. Vegetation line is ascending towards higher elevation.
3. Vegetation production is increasing more significantly on the south side than the west side of the mountains.

To answer these questions, vegetation cover is examined at a 15-years interval, 2004 and 2019 respectively by analysing aerial photographs and examining the relationship with key variables; temperature, precipitation, and topography (elevation, aspect, and slope).

2. Theoretical background

The framework for the study is set in this section and the background is described. Iceland is put in a context of its geographical location where different definitions of the Arctic are explained, the study is put in a wider context of previous studies on changes in vegetation cover, topographic variables are explained and how they have impact on vegetation production and classification systems used as a base for the study are described.

2.1. The Arctic

The Arctic occupies a large area of land and sea in the high latitudes. Stretching from Eurasia to North America it makes up an entity of a highly fragile ecosystem which responds extremely dynamically to changes in the environment. The geographical setting of the Arctic has been defined in various ways in the literature, depending on the field. There are geographical definitions such as the Arctic Monitoring and Assessment Programme (AMAP) delineating the boundaries north of the Arctic Circle (66°32'N) and north of 62° in Asia and 60° in North America along with some other modifications presented in figure 1 (AMAP, 2017). Conservation of Arctic Flora and Fauna (CAFF) has defined the Arctic according to vegetation zones where Iceland falls within the subarctic zone and the climatic definition of the arctic is where mean July temperature in lower than 10° C (AMAP, 2017). Iceland (central latitude 65°N) is thus on the boarder of the subarctic and arctic region.

2.1.1. Vegetation responses to climate change

During the ongoing era of climate change, studies have reported substantial changes in vegetation cover, in space and time. To understand how vegetation cover responds to climate change, it is necessary to reflect on the main elements of vegetation development, i.e., the vegetation response, productivity, and distribution (Afuye et al., 2021). These elements have been fairly studied recently in relationship to various mountain climate variables, such as temperature, precipitation, and topography (elevation, slope, and aspect). Studies have shown that temperature is by far the most influencing factor on plant distribution (Lookingbill and Urban, 2003) where warmer summer temperature results in higher productivity and longer growing seasons (Raynolds et al., 2008). Summer temperature is the variable defining the length of the growing season by bringing forward the start and prolonging the fall which in turn highly affects the phenology of the vegetation (De Beurs and Henebry, 2010; Zhou, 2020; Li et al., 2020; Richardson et al., 2013).

Normalized difference vegetation index (NDVI) is an index for estimating changes in biomass production, and nowadays widely used in environmental and vegetation studies. The NDVI value is given at a range between -1 and 1 indicating the photosynthetic activity, where 1 means highest productivity but -1 high water stressed vegetation (Gessesse et Melesse, 2019). A study by Raynolds et al. (2008) showed that a 5° C increase in summer warmth index (SWI) corresponds to an increase of 0.07 in NDVI. Other studies have shown the same results where longer growing seasons derive increased NDVI, yet it is considered most significant for sparse vegetation and graminoid vegetation type (Raynolds et al., 2008). Conversely, decreasing NDVI trend has also been detected in the Arctic, which is assumed to be related to increased winter warming and reduction of protecting snow cover (Bokhorst et al.,2009).

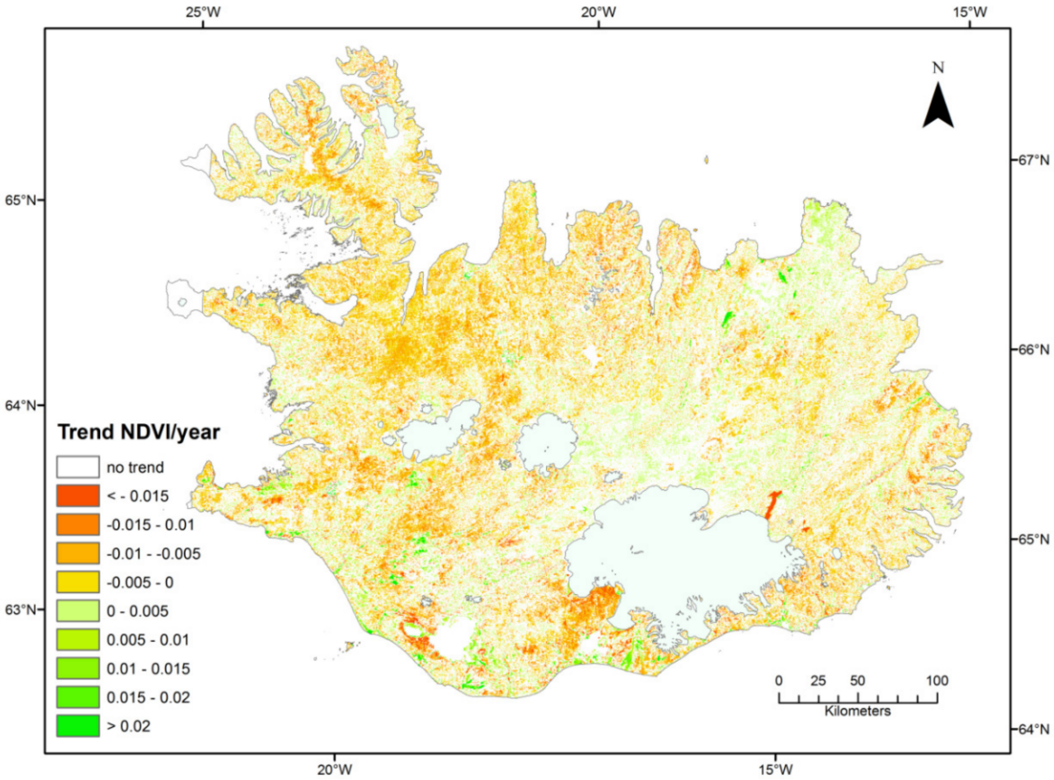


Figure 1. Iceland maximum annual NDVI trend from MODIS Aqua, 2002 - 2013. Theil-Sen robust regression, $p<0.05$. Map adapted from ©Warming Sheep and Volcanoes (Raynolds et al., 2015)

Arctic vegetation is thus highly sensitive towards changes in the climate system, especially changes in summer temperature. This means impact of climate warming but interannual variability (IAV) is also considered an influencing factor on vegetation growth although less studied (Hurrell, 2003; Chen et al., 2019). Yet, it is recognised that interannual variations in temperature and precipitation in Iceland is highly influenced by the North Atlantic Oscillation (NAO). Negative NAO brings cold and dry periods with less productive vegetation whereas positive NAO brings warm and wet green periods (Olafsson and Rousta, 2021). Change in vegetation is considered to imply severe impact on different arctic components such as hydrological cycles, human occupation, and wildlife (Walker et al., 2005). Furthermore, arctic vegetation is important feedback for the climate system as changes in vegetation changes the fluxes of CO^2, mainly driven by longer growing seasons (Leblans et al., 2018). Creating an understanding of the relationship between climate and vegetation responses is thus vital for future planning and policy making purposes.

2.1.2. Topography and microclimate

Vegetation development is highly influenced by topography as the heterogeneity of the terrain is greatly affecting the surface´s physical and ecological condition. Microclimate controls vegetation distribution and vegetation growth, especially in mountain environments where topography is playing a principal role. Topoclimate is furthermore contributing to disturbances such as landslides, heavy rainfall, and soil moisture (Franklin et al., 1995). Elevation is considered the most important factor, while aspect and slope control microclimate and sun angle. In the northern hemisphere, south facing slopes receive considerably more solar radiation than the north facing slopes, with impact on local microclimate (e.g., surface radiation, precipitation, and soil moisture conditions) (Dobrowski et al., 2009; Titshall et al. 2000). Topography is thus along with temperature considered a large contributing factor to biomass production and distribution with the highest biomass values derived from low-elevation, high-radiation and mostly south-southwest facing valley slopes. This underlines the importance of including topographic variables when exploring vegetation dynamics (Riihimäki, 2017).

Higher temperature not only means changes in vegetation growth but also retreat of glaciers which implies substantial changes in natural landscape and land cover changes. Studies around Hofsjökull glacier in the central of Iceland have shown almost 50% increase in vegetation cover between the years 1992 and 2017, mainly south and west of the glacier following substantial retreat of the glacier (Pavri and Farrell, 2020; Arnardóttir et al., 2020). Other areas in the northern hemisphere, where glaciers are retreating, have shown the same development, i.e., mountainous areas in Kazakhstan (55°26′–40°56′ N and 46°27′–87°18′ E) have reported great expand in sparse vegetation cover. The same study has identified the vegetation line to have ascended by 100 m to 200 m.a.s.l. in the western and southern parts (Dimeyeva et al., 2015). These implications require further inspection in other mountain environments such as Tindfjöll.

2.1.3. Greening vs. Browning

Recently, not only increase (greening), but also decrease (browning) in biomass production has been reported in the Arctic (Callaghan et al., 2021). Satellite data analysis of Arctic tundra (1985 – 2016) has shown a 37.3% increase in biomass production, 4,7% has shown a decrease, while 58% have not shown any change. The greening took place in warmer areas where air temperature, soil gradient and soil moisture was high whereas browning was noted in dryer and cooler areas (Berner et al., 2020). Studies have further shown an increase in the NDVI trend in the northern hemisphere, contrary to Raynolds et al. (2015) who reported greater areas showing decrease in NDVI than increase between the years 2002-2013. This was especially significant for the vegetation type moss-lava. When the trend by elevation was analysed, it was identified that there was only an increase in vegetation above 900 m.a.s.l. This reporting is in accordance with other studies such as Epstein et al. (2015), identifying that in the wake of three decades of constant greening (from 1980´s), SWI and increase in biomass production has been slowing down (Bhatt et al. 2013, Frost and Epstein 2014).

2.2. Vegetation classification systems

Vegetation classification systems are a practical tool for vegetation analysis and well suitable as basis for environmental management. Different systems have been developed and established both on a local, regional, and global scale, however, there is no single way to classify vegetation properties (Cáceres and Wiser, 2011). The classification systems are normally based on one or multiple criteria, whereby the most common method is subject to grouping similar vegetation types into classes based on different properties such as type, density, height, and abundance. Other methods are based on common factors such as physiognomy, structure, plant functional traits, species composition or climatic and soil conditions (UNESCO, 1973).

Vegetation classification involves assigning or determining membership to vegetation types which can be estimated by different methods according to different practices and different rules. These include [1] expert-based rule definition where membership rules are based on global properties such as climate, physiognomy and/or structure (UNESCO, 1973), and computer-based [2] unsupervised classification based on clustering identical objects, [3] supervised classification based on training areas to define a membership rule and [4] assignments where membership rule is defined according to supervised classification method, expert definition, or clustering (Cáceres and Wiser, 2011).

Below is unfolded the two approaches used in this study, one developed in Sweden and another forming the basis of vegetation mapping in Iceland. The approaches are based on the idea of identifying homogenous classes on the image, where the distinction between classes is clear. The National inventory of landscapes in Sweden addresses the problem of homogeneity by allowing only assessment of vegetation cover but not subclasses, meaning that some generalisation is allowed (Allard et al., 2003). The map of terrestrial habitat types is on the other hand a well-developed system considering the identity of Icelandic Mountain vegetation cover which is highly useful in this study. These underlying factors must be explained to enable understanding of why and how the analysis in this project was performed. Following is a short description of the approaches but a more detailed attribution is described in the method section.

2.2.1. National Inventory of Landscapes in Sweden

In Umeå, Sweden, the Department of Forest Resource Management and Geomatics has implemented a method for analysing landscape composition published in the Swedish manual for aerial photo interpretation in the national inventory of landscapes (hereafter NILS). It was developed to construct a framework for the evaluation of biodiversity and landscape processes on a temporal and spatial scale. The framework is based on the principle of delineation of polygons, interpretation of variables within the polygons, and mapping. It only considers homogenous vegetation and allows some generalisations in the analysis process (Allard et al., 2003).

The method includes two steps of identification, interpretation of aerial photographs and field measurement. One of the major factors included in the analysis is identification and digitisation of sparsely occurring objects which must be systematically classified. This method requires field measurement to establish a necessary ground truth to estimate the accuracy of the interpretation.

2.2.2. Hierarchical classification of the Icelandic Institute of Natural History

To elucidate the vegetation cover in Iceland, the Icelandic Institute of Natural History (hereafter IINH) produced in 2016 (revised 2018), a map of terrestrial habitat types in Iceland (1:25 000) representing the main habitat types. It was produced according to the hierarchical classification of IINH which is based on the EUNIS-habitat classification system of the European Environment Agency (EEA). The system aims at identifying habitat types by using the Braun-Blanquet approach, a species-based habitat classification (NI, 2018; European Environmental Agency, 2022; Westhoff, 1978). The Braun-Blanquet approach was developed in Europe and has been the principal method for decades, and a primary method for the classification of vegetation in the Arctic and Iceland alike (Walker et al., 2018; Westhoff, 1978; Braun-Blanquet, 1948).

The IINH classification comprises of 4 main categories: collective vegetation cover, vascular plants, mosses, and the proportional coverage of each vegetation class. It proposes 12 main classes with subclasses, a total of 64 classes. This study aims at assessing the sparsely vegetated environment of Tindfjöll which results in limited number of classes, the classes are defined and described thoroughly in the data and methods sections below.

3. Data and methods

This section provides an overview of the study, including a description of the study area and its geographical and environmental settings. It is followed by an overview of the data used, and a detailed description of the method employed.

3.1. Study area

Iceland is an island (103 000 km^2) in the North Atlantic, close to the Arctic Circle. Due to the high latitude location, solar altitude is always rather low, causing a large difference in day length between winter and summer. Glaciers cover around 11% of the country, mainly situated in south due to frequent cyclones bringing heavy winds and precipitation from south towards the coast of Iceland. The mountains also influence the climatic conditions as they act as a shelter to the interior highlands, refraining clouds and precipitation to cross over. This increases cloudiness and precipitation windward of the mountains but decreases on the other hand the same factors leeward, creating rain shadow and clear weather behind the mountains (Einarsson, 1971).

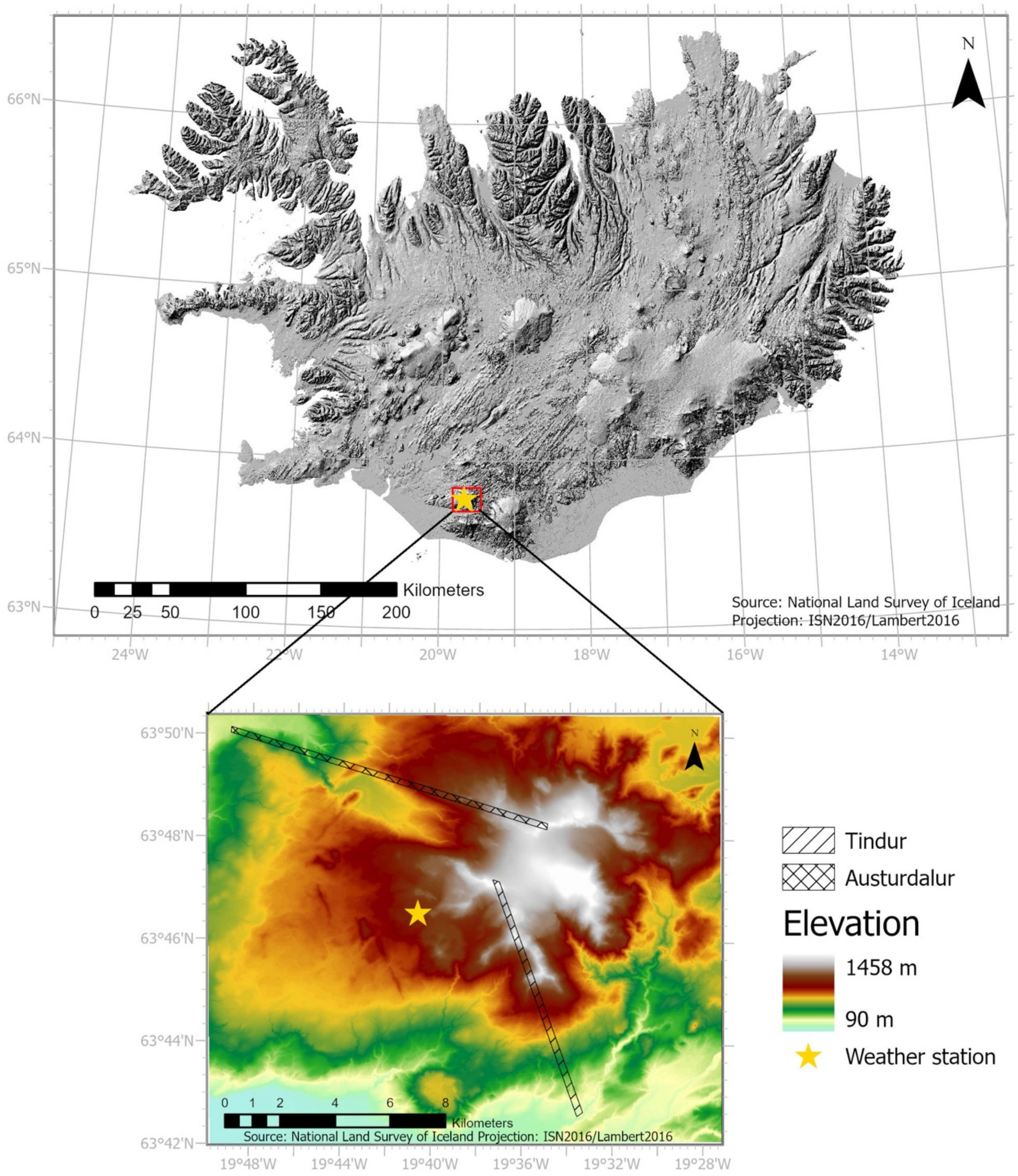


Figure 2. Tindfjöll study area. Tindur (south facing) and Austurdalur (west facing) transect sites are shown on the lower figure.

Tindfjöll is a mountain area in Southern Iceland which defines the limit to the central highlands. Its geographical setting lies between the latitudes 63°42´N and 63°51°N and longitudes

19°26´W and 19°47´W. The area stretches from around 300 – 1458 meters above sea level (Fig. 4). It is situated at the eastern volcanic zone and is still classified as an active volcano even though no eruption has been identified since the end of last ice age. It is a stratovolcano covering around 300 km^2 and is within a 15 km distance from its neighbouring and recently more famous stratovolcano, Eyjafjallajökull. The culminating point has around 13 km^2 glacier which is continuously shrinking, the summit (1462 m above sea level) being ice free during summer. The ice cap has 6 outlet glaciers, mostly towards north and east, providing water into Valá towards northwest through the valley of Austurdalur and to southeast through the gorges of east and west Botná into Gilsá river (Moles et al., 2018; Björnsson, 2017). The name of the mountains derives its name from two sharp and outstanding peaks (in south of the mountain mass and clearly visible from the plains below. Two peaks also characterise the summit of the glacier, where the twin summits Ýmir (1462 m) and Ýma (1448 m), meaning male and female giant, reign. There are other slightly lower peaks in the area, Saxi (1308 m), Hornklofi (1237 m) and Tindur (1251 m) (Björnsson, 2017).

The infrastructure in the area is limited. There is one highland road leading from Fljótshlíð in South to three mountain huts which are located there. It is still minimally visited by tourists who are there mostly during winter and spring for skiing and snow sport purposes. However, tourism, hiking and mountaineering is rapidly growing in Iceland which might increase the number of visits in the future. It is a grazing area where sheep from the neighbouring regions of Fljótshlíð and Rangárþing Ytra graze over the summer months.

The area has hitherto been minimally studied, especially regarding vegetation but also its landscape and geology. The mountains were built up during the last glacial era which has marked the development and landscape but there are no signs of eruptions since the end of the last glacial period. Around 54 000 years ago, a great explosion dispersed thick layer of sediment over the region, estimated around 8 – 12 km^3 in volume (Björnsson, 2017).

3.1.1. Climate

Weather recordings are available for Tindfjöll since October 2005 when a weather station was installed and has since then provided continuous temperature measurements. Located at 63°77.572´N, 19°67.732´W, the weather station is situated at an altitude of 870 meters above sea level (Hjartarson, 2007). Table 1 presents the August temperature data recorded at the weather station for the years 2006 and 2019. The first available recordings in August are from the year 2006 explaining why there is no data provided from 2004. The table shows the mean annual temperature, and the highest and lowest values for August 2006 and 2019.

Table 1 August temperature, recordings from the weather station in Tindfjöll (Unpublished data, IMO)

Year		*2006*	*2019*
Elevation	870 m. a. s. l.		
Mean August temperature		7.8° C	6.2° C
Highest August temperature		15.5° C	14.6° C
Lowest August temperature		1.6° C	-0.2 ° C

Precipitation varies greatly in Iceland where frequent cyclones bring wet air from the south, and the most significant amount of precipitation falls in South and Southeast due to topographical factors. The mountainous landscape has considerable effect on temperature and precipitation as temperature decreases with height above sea level whereas cloudiness and precipitation increase windward of the mountains but decrease leeward (resulting in rain shadow), The highest rainfall present at the glaciers in southern part of Iceland (more than 4000 mm/year) (Einarsson, 1971). Precipitation in Tindfjöll is therefore considerably high, between 2500 and 3500 mm/year (Fig. 5).

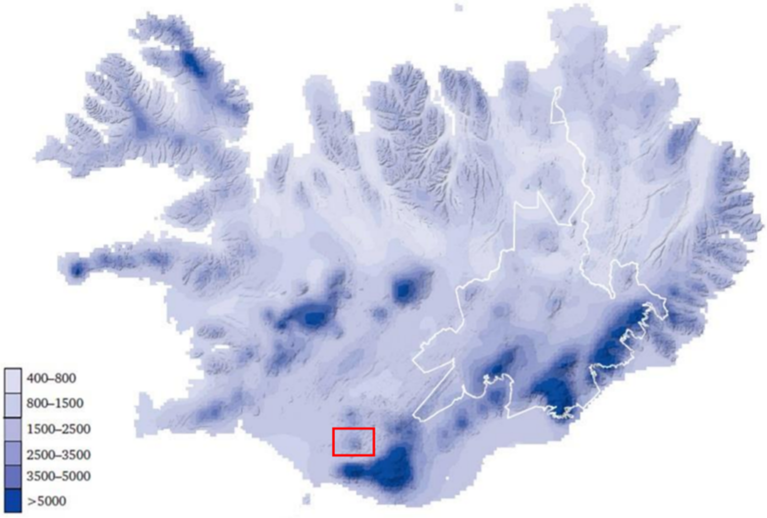


Figure 3 Mean annual precipitation (mm) in Iceland. Tindfjöll within the red quadrangle. Map adapted from Nýheimar https://nyheimar.is/lifandi-kennslustofa/loftslag-og-leidsogn/birtingamyndir-og-ahrif-loftlagsbreytinga/vedurfar/. (Source: Unpublished data, IMO).

3.1.2. Vegetation

This thesis investigates the changes in vegetation cover of Tindfjöll. A definition of wilderness and alpine landscape in Iceland is proposed as: Large bare open areas, land cover above 200 – 400 meters, more sparsely vegetated than the lowlands, dominant vegetation is a low-growing plant species, and areas above 700 meters are considered mostly non-vegetated (IINH, n.d.).

Tindfjöll is a sparsely vegetated environment, consisting of semi-natural vegetation cover, which is defined by means that there is only natural vegetation with native species, which regenerate themselves. There is little human intervention, whilst sheep grazing from the nearby region has been a tradition for decades. (Herzon et al., 2021). The species are of different types, small shrubs, grasses, mosses, and vascular plants. Semi-natural vegetation is important and plays a vital role in relation to different fields such as biodiversity, ecosystem services, carbon storage, and natural hazard prevention (Ahlström et al., 2015; Buitenwerf et al, 2018).

3.2. Data

This section describes the variables used for the analysis followed by a description of the method applied. To examine and map the vegetation cover, remote sensing data, including satellite imagery, aerial photography, and different data derived from other remote sensing instruments are considered the principal sources. Other ancillary data sources, including temperature data and digital elevation model (DEM), used to produce slope, and aspect data, are further presumed an important data source for reflecting the environmental factors controlling spatiotemporal development of vegetation cover (Golden et al., 1995).

The data sources used for the analysis of vegetation cover is primarily based on high quality and high-resolution aerial photography data. The availability of aerial photography is limited, as the production requires specialized equipment such as aeroplane, high-quality cameras and human knowledge and skills which is costly and time consuming. Two private companies and one governmental office have carried out aerial photography in Iceland, Loftmyndir ehf (still producing data), Samsýn (until 2015) and the National Land Survey Institute of Iceland possesses around 140 000 aerial photographs for the years 1937–2000. The lowland surface is regularly photographed, and the highlands with some years interval. These photographs are an important source of land cover data and for the purpose of this study available photography was accessible and derived for the years 2004 and 2019.

To analyse vegetation dynamics in relation to elevation, slope, and aspect we used high resolution (2m) digital elevation model (IslandsDEM), retrieved from the National Land Survey Institute of Iceland, temperature data based on daily recordings in Tindfjöll, and precipitation data from nearby lowland weather station obtained from the Meteorological Office of Iceland.

The data was analysed using ArcGIS Pro 2.7.6. software by ESRI and stored in a geodatabase. Temperature and precipitation data was analysed and visualized with the software Excel 16.59 by Microsoft. Below the data types are introduced, what they are useful for in relation to this study, their biases and how to overcome them.

3.2.1. Aerial photography

The primary data source selected for the analysis is aerial photography based on the criteria of availability in relation to quality and resolution of available images. The images are expected to provide important information about the environment allowing the detection of vegetation change and spatial-temporal development. Aerial photography has been commonly used for analysing landscape change since the 1930´s, offering an important and detailed information about landscape, terrain composition, and vegetation development through time (Pinto et al., 2019; Morgan et al., 2010; Allard et al., 2003). Using aerial photographs for analysing environmental issues and changes is an efficient, accurate and flexible remote sensing application. They are practical for analysing relatively small spatial areas as they provide detailed information (Bakrac et al., 2021; Allard, et al., 2003).

Techniques in photography have also considerably changed over time, and even though digitizing is beneficial, there are also some challenges to be addressed such as the spatial resolution. When scanning older images into digital imagery, it can lead to reduced spatial resolution which determines the information provided with the image (Nelson et al., 2001). This is the case for the data used in this study as the land cover of the Icelandic Highlands is regularly photographed from an aeroplane, yet repeated photographs for the same area are only available with some years interval. Older photographs (before the year 2004) are mostly black and white, whereas photographs until the year 2017 were taken on a film but later scanned and transformed into a digital format.

For the comparative analysis, using black and white photographs was not considered an option, as the comparison of black and white photographs to digital high-resolution photography would not give a reliable result. The scanned photographs were inspected carefully and considered of adequate resolution for the analysis. The scope of the study was therefore limited to the available data and the data selected was acquired in August 2004 and in August 2019.

Assessment of vegetation cover using remote sensing data, requires a resolution common to all images. Nelson et al. (2001) proposes definitions of resolution for aerial photography including ground sampled distance (hereafter GSD). GSD is defined as "the size of the smallest object on the ground that can be detected on the image" measured in centimetres or meters. The GSD is based on the ground resolution, which means how scale and the camera sensors can identify objects on the ground. Ground resolution is calculated with the following equation:

$$R^2 = \frac{H}{\mathrm{RP}\ x\ F}$$

R^2 = The cycles/mm distance in the image representing ground distance.
RP = Resolving power of the camera
F = Focal length (m)
H = Height above ground (m)

The scale of the photograph is the ratio between the focal length and the height above ground. GSD means that all objects of same size or bigger can be identified but smaller cannot be detected (Nelson et al., 2001). Definition of GSD is especially useful for classifying image objects where the aim is to explore changes in vegetation. In this case high resolution aerial photography is of great advance. The available aerial photographs provide a 25 cm GSD, meaning that vegetation patches smaller than 25 cm cannot be analysed and thus defines the potential accuracy.

The study is based on data retrieved from Loftmyndir ehf, a privately owned company. The data consists of stereo ortho-mosaic which have already been georeferenced. The orthophotos are a mosaic of tiles that overlap and create a stereo data. Data is retrieved from online databases, firstly by establishing a Web Map Service (WMS) connection to Loftmyndir ehf, the Icelandic provider of aerial photos, and secondly by downloading data. The timespan of the research is limited by the aerial photos available for the study site. The aerial photographs obtained from Loftmyndir ehf are of the best available quality to examine and identify changes in vegetation on a small scale, as they offer the best available resolution. The data is provided in the geodetic reference system ISN93.

The aerial photos from the year 2019 were taken on the 9th of August 2019 from an altitude of 3030 m to 3070 m whereas the photos from 2004 were taken on the 12th of August 2004 from an altitude of 3870-3880 m. The photos from 2004 were taken on a film and later processed to a digital form whereas the photos from 2019 were taken on a digital camera, UltraCam Falcon Mark 2. It has a light sensor chip of 17,310 x 11,310 pixels. The photos propose a mosaiced tiles of repeated photography, where every two images overlap to propose a stereo quality, which is considered the best available. The photos from 2004 might represent a slightly lower resolution and quality since processing photos into digital format reduces the overall quality of the images. Higher elevation also means bigger scale as described previously. The photos were carefully inspected and considered of an adequate resolution for the comparative analysis. However, their resolution must be considered when interpreting the results.

3.2.2. Digital Elevation Model - IslandsDEM

Ancillary data used for the analysis is based on Digital elevation model (DEM), which represents the continuous variation of a surface relief. The model is produced by applying an ordered sequence of numbers that corresponds to the spatial distribution of the landscape elevation above sea level. DEM is a raster matrix, where the value of each cell centre of the raster represents the elevation of the surface. (Noorollahi, 2005).

For the reproduction of elevation, slope, and aspect data, IslandsDEM 1.0. (Created by the National land survey institute of Iceland, 2020) was used. It is based on a high-quality version of the ArcticDEM (retrieved from the Polar Geospatial Centre), providing improved quality data of the Icelandic surface by adding lidar and drone photography. The method for the improvement was created in cooperation of the National Institute of Land Survey, Icelandic Meteorologic Office, and the Polar Geospatial Centre. It includes coordinated geospatial position, mosaiced tiles with time layer and, lidar model of glaciers from Icelandic glaciers (Jóhanesson et al., 2013).

To explore the vegetation dynamics on a spatial scale, a DEM can be used to reproduce data such as isometric projections to generate topography (terrain profiles between designated points), slope angle, and aspect (direction of slope). These terrain-related factors are useful for spatial analysis of vegetation development since mountain landscape is not a homogeneous surface and should therefore preferably be considered spatially (Noorollahi, 2005; Dorner et al., 2002; Urban et al., 1987).

3.2.3. Temperature and precipitation data

The primary aim of this research was to assess whether climate warming is having an impact on mountainous vegetation cover in Iceland. To explore changes in temperature, daily temperature data along with mean monthly average temperature measured at the Tindfjöll weather station (63°77´572´N, 19°67´732´W) was obtained from the Meteorological Office of Iceland (Unofficial data IMO, 2022). The recordings started in October 2005; the timespan is therefore from January 2006 until December 2019. As the goal of the temperature data is to observe a trend in the data series, it is considered acceptable to use a time series covering slightly shorter timespan than the interval between the aerial photographs used for the analysis. The alternative would be to use temperature data from the nearby weather station, but that station is situated at the lowlands and hence would not reflect the harsh mountain temperature data.

Other ancillary data is precipitation data from the nearby weather station Sámsstaðir (63°44´122'N, 20°06´544'W; 90 m.a.s.l.) situated at the lowlands southwest of the study area. This data is used as a reference, showing mean monthly average precipitation for the years 2008 and 2018. Precise data for the study area is not available but figure 5 illustrates approximate mean annual precipitation for the mountain area.

The temperature and precipitation data were derived as an Excel file from IMO, all processing's and visualizations were further processed using Microsoft Excel 16.59.

3.3. Methodology

This study represents a comparative analysis of temporal and spatial change in vegetation cover between 2 study transects. For the analysis a classification method is used to determine vegetation cover with respect to temperature and topography, i.e., elevation, slope, and aspect. Two factors are fundamental for the study, [1] the physiognomy or the general appearance of the vegetation cover and [2] density, describing height, density, and coverage of data. Classifying image objects where identical objects are assigned to a class is the principal method for assessing vegetation cover, yet different approaches can be applied depending on the data sources used for the classification (Looijen, 2004). This study is primarily based on classification by on-screen hand digitizing where aerial photographs are manually classified and interpreted. To study the vegetation change with respect to temperature and topography, the classified data is inspected by a comparison to time series analysis of temperature data and by an overlay of the topographical data.

The platform for analysing the data is ArcGIS Pro 2.7.6. software from ESRI and Microsoft Excel. All data was commonly projected into the Icelandic geodetic (projected) reference system, ISN2016/Lambert2016.

3.3.1. Study setting

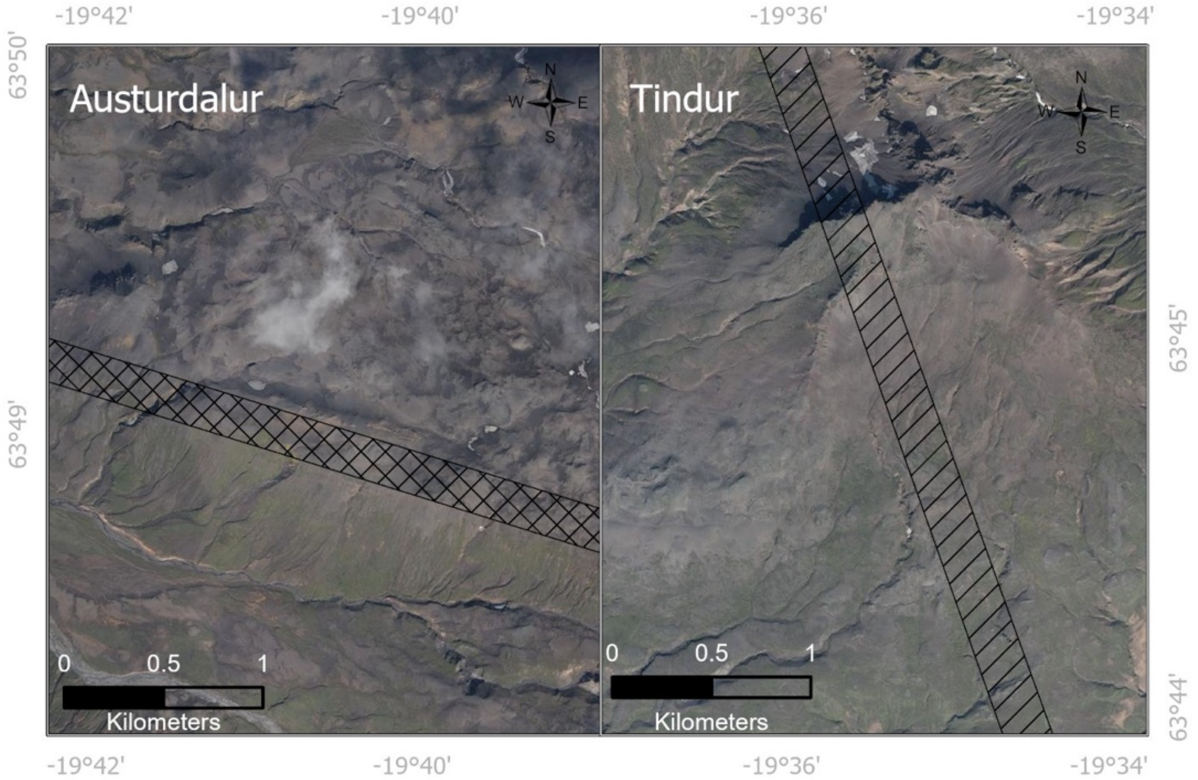


Figure 4 Austurdalur and Tindur transects, showing an example of the image characteristics (Source: Loftmyndir; Projection: ISN2016/Lambert2016)

To establish the research, two altitudinal transects were created, [1] Austurdalur and [2] Tindur. Figure 4 shows the larger geographical context and Figure 6 shows a profile of the transects. Both transects represent similar elevation from an altitude of 300 m to 1300 m. The criteria for the transect establishment is the goal of gathering information about vegetation change according to elevation, slope, and aspect, therefore achieving highest possible altitude, one south facing, and other west facing was fundamental.

Table 2 Geographical setting for Austurdalur and Tindur transect corners. Projection ISN2016/Lambert2016.

	Location			
Austurdalur corners	63°50.1352214´N	63°50.0248214´N	63°48.3002060´N	63°48.1836353´N
	19°48.9619592´W	19°48.9815143´W	19°34.9520766´W	19°34.9897749´W
Tindur corners	63°47.2001351´N	63°47.1599188´N	63°42.5959016´N	63°42.6775199´N
	19°37.3550948´W	19°37.0579643´W	19°33.5570015´W	19°33.3017686´W

[1] Austurdalur transect is situated Northwest of Tindfjallajökull glacier. The size of the transect is built on the criteria of gaining the maximum elevation difference, reaching from a

low of 300 m up to a maximum of 1300 m. The size is 2.5 km^2, 206 m wide and 12 km long. [2] Tindur transect is located south of the glacier, sloping towards south-southeast. The size of the transect is 2 km^2, with the width of 205 m and length of 9,1 km. Due to heterogeneity of the environment, different aspects are within the transects including different slope angles which are unevenly distributed across the transects.

3.3.2. Vegetation cover classification

Before starting the digitizing process, the study area was inspected, and classes defined. This means that image characteristics were related to features on the ground. This method has clear advantages and is anchored in the human capacity of identifying homogeneous image objects by assessing the reflectance of the image. The image objects were then separated into different layers according to different terrain characteristics such as clear field patterns, different vegetation cover or different density (Looijen, 2004). This is a hierarchical system which means that it has an internal structure where each class is clearly and systematically defined and described. To establish a successful hierarchical classification there must be a clear distinction between classes, which relies mostly on the resolution and the clarity of the images or photography used for the classification (Gregorio, 2005; Allard et al., 2003). This requirement was a challenge to fulfil as the distinction between classes was often unclear due to similarities of colours. This problem is overcome by mixing two classification methods, the hierarchical system of IINH and the National Inventory for Landscape in Sweden (NILS) which considers this problem of unclarity and allows simultaneously some generalisations (see chapter 2.2.1. and 2.2.2.).

Following is definition and description of classes used for the classification in this study. The definitions are based on the vegetation map by IINH, where hierarchical structure relies on coverage and characteristic of vegetation (Ottósson et al, 2016). Table 3 presents a definition of classes and a detailed description of each class; the classes are as follows: [1] Heathland is found on a dry land where the soil thickness is considerable (>50 cm). Vegetation cover is mostly continuous, and the dominant spices are mosses and lichens, possibly some willow, heath, or grasses. There can however be found some discontinuity where open mould is between the heath [2] Grassland where land is fully and densely vegetated and characterised by grass spices. However, the grassland is often mixed with mosses, willows, and other vascular plants. Soil thickness is usually limited. Grassland can be vigorous on a sunny side hill, even with some flowering vascular plants. It is found in slopes, dells, and valley heads where snow cover is dominant during winter. It is also found within valley heads [3] Moss-heath is a semi vegetated or discontinuous land cover which is dominant in mountainous areas where snow cover is dense during winter. It is also found in slopes and hills where precipitation is considerable. Mosses are dominant and characterise the land. However, there can be found other spices such as low willow and few other vascular plants [4] Sand/gravel habitat type is a sparsely vegetated land where vegetation cover is less than 10% or no vegetation. This habitat is the most common in Iceland and is common on the highlands where soil is dry. Mosses are rare, mostly found in the proximity of large rocks, but the main species found within these habitats are low vascular plants which thrive on a rough surface. Vegetation within this class is highly sensitive to erosion and disturbance whether natural or anthropogenic. [5] Glaciers where land cover is snow or ice all year round. No vegetation is found within these areas. Figure 7 presents an example of each vegetation class.

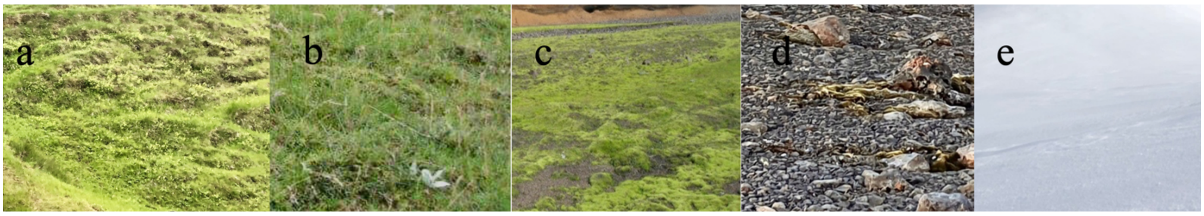


Figure 5 An example of vegetation classes: a) Heathland, b) Grassland, c) Moss-heath, d) Sand/Gravel, e) Glacier. Photos: Borgþór Magnússon and Guðrún Guðjónsdóttir

Table 3. Vegetation classes used in the study. Source: IINH

Class	*Coverage*	*Location*	*Characteristic*
Heathland [1]	Fully vegetated, continuous, or discontinuous (100%)	Dry land with thick and often fertile soil, lowland	Mosses, lichens, willows, heath, and grass
Grassland [2]	Fully vegetated, continuous (100%)	Slopes, dells and, valley heads with thin soils	Grass spices, mosses, vascular plants, flowering vascular plants on a sunny hill, and willows
Moss-heath [3]	Semi-vegetated, discontinuous (25-75%)	Mountainous areas where snow cover is abundant during long winter season. Hills and slopes with high precipitation	Mosses, willow and, few vascular plants
Sand/gravel [4]	Sparsely vegetated (<10%)	Highland where soil is arid and infertile	Low vascular plants which thrive on an infertile ground. Mosses only found in shadow of large rocks.
Glacier [5]	No vegetation	High mountains	Snow/ice

3.3.3. On-screen hand digitizing

Vegetation cover was manually digitised with the on-screen digitising method when the classes had been defined and described. This method is based on visual interpretation by inspection of aerial photography, where data is signed into different classes based on visual similarities. The classification was then used to construct vegetation data which allowed detection of both temporal and spatial change through time and space. The vegetation cover data was constructed by creating a vector layer and digitizing polygons, whereby each polygon was assigned to the appropriate class. A raster layer was then created based on the vector polygon layer for each of the transect sites to perform the overlay analysis.

The digitizing process depends on the best possible image resolution. Different scale factors were tried and tested, ranging from 1:750 to 1:1 500. Mostly, the highest resolution (scale 1:750) was considered too fuzzy to be able detect vegetation class with certainty, therefore, the parameter 1:1 500 was used in most cases.

3.3.4. Temperature and precipitation data

Daily temperature and precipitation data were derived from the Meteorological Office of Iceland and provided as an excel sheet. The temperature data was analysed using time series analysis for the timespan 2006-2019. It was further analysed as a mean monthly average temperature for the years 2006-2019 and daily data for August 2006 and 2019. Along with the time series analysis a trend line was plotted. The precipitation data for Sámsstaðir weather station was analysed as a mean monthly average precipitation for the years 2008 and 2018. The temperature and precipitation data were analysed in the software Excel version 16.61 and visualised accordingly.

3.3.5. Elevation zones, aspect, and slope angle

The platform used to analyse the topographical data is ArcGIS Pro software from ESRI. Performance of the elevation analysis was dependent on the digital elevation model IslandsDEM which was reclassified with the geoprocessing tool [reclassify] and sliced into 100 meters elevation zones. This method allowed a detailed analysis within each zone of the transect. Aspect was also created from the DEM, underlined by the selection of transect sites, one south facing and the other west facing. Each transect was divided into three different slope angles by a reclassification of the slope angle into low (<10°), medium (10-45°), and high (>45°) slope angles.

For the raster analysis of the vegetation change in relation to elevation zones, aspect, and slope angle, a Boolean overlay method was applied. This means that the classified vegetation raster layer was multiplied using [raster calculator] geoprocessing tool with the overlaying elevation, aspect, or slope layer. Each cell in the raster is multiplied with the overlaying cell and the result shows vegetation cover in relation to each variable.

3.3.6. Estimation for horizontal digitizing errors

Manual digitizing inevitably produces some errors in polygon delineation during the digitizing process. To produce a reliable source of data, the errors must be estimated. The typical errors in analogue maps are estimated from 0.43 mm to 0.77 mm (Thapa and Bossler, 1992). The only available sources when digitizing is the geometry of the contour and the scale of the image. The information derived from the images is not always tangible and therefore creates a risk of potential delieation errors. Errors are usually due to human factors when digitizing and / or the software used, which means a deviation of the digitized contour from the real position (Achilleos, 2010). When capturing features manually by digitizing images these positional errors are common but difficult to overcome. To estimate the error, accuracy assessment is performed where ground truth is established by real world reference points which are compared to the digitized feature on the map.

3.3.7. Accuracy assessment

To evaluate the classification performed in this study as well as to create a link between the aerial photography data and the real surface of the Earth, ground truth was established by collecting reference data in the field. This process is vital for the analysis since the method relies mostly on visual and personal interpretation and classification which is always subjective (Bolstad et al., 1990). There is limited accessibility to the study area during winter. Therefore, a field visit was not possible until spring when snow had melted, and roads were open. For this reason and bad weather conditions, the field work was delayed until 18th of May 2022, therefore, an efficient sample technique was vital. First Austurdalur was visited and Tindur later the same day when weather was adequately good.

A reference map was used to derive the field (reference) samples, 20 samples were collected for each transect, a total of 40 samples, by a random systematic sampling technique: Each sampling unit consists of a transect of sampling points where the first point was randomly selected, and the rest of the point data was selected by a fixed approximately 100 meters interval (Clark and Hosking 1986). Systematic sampling design is considered a precise and efficient technique which allows for less sampling points (Stehman, 1992). Even though the number of sampling points is small for such a field reference, Cochran (1977) pointed out that small data sets would be subject to insignificant bias using this sampling method and that already with 50 sampling points the bias would be minimal. To improve the accuracy assessment of the classification results, repeated sampling of the transects could be done. There are limiting factors and certain requirements for collecting the field reference data. First and foremost is the accessibility to the study area and topographical features such as canyons, rivers, cliffs etc., weather must be passable for safe working environment and electronics (GPS) must be available and function.

Classification accuracy was calculated for each transect by constructing an error matrix (Congalton, 1991). The error matrix consists of the classified data points collected from the map represented along the rows compared to the reference points (ground truth) represented along the columns. The diagonal between the two datasets represents the agreement between the two datasets, used to estimate the probability of the classification data to be a chance agreement. The user´s accuracy (point assigned to a certain class that is not truly a member of that class, error of commission) and producer´s accuracy (data point assigned to a class other than the true class, error of omission) was calculated. The field reference data was then compared to the classification data and total accuracy calculated. To summarise the results of the accuracy assessment, Cohen´s (1960) Kappa coefficient [KAPPA] was calculated with the following equation:

$$\kappa = (Po - Pe) - (1 - Pe)$$

κ = Kappa
Po = Total accuracy
Pe = Random accuracy

The reference map was created in ArcGIS Pro with the geographical coordinate system ISN2016/Lambert2016. By exporting the data points, they were transformed into WGS84. The field data collection was performed using the smartphone application, Gaia GPS v2022.4. The geographic coordinates were registered in EXCEL and can be addressed in Appendix II.

4. Results

The transects used for the comparative analysis span a wide range of elevation, slope angle, and aspect. The elevation ranges from approximately 300 m above sea level to around 1300 m and the transects represent south and west facing aspect. The temporal timespan is an interval of 15 years, 2004 and 2019. It must be noted that the findings are based on hand digitizing method which means that it relies on the personal interpretation of the interpreter, previously discussed in chapter 3.2.2. The classification is therefore solely the production of the person performing the digitization and requires the results to be interpreted as such. Accuracy assessment as explained in chapter 3.3.7. was performed to enhance the reliability and accuracy of the analysis with an effort to minimize the errors.

4.1. Comparative analysis of aerial photography

4.1.1. Austurdalur (west facing)

By visually exploring the transect and the change between the years 2004 and 2019 (figure 8), an overall increase in vegetation cover was identified. These findings are illustrated on the pie charts (figure 12). An increase was reported both for [2] grassland and [3] moss-heath, whereas no [1] heathland class was identified. The results further show that [2] grassland covered (2%) of the area, (24%) is covered by [3] moss-heath whereas [4] sand/gravel was the largest class within the transect, covered approximately (67%) of the overall vegetation cover. Grassland and moss-heath showed an increase (1%) and (3%) respectively, whereas sand/gravel and glacier showed a decrease of (-2%) and (-1%) respectively. A detailed summary of the results can be found in appendix A.

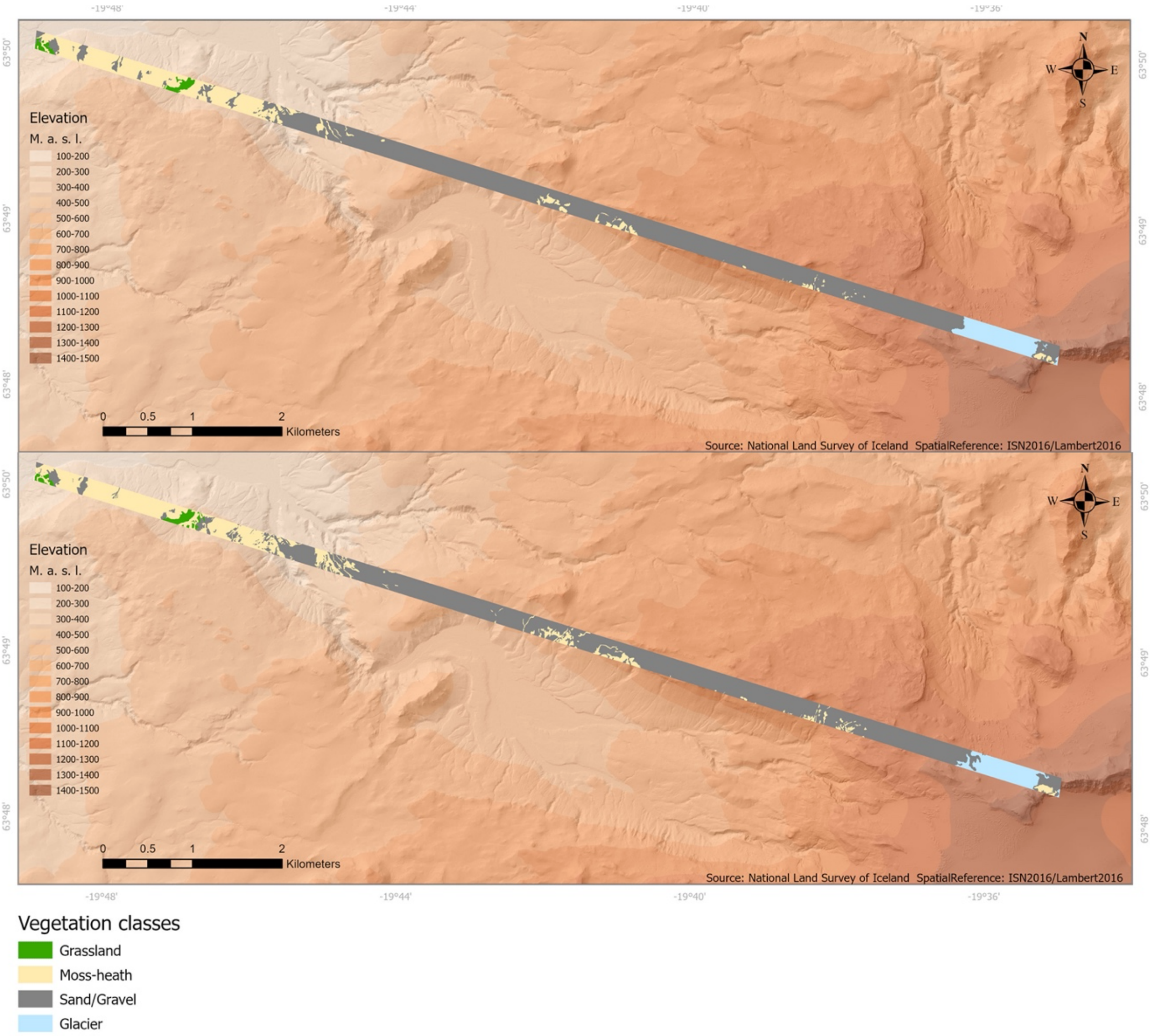


Figure 6 Austurdalur transect representing vegetation cover in the year 2004 and 2019.

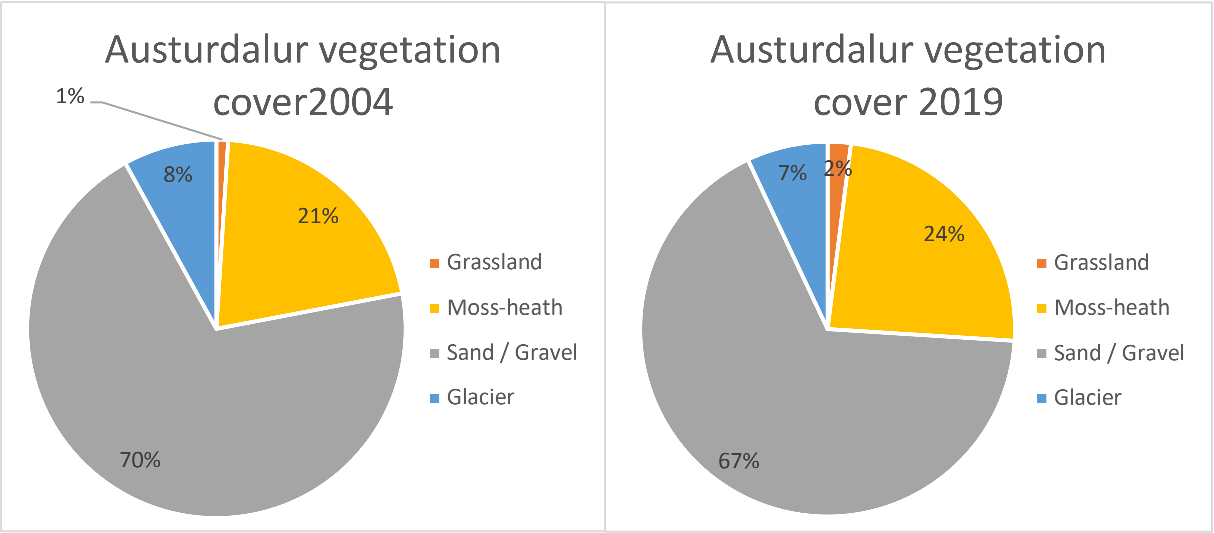
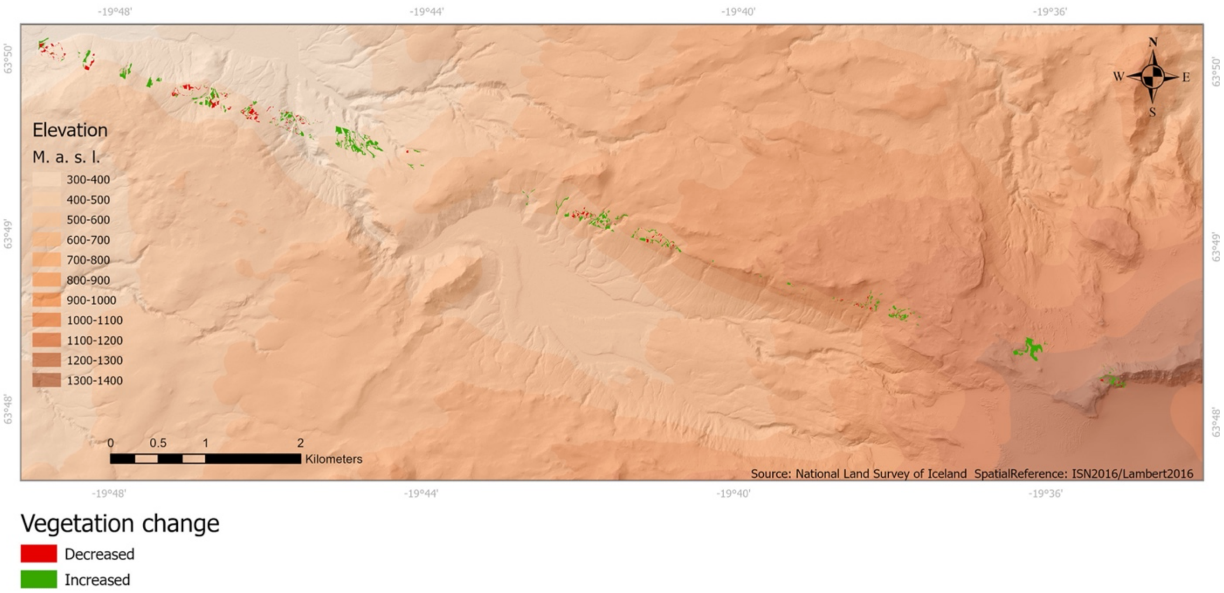


Figure 7 Austurdalur vegetation cover 2004 and 2019



Source: National Land Survey of Iceland SpatialReference: ISN2016/Lambert2016

Figure 8 Vegetation change in Austurdalur between the years 2004 and 2019. Red indicates decreased vegetation and green increased vegetation.

Figure 9 represents the quantitative changes in vegetation between the two years and further visualizes which classes have increased vegetation cover between the two years and which classes have shown a decrease in vegetation cover. These findings are further illustrated in figure 10 which addresses where the changes have occurred and if they have been towards increased or decreased vegetation cover.

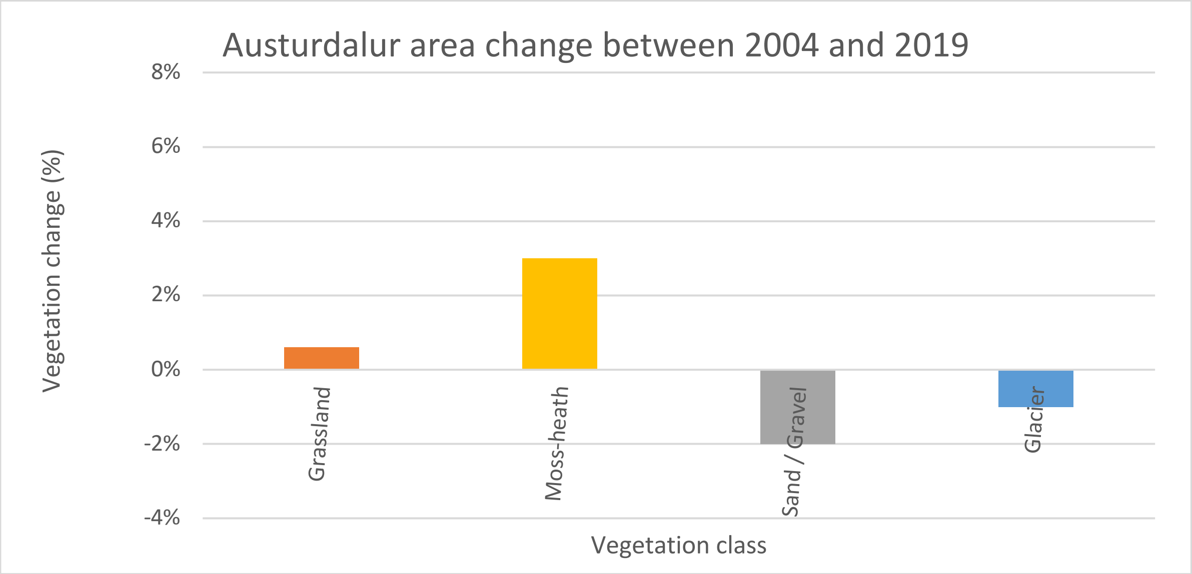
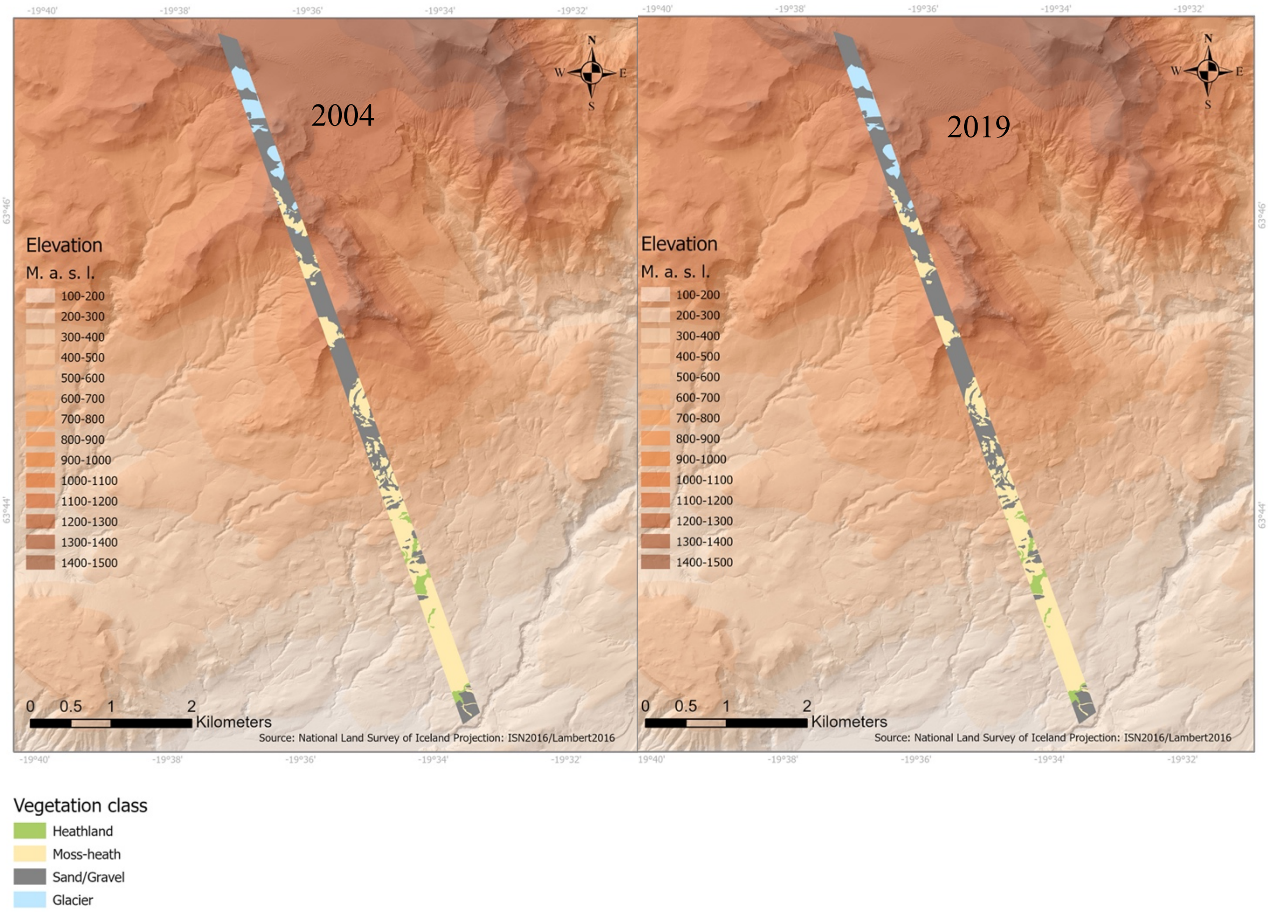


Figure 9 Austurdalur area change in vegetation cover from 2004 to 2019 (%)

4.1.2. Tindur (south facing)

Figure 12 illustrates vegetation cover distribution within Tindur transect for the years 2004 and 2019. A summary of the results can be further explored in detailed tables represented in appendix I. In 2019, [1] heathland covered (2%) of the study area, whereas no [2] grassland was detected, [3] moss-heath represented the largest vegetation coverage (47%), while [4] sand/gravel was the second largest class (45%) and [5] glacier covered approximately (6%) of the study area. These findings are further illustrated with the pie charts in figure 13. When changes between 2004 and 2019 were examined, it was identified that moss-heath was the only class showing an increase in coverage (7%), whereas all other classes were showing a decrease, heathland (-2%), sand/gravel (-3%) and glacier (-2%). Vegetation cover has thus been increasing while non or sparsely vegetated sand/gravel and glacier were decreasing and retreating.



Source: National Land Survey of Iceland Projection: ISN2016/Lambert2016

Figure 10 Tindur vegetation distribution 2004.

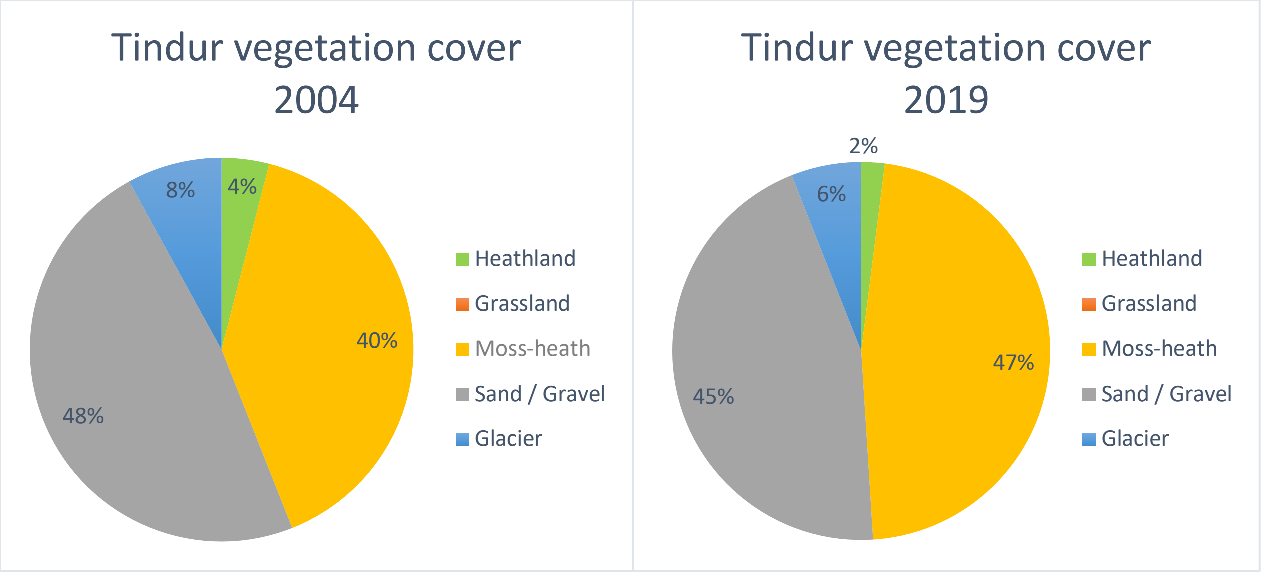


Figure 11 Tindur vegetation cover 2004 and 2019

The changes in vegetation cover are illustrated on a map (figure 14) where green indicates areas where vegetation cover has increased and red shows areas where vegetation cover has decreased. The same changes are illustrated in figure 15 where the changes are separated by classes.

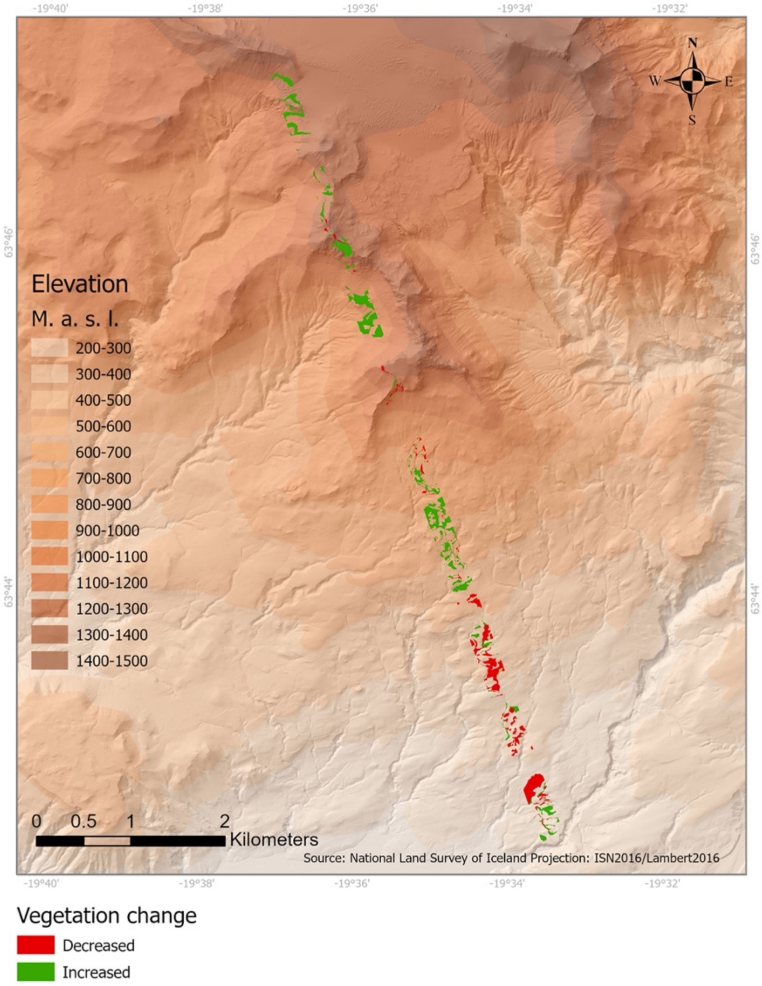


Figure 12 Change in vegetation cover for Tindur transect between the years 2004 and 2019. Red indicates decreased vegetation and green increased vegetation.

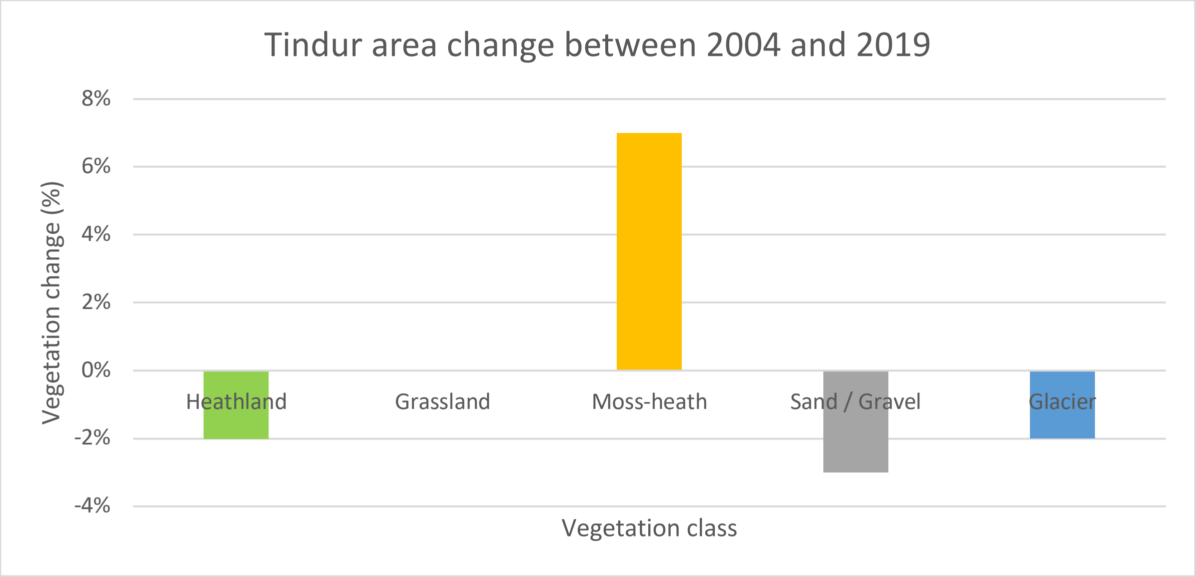


Figure 13 Tindur area change in vegetation cover between the years 2004 and 2019 (%)

4.2. Temporal vegetation distribution in relation to climate warming

When the change in vegetation cover between the two years is compared to mean monthly average temperature for similar timespan (2006-2019), the findings indicate an increase in vegetation cover analogue to increased trend in mean monthly average temperature. The increase in temperature is approximately 1°C along the 15-year timespan.

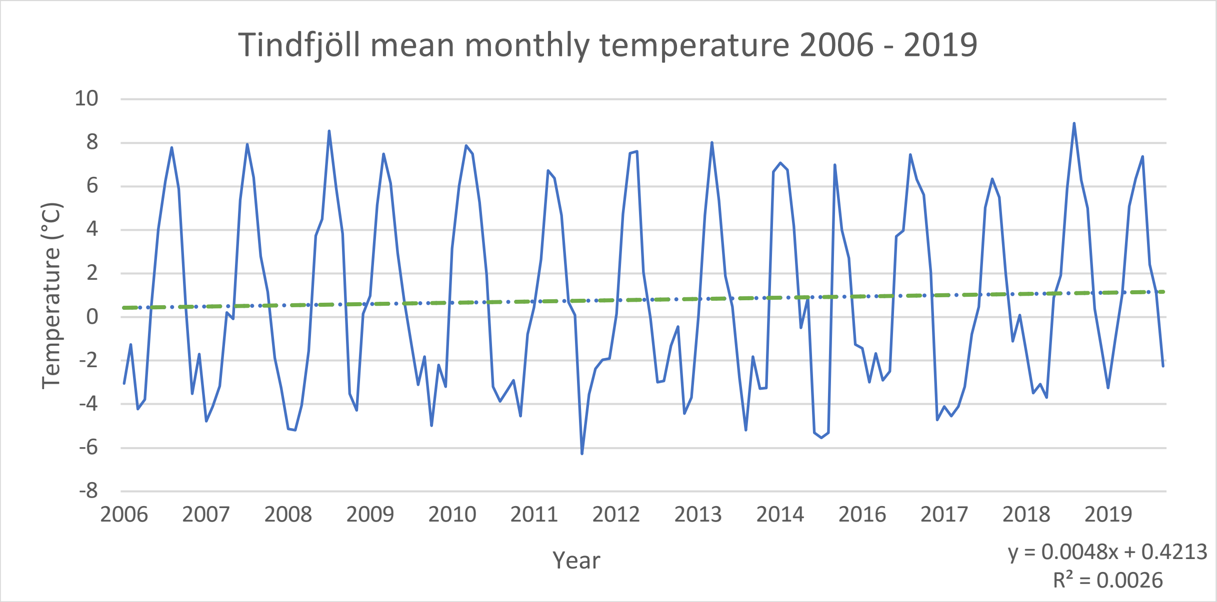


Figure 14 Mean monthly temperature 2006-2019 with a trend line (green dashed line) (Source: IMO, 2022).

The mean monthly average temperature for the years 2006 and 2019 further shows that spring starts earlier in the year 2019 compared to the year 2006 and the summer maximum is moreover reached about 1 month earlier for the same years (see figure 17a). Figure 17b illustrates the

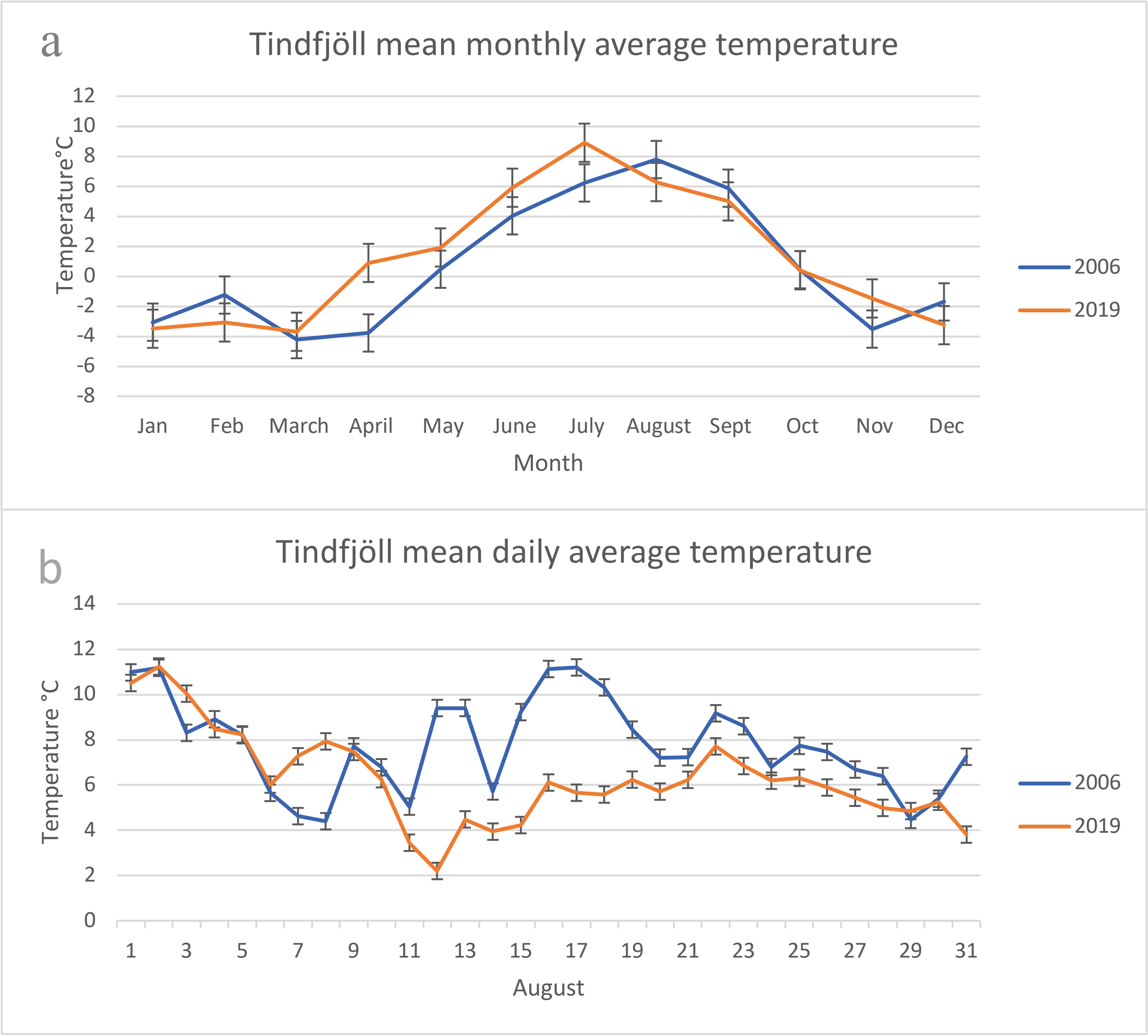


Figure 15 a) Mean monthly average temperature 2006 and 2019 b) Mean daily average temperature in August 2006 and 2019 (Source: IMO, 2022).

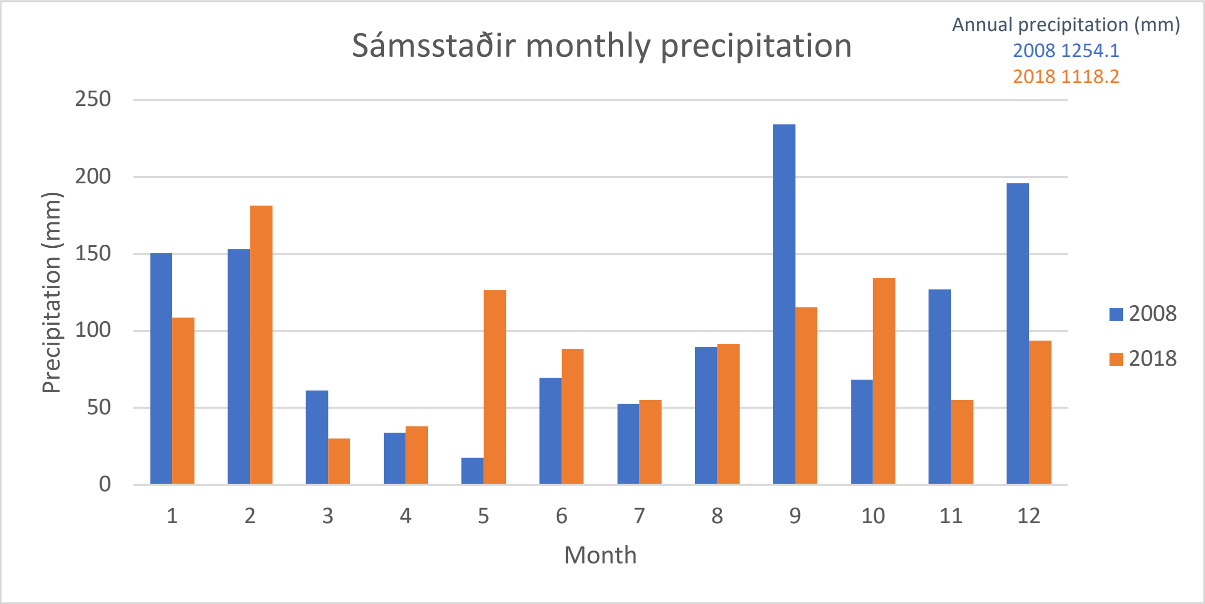


Figure 16 Monthly precipitation at Sámsstaðir weather station 2008 and 2018 (Source: IMO, 2022).

variation within the month of August for the same years. Figure 18 shows the precipitation variation (monthly precipitation) at Sámsstaðir weather station at the lowlands southwest of Tindfjöll for the years 2008 and 2018.

4.3. Spatial vegetation distribution in relation to elevation

Vegetation cover was also examined in relation to elevation where changes were explored within 100 meter elevation zones.

4.3.1. Austurdalur

The vegetation cover within Austurdalur transect has shown an increase for the class moss-heath through all elevation zones. Grassland has also shown an increase between 500 and 700 meters, whereas it has decreased at lower zones between 300 and 500 meters. The classes sand/gravel and glacier have on the contrary shown a significant decrease. Overall, the vegetation cover has thus increased whereas the non- or sparsely vegetated classes have decreased. Figure 19 represents the distribution of vegetation cover in relation to elevation zones and detailed tables presenting the results is to be found in appendix B.

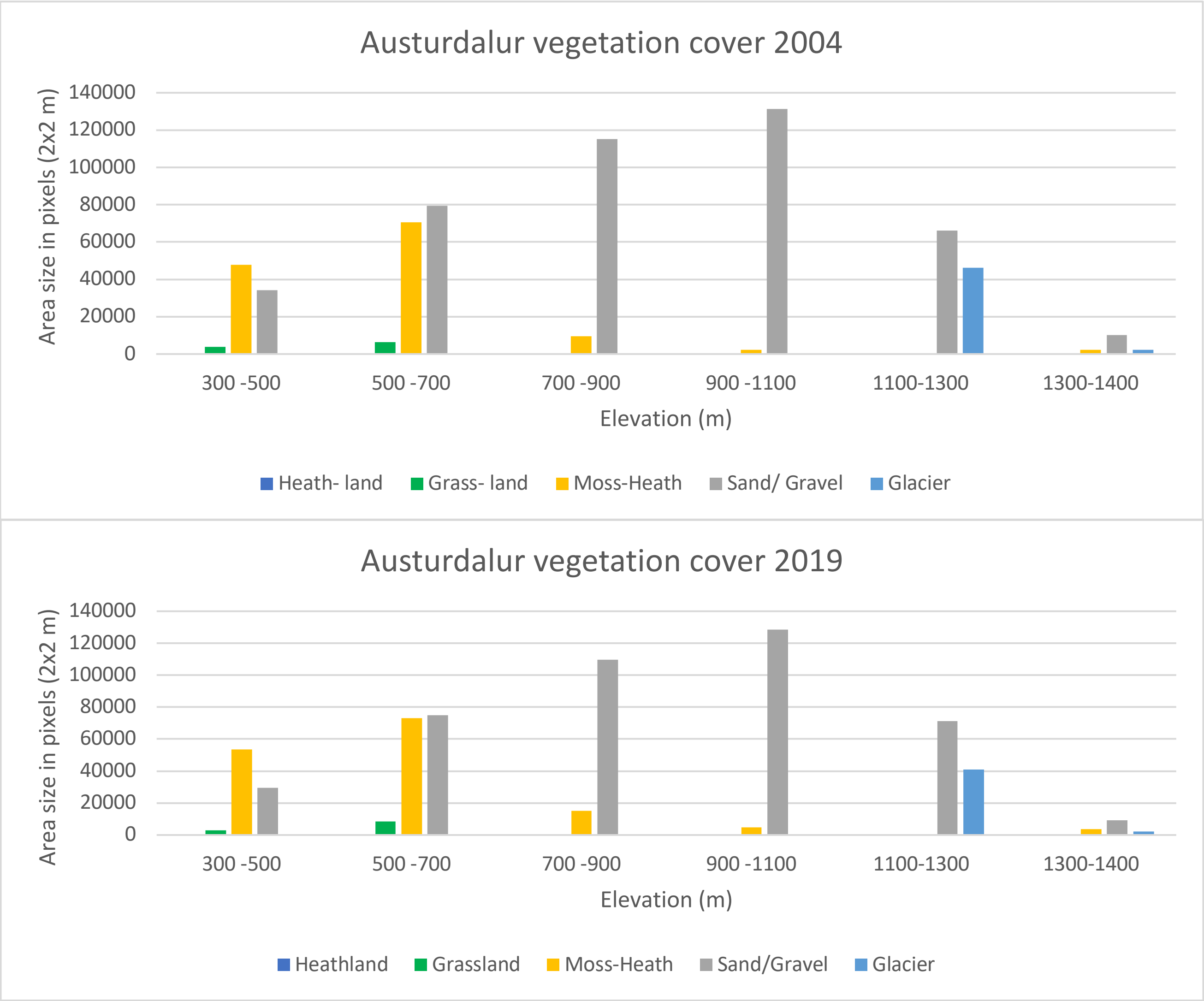


Figure 17 Austurdalur area of vegetation change in relation to elevation (m) between the study years 2004 and 2019. Figure shows area size in number of pixels (2x2).

4.3.2. Tindur

When Tindur transect vegetation change was explored in relation to elevation it was identified that the vegetation line is slightly moving upwards. The vegetation class moss-heath was detected at the altitude of over 1300 m in 2019, whereas no moss-heath was recorded for that altitude in 2004 (see figure 20). Moss-heath has decreased at lower altitudes but increased at higher elevation zones between the two study years. Heathland is also identified to be smaller in the year 2019 than in 2004, especially around 500 m altitude.

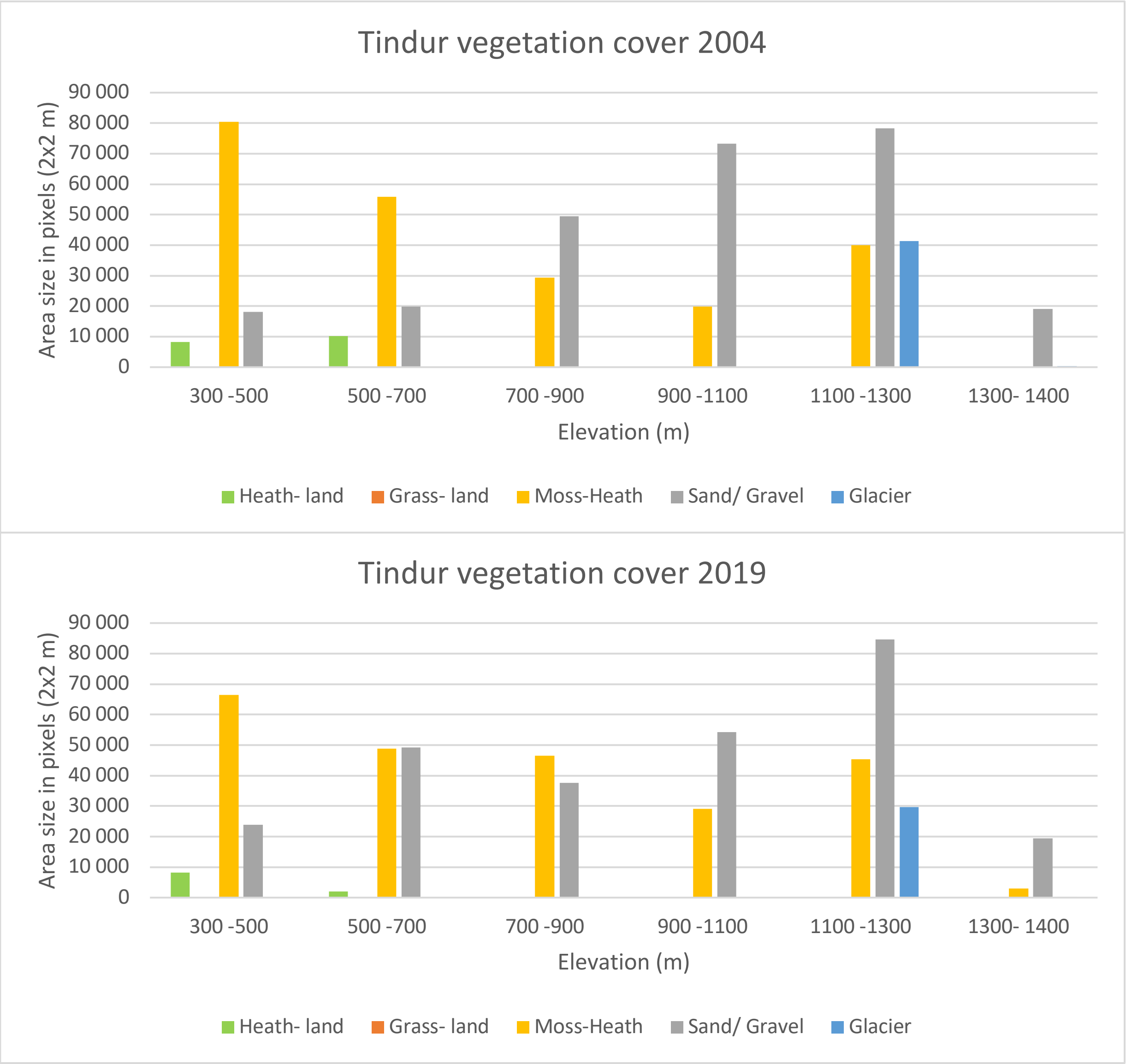


Figure 18 Tindur area of vegetation change in relation to elevation (m) for the study years 2004 and 2019. Figure shows area size in number of pixels (2x2).

4.4. Spatial vegetation distribution in relation to aspect

Vegetation cover is shown to be substantially affected by aspect. The pie charts (figure 9 and figure 13) show how the vegetation classes are proportionally distributed. These findings show that vegetation cover is significantly more abundant in the south facing study site (Tindur) with approximately 49% vegetation cover whereas in the West facing site (Austurdalur) has only around 26% vegetation cover. This is in accordance with previous studies which have reported that incoming solar radiation is having a great impact on vegetation dynamics, south facing slopes showing higher vegetation coverage than north facing slopes (Dobrowski et al., 2009;

Titshall et al. 2000). The changes in vegetation cover have also been shown to be more intense within the south facing transect of Tindur than the west facing transect of Austurdalur.

4.5. Accuracy assessment

To evaluate the findings and assess the accuracy of the study, an accuracy assessment was performed. An error matrix was constructed by comparing reference data points to the same point on the digitised map, hence calculating both user´s and producer´s accuracy as well as the total accuracy. Kappa coefficient was calculated to examine and summarise the results. The Kappa calculation confirmed an agreement between the datasets for both transects. Austurdalur shows a moderate agreement (0.52) while Tindur shows a fair agreement (0.29). Overall accuracy for Austurdalur transect is 70% but 50% for Tindur transect. Detailed information about the accuracy of the study can be found in appendix C.

5. Discussion

5.1. Climate warming and vegetation dynamics

For decades, it has been argued in the literature that climate warming is greatly affecting vegetation dynamics, and even stronger impact has been identified in the high latitudes (IPCC, 2014; Prevéy et al. 2017). The findings from this study support these reporting, with both transect sites showing a conservative change in vegetation cover between the two study years. Time series analysis of data from the weather station in Tindfjöll further agrees with the global climate warming, showing an increased trend in temperature of approximately 1°C between the years 2006-2019 (IMO, 2022).

Previous studies have suggested that temperature is the most influencing factor on plant distribution, and agree that a considerable increase in NDVI index, which is an indicator of increased vegetation productivity and greening of the arctic, is due to climate warming (Lookingbill and Urban, 2003; Reynolds et al., 2015). This study indicates an increase in vegetation cover, the vegetation class moss-heath for both transects, Austurdalur for all elevation zones and Tindur for elevation zones over 700 m. Reporting of browning where vegetation productivity has decreased is however also argued in the literature. Raynolds et al.,

(2015) have suggested that disturbance caused by the eruption in Eyjafjallajökull in 2010 is a contributing factor to a browning in the neighbourhood of the volcano. This reporting corresponds to the finding of this study where vegetation has decreased for Tindur transect below 700 m (see figure 20). Other studies have suggested a decrease in vegetation cover to be related to increased winter warming and the reduce of protecting snow cover (Bokhorst et al.,2009).

Vegetation cover in Iceland has undergone a considerable erosion since the settlement (around 870 CE), at the time some 60% of the country was covered with vegetation, while today only around 27% is vegetated. Largely considered due to grazing of livestock, deforestation, disturbances by frequent volcanic eruptions and periods of cooling trends are considered among the main factors behind the erosion (Arnalds et al., 2001; Crofts, 2011). Icelandic soils are highly vulnerable to erosion as the most common soils, the volcanic Andosols and Vitrisols weather very easily due to lack of cohesion (Arnalds et al., 2001). Vegetation cover in mountain areas have received less attention until recently, yet it is vital to create an understanding of distribution and dynamics of vegetation cover in the mountain environment as it plays an important role in preventing erosion, against natural hazards such as landslides and rockfall as well as being an important carbon sink and a feedback loop (Brang et al., 2001; Arnalds, 1987; Gitelson et al., 2002).

5.1.1. Longer growing seasons

Figure 17 a) shows that spring arrives about a month earlier in the year 2019 than in the year 2006 and the same figure shows further the maximum summer temperature to be reached approximately one month earlier between the same years. This means however delayed dormancy as autumn is stretched and winter does not arrive earlier. These findings correspond to previous studies which have carefully examined phenology and its relationship to climate change (Prevéy et al. 2017). Longer growing seasons with shifts in vegetation phenology is considered a robust indicator of climate warming where both early spring and delayed dormancy is the contributing factor (Piao et al., 2006, White et al., 2009; Zeng et al., 2011) reported an earlier start of the growing season in the northern high latitudes of an average of 4.7 days per decade and delayed end of the growing season by 1.6 days. This phenomenon was however considered not evenly distributed and significantly higher in North America than in

Eurasia. Wenquan et al. (2011) agree with these reporting but identify that it is rather the delayed dormancy that fuels the extended growing season length in North America.

Earlier growth onset is especially significant for early growing species such as shrubs even though all species have been reported sensitive towards high-latitude location (Radville et al., 2016; Prevéy et al. 2017). The change varies however not only according to latitude but also with relation to longitude, which emphasises the consideration that inter annual variation has large impact on vegetation growth (Hurrell, 2003; Chen et al., 2019). Long-term monitoring is therefore essential. Olafsson and Rousta (2021) have addressed the inter annual variation by examining the NAO and its influence on vegetation productivity, finding that negative NAO brings cold and dry periods with less productive vegetation while positive NAO brings warm and wet green periods with more productive vegetation.

5.1.2. Winter warming

Climate warming not only means increased summer temperature, but also winter warming which is projected to become even more prominent than summer warming (European Environmental Agency, 2014). The mean monthly average temperature comparison between the years 2006 and 2019 (figure 17 a)) does not indicate higher winter temperature, yet the time series analysis in figure 16 shows an increased trend in mean monthly temperature. The increase is around 1°C for the period 2006-2019 which implies a warming trend in both summer and winter temperature. South side of the mountain is considered to represent higher precipitation than the west side, and the south facing transect of the study shows a decrease in vegetation cover below 700 m. This decrease in vegetation cover might thus be considered due to less snow cover as higher temperature might imply increase in rain at lower altitudes at the expense of snow during the winter months.

This phenomenon is still poorly studied and requires careful attention. Snow cover plays a vital role in arctic climate as it is an important insulation of the soil during heavy frost periods and hence a critical factor for the prevention of frost damage. Earlier spring may also increase the risk of frost damage due to more frequent frost events during the growing season. Hence, the high latitudes are highly sensitive to winter climate change (Kreyling, 2010; Liu et al., 2018), and the above-mentioned findings of this study might indicate the future impact of climate warming and higher winter temperature. It is thus important to enhance research in this field and to monitor changes in vegetation cover in relation to snow cover.

5.1.3. Precipitation

Precise precipitation data for the transect sites is not available, therefore accurate estimation of difference in precipitation between the sites is not available and the interpretation must therefore be accepted with caution. According to Einarsson (1971), the mountainous landscape of the study sites significantly affects the precipitation in the area while cyclones bring wet air from the south with increased precipitation windward of the mountains creating a rain shadow (decreased precipitation) leeward. Tindur transect site is located windward whereas Austurdalur transect site is located leeward. The highest rainfall in Iceland is at the glaciers in South of Iceland fuelling the glacier formation (Einarsson, 1971). Yet climate warming is significantly affecting the class glacier, which has shown a decrease between the years for both transects.

Interestingly, the class moss-heath includes 47% coverage in Tindur transect site (south facing) but only 24% coverage in Austurdalur transect site (West facing) (2019) where both transects have shown an increase for the class moss-heath, 7% and 3% respectively. 45% is covered with sand/gravel in Tindur study site but 67% in Austurdalur, both transects showed identical decrease for the class sand/gravel (3%). These findings go hand in hand with the described rain pattern and rain shadow in the area, however the lack of accurate precipitation data limits the interpretation.

5.2. Vegetation distribution in relation to topography.

5.2.1. Elevation

This study has considered heterogenous landscape and its relation to vegetation distribution. Elevation plays an important role and has significant influence on vegetation distribution as higher altitude means lower temperature (elevational gradient) (Rist et al., 2020). There has been reporting of the vegetation line moving upwards in the high latitudes on the northern hemisphere (Dimeyeva et al., 2015). Similarly, the findings of this study have also shown that vegetation line in Tindur study site is ascended for about 150 m between the two study years, reaching elevation above 1300 m. The vegetation class moss-heath is further identified to have increased more substantially with elevation, see figure 19 and figure 20.

5.2.2. Aspect and slope

A significant difference in vegetation cover is between the two transects according to aspect and slope. 49% of Tindur transect site was classified as heathland or moss-heath whereas only 26% of Austurdalur transect site was classified as grassland or moss-heath. The class sand/gravel covered 45% of Tindur transect site in 2019 and 67% of Austurdalur transect site while glacier covers 7% and 6% respectively. More intense solar radiation in south facing slopes along with heavier rainfall windward (south) of the mountains is likely to contribute to the difference as the altitude of the transects is similar between the two transects (Dobrowski et al., 2009; Titshall et al. 2000; Einarsson, 1971). Studies have further shown that in the northern hemisphere, the south facing slopes which receive more sunlight are expected to be more stable than North facing slopes and hence prevent erosion and natural hazards such as landslides (Claessens et al., 2013), potentially explaining the smaller fraction of sand/gravel at Tindur.

5.3. Limitations

Limitations due to uncertainty of the imagery data used for the analysis is an important and controlling factor which must be considered. The uncertainty can produce errors and inaccuracy of results and emerge in defective classification which can accumulate. Other factors such as shadows can also influence the interpretation (Lemenkova, 2015). The results show that there are both temporal and spatial variations within the study area, however, it must be considered that the study method relies mainly on human interpretation and manual digitizing which can be a subject to errors. The changes detected in the vegetation cover are relatively small (<8%) and requires attention. The reliability of the classification was evaluated by evaluating the overall performance of the classification and calculation of Kappa coefficient and the computed accuracy might indicate an uncertainty which is larger than the changes detected. Therefore, more transects providing reference data would further enhance the reliability. Other measures to limit digitising errors such as allowing some generalizations, use of features in the software (topological rules to avoid gaps and slivers while digitizing) have also been taken. Yet, a fundamental for the classification method is the criteria of homogeneity of objects which is often vaguely fulfilled, as the division between classes is not always very clear.

This study only considers the density and appearance of vegetation cover, but not species richness within the transects. Therefore, to examine more closely individual species within the transects, a more detailed field work and analysis would be required.

6. Conclusion

This study has proposed a very detailed and high scale analysis of two transects in Tindfjöll mountain area in Iceland, with the aim of comparing and assessing the change in vegetation cover between two years, 2004 and 2019. The objective was to analyse how vegetation cover is responding to warming climate in relation to topographic factors; elevation, aspect, and slope angle.

The findings have shown that:

- Vegetation cover has responded to warmer temperature and longer growing seasons with increased vegetation cover, especially moss-heath, at the expense of the classes sand/gravel and glacier. The most significant increases were found above 700 m altitude at the south facing slopes (Tindur) while increase in west facing slopes was moderate. Decrease in vegetation cover below 700 m for the south facing transect requires attention and is considered due to increased winter warming and less protecting snow cover.
- More dense vegetation coverage was detected at the south facing slope (Tindur) than at the west facing slope (Austurdalur) where the former site, with more incoming solar radiation creates a microclimate favourable to vegetation production.
- Vegetation line has ascended at south facing Tindur transect, by approximately 150 m elevation.

The transects represent elevation range from 300 m to 1300 m and two different aspects, South and West. The results illuminate the sensitivity of mountain areas towards climate change, how climate warming and longer growing seasons have increased vegetation cover whereas less protecting snow cover is considered to have decreased vegetation cover. The microclimate created by elevation, aspect and slope is furthermore greatly affecting vegetation dynamics as temperature decreases with height and the low sun angle of the Arctic provides more incoming solar radiation at the south facing than west facing slopes. The Arctic, where warming is two times faster than the rest of the planet, is an important carbon sink and a feedback loop. The knowledge gained in this study may indicate the responsiveness of the the high latitude environment to climate change and can indicate how other mountain areas of the Arctic are responding and serve as an implication for future vegetation development in these areas. Further assessment and monitoring of vegetation change are thus essential to scale up the complex arctic environment for future management and policy making.

7. References

Achilleos, G. A. (2010). Approaching a model for estimating horizontal errors of digitized contours. *Journal of Spatial Science Vol. 55, No. 1, June 2010, 147–164* https://doi.org/10.1080/14498596.2010.487856

Afuye, G.A.; Kalumba, A.M.; Orimoloye, I.R. (2021). Characterisation of Vegetation Response to Climate Change: A Review. *Sustainability, 13, 7265.* https://doi.org/10.3390/su13137265

Ahlström, A., Xia, J., Arneth A., Luo, Y. and Smith, B. (2015). Importance of vegetation dynamics for future terrestrial carbon cycling. *Environ. Res. Lett.* **10** 054019 https://doi.org/10.1088/1748-9326/10/5/054019

Allard A., Nilsson B., Pramborg K., Stahl G. and Sundquist S. (2003). Manual for aerial photo interpretation in the national inventory of landscapes in Sweden. https://www.diva-portal.org/smash/get/diva2:657639/FULLTEXT01.pdf

AMAP (2017). Snow, Water, Ice and Permafrost in the Arctic (**SWIPA**) https://www.amap.no/documents/doc/snow-water-ice-and-permafrost-in-the-arctic-swipa-2017/1610

Arnalds, O., Thorarinsdottir, E.F., Metusalemsson, S., Jonsson, A., Gretarsson, E. and Arnason, A. (2001). Soil Erosion in Iceland; Soil Conservation Service and Agricultural Research Institute: Reykjavik, Iceland,.

Arnalds, A. (1987). Ecosystem disturbance in Iceland. *Arctic and Alpine Research, 19 pp. 508-513.*

Arnardóttir, A., R., Sveinsdóttir, G., H., Arnarson, H. Ö., Sveinsdóttir, I., Árnason, Ó., Macrae, P., and Oxley, S. (2020). Landslag á Íslandi Flokkun og kortlagning landslagsgerða á landsvísu. https://www.skipulag.is/media/landsskipulagsstefna-vidbaetur/Skyrslan_Lokaeintak-2-.pdf

Bakrač, S., Marković, V., Drobnjak, S., Đorđević, D., & Stamenković, N. (2021). Using historical aerial photography for monitoring of environment changes: a case study of Bovan Lake, Eastern Serbia. *Journal of Environmental Engineering and Landscape Management*, *29*(3), 305-317. https://doi.org/10.3846/jeelm.2021.15567

Berner, L.T., Massey, R., Jantz, P. et al. (2020). Summer warming explains widespread but not uniform greening in the Arctic tundra biome. *Nat Commun* ***11,*** *4621.* https://doi.org/10.1038/s41467-020-18479-5

Bhatt, U. S., D. A. Walker, M. K. Raynolds, P. A. Bieniek, H. E. Epstein, J. C. Comiso, J. E. Pinzon, C. J. Tucker, and I. V. Polyakov, (2013). Recent declines in warming and arctic vegetation greening trends over pan-Arctic tundra*. Remote Sensing (Special NDVI3g Issue), 5, 4229-4254*; doi:10.3390/rs5094229.

Björnsson, H., Sigurðsson, B., D., Davíðsdóttir, B., Ólafsson, J., Ástþórssson, Ó., S., Ólafsdóttir, S., Baldursson, T., Jónsson, T. (2018). *Loftslagsbreytingar og áhrif þeirra á Íslandi – Skýrsla vísindanefndar um loftslagsbreytingar*. Veðurstofa Íslands.

Björnsson, H. (2017). *Glaciers of Southern Iceland.* In: The Glaciers of Iceland. Atlantis Advances in Quaternary Science, vol 2. Atlantis Press, Paris. https://doi.org/10.2991/978-94-6239-207-6_5

Bokhorst, S. F., Bjerke, J. W., Tømmervik, H., Callaghan, T. V., & Phoenix, G. K. (2009). Winter warming events damage sub-Arctic vegetation: Consistent evidence from an experimental manipulation and a natural event. *Journal of Ecology, 97(6), 1408–1415*. https://doi.org/10.1111/j.1365-2745.2009.01554.

Brang, P., Schönenberger, W., Ott, E., Gardner, R.H. (2001). *Forests as protection from natural hazards*. In: Evans, J. (Ed.), The Forests Handbook. Blackwell Science Ltd., Oxford, pp. 53-81.

Braun-Blanquet, J. (1948). La végétation alpine des Pyrénées Orientale. *Cons*
Bring, A., I. Fedorova, Y. Dibike, L. Hinzman, J.M. Karlsson, S.H. Mernild, T. Prowse, O. Semenova, S. Stuefer and M.-K. Woo, (2016). Arctic terrestrial hydrology: A synthesis of processes, regional effects, and research challenges. [Special Issue] *Journal of Geophysical Research: Biogeosciences, 121:621-649.*

Buitenwerf, R., Sandel, B., Normand, S., Mimet, A. and Svenning, J. C. (2018). Land surface greening suggests vigorous woody regrowth throughout European semi-natural vegetation. https://doi.org/10.1111/gcb.14451

Böhner, J., Antonić, J. (2009). Editor(s): Tomislav Hengl, Hannes I. Reuter,Developments in Soil Science, *Elsevier,Volume 33,Pages 195-226,*
Cáceres, M. D. And Wiser, S. K. (2011). Towards consistency in vegetation classification. *Journal of Vegetation Science. Volume 23. Isssue 2, p. 387-393* https://doi.org/10.1111/j.1654-1103.2011.01354.x

Chen, C., Bin, Wenping, H., Lanlan, Y., and Yafeng, G. (2019). Increasing interannual variability of global vegetation greenness. *Environ. Res. Lett.* 14 124005. https://iopscience.iop.org/article/10.1088/1748-9326/ab4ffc

Cochran, W. G. (1977). *Sampling Techniques.* John Wiley and Sons, Inc.

Cohen, J. 1960. A coefficient of agreement for nominal scales.Educ. Psychol. Measure. 20: 37-46.

Congalton, R.G. 1991. A review of assessing the accuracy ofclassifications of remote sensed data. *Remote Sens.Environ.37: 35-46.*

Crofts, R. (2011). *Healing the Land: The Story of Land Reclamation and Soil Conservation in Iceland*; Soil Conservation Service of Iceland: Reykjavik, Iceland,.

De Beurs, K. M., & Henebry, G. M. (2010). A land surface phenology assessment of the northern polar regions using MODIS reflectance time series. *Canadian Journal of Remote Sensing*, 36(sup1), S87–S110.

Dimeyeva, L., Sitpayeva, G., Sultanova, B., Ussen, K., Islamgulova, A. (2015). *High-Altitude Flora and Vegetation of Kazakhstan and Climate Change Impacts.* In: Öztürk, M., Hakeem, K., Faridah-Hanum, I., Efe, R. (eds) Climate Change Impacts on High-Altitude Ecosystems. Springer, Cham. https://doi.org/10.1007/978-3-319-12859-7_1

Callaghan, T.V., Cazzolla G., R. & Phoenix, G. (1999). The need to understand the stability of arctic vegetation during rapid climate change: An assessment of imbalance in the literature. *Ambio **51,** 1034–1044 (2022).* https://doi.org/10.1007/s13280-021-01607-w

Claessens, L and Temme, A J A M and Schoorl, J M (2013) *Mass-Movement Causes: Changes in Slope Angle.* In: *Treatise on Geomorphology Volume 2: Quantitative Modeling of Geomorphology. Reference Module in Earth Systems and Environmental Sciences, 2 . Elsevier , London, UK, pp. 212-216.*

Clark W.V., and Hosking P.L., 1986. *Statistical methods for geographer*, John Wiley & Sons, New York.

Dorner, B., Lertzman, K., and Fall, J., (2002) Landscape pattern in topographically complex landscapes: issues and techniques for analysis. *Landscape Ecology 17: 729 – 743.* https://link.springer.com/content/pdf/10.1023/A:1022944019665.pdf

Einarsson, M. Á. (1971). *Climate of Iceland.* https://www.vedur.is/media/loftslag/myndasafn/frodleikur/Einarsson.pdf

European Environment Agency, (2014). Projected changes in annual, summer and winter temperature.

European Environment Agency, (2022). *EUNIS habitat classification.* https://www.eea.europa.eu/data-and-maps/data/eunis-habitat-classification-1

Franklin, J. (1995). Predictive vegetation mapping: geographic modelling of biospatial patterns in relation to environmental gradients. *Physical Geography 19(4):474–499*

Frost, G. V., and H. E. Epstein, (2014). Tall shrub and tree expansion in Siberian tundra ecotones since the 1960s. *Global Change Biol.*, 20, 1264-1277.

Gessesse, A., A. and Melesse, A., M. (2019). *Temporal relationships between time series CHIRPS-rainfall estimation and eMODIS-NDVI satellite images in Amahara Region, Ethiopia.* In Extreme Hydrology and Climate Variability. https://www.sciencedirect.com/science/article/pii/B9780128159989000087

Gitelson, A., A., Kaufman, Y., J., Stark, R. and Rundquist, D. (2002). Novel algorithms for remote sensing estimation of vegetation fraction. *Remote Sensing of Environment, 80 (1), pp. 76-87*

Gísladóttir, F. O., Arnalds, O. and Gísladóttir, G. (2005). The Effect of Landscape and Retreating Glaciers on Wind Erosion in South Iceland. *Land Degrad. Develop. 16: 177–187* DOI: 10.1002/ldr.645

Golden, M., Johnson, J., Landrum, V., Powell, J., Varner, V. and Wirth, T. Maus P. (editor). (1995). *Guidlines for Use of Digital Imagery for Vegetation Mapping.* https://books.google.is/books?hl=en&lr=&id=vcX1CJJL85kC&oi=fnd&pg=PA1&dq=most+used+satellites+for+vegetation+mapping&ots=E1JD3B6x9R&sig=pkUf0AwASJ1dFomfCkA5vcdLt6c&redir_esc=y#v=onepage&q=most%20used%20satellites%20for%20vegetation%20mapping&f=false

Gregorio, A. (2005). *Land Cover Classification System. Classification concepts and user manual.* https://books.google.is/books?hl=en&lr=&id=xUyVNK98gTkC&oi=fnd&pg=PR4&dq=land+cover+classification&ots=qs-5CmELrW&sig=n15qLTIdq4ExAtYAqGJjGW3cN_U&redir_esc=y#v=onepage&q=land%20cover%20classification&f=false

Hatfield, J. L. and Prueger, J. H. (2015). Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes, Vol. 10, Part A. P 4-10.* https://doi.org/10.1016/j.wace.2015.08.001

Herzon, I., Raatikainen, K. J., Wehn, S., Rūsiņa, S.A., Helm, S. A., Cousins, O., and V. Rašomavičius. (2021). Semi-natural habitats in boreal Europe: a rise of a social-ecological research agenda. *Ecology and Society 26(2):13*. https://doi.org/10.5751/ES-12313-260213

Hjartarson, G. (2007). *Skýrsla um veðurmælingar í Tindfjöllum 1. nóvember 2005 - 31. júlí 2007.* http://www.isalp.is/wp-content/uploads/2020/09/sk%C3%BDrslaumve%C3%B0urm%C3%A6lingar%C3%ADTindfj%C3%B6llum.pdf

Hurrell, J. W. (2003). Climate variability: North Atlantic and Arctic Oscillation. In J. Holton, J. Pyle, & A.J. Curry (Eds.), *Encyclopedia of Atmospheric Sciences* (pp. 439–445). Academic Press.

Kreyling, J., Grant, K., Hammerl, V. *et al.* (2019). Winter warming is ecologically more relevant than summer warming in a cool-temperate grassland. *Sci Rep* **9,** 14632 https://doi.org/10.1038/s41598-019-51221-w

Kreyling, J. (2010). Winter climate change: a critical factor for temperate vegetation performance. *Ecology* **91**, 1939–1948

Laska, G. (2001). The disturbance and vegetation dynamics: A review and an alternative framework. Plant Ecology 157: 77–99, 2001 https://link.springer.com/content/pdf/10.1023/A:1013760320805.pdf

Leblans, N. I., Sigurdsson, B. D., Vicca, S., Fu, Y., Penuelas, J. and Janssens, I. A. (2018). Phenological responses of Icelandic subarctic grasslands to short -term and long - term natural soil warming. doi: 10.1111/gcb.13749

Lemenkova, P. (2015). Topology, Homogeneity and Scale Factors for Object Detection: Application of eCognition Software for Urban Mapping using Multispectral Satellite Image.

Li, K., Liu, X., Hu, Y., Mohammat, A., Geng, F., & Han, W. (2020). Long-term increasing productivity of high-elevation grassland caused by elevated precipitation and temperature. *Rangeland Ecology & Management*, 73(1), 156–161.

Liu, Q., Piao, S., Janssens, I. A., Fu, Y., Peng, S., Lian, X. U., ... & Wang, T. (2018). Extension of the growing season increases vegetation exposure to frost. *Nature communications*, *9*(1), 1-8.

Looijen, J., (2004). Land Cover Mapping Using Remote Sensing And GIS. Lecture handout. ITC.

Lookingbill and Urban, (2003). Spatial estimation of air temperature differences for landscape scale studies in montane environments. *Agricultural and Forest Meteorology, 114 pp. 141-151*

Moles J. D., McGarvie D, Stevenson J. A. & Sherlock S. C. (2018). Geology of Tindfjallajökull volcano, Iceland. *Journal of Maps, 14:2, 22-31*, DOI: 10.1080/17445647.2018.1425163

Morgan, J. L., Gergel, S. E., and Coops, N. S., (2010). Aerial Photography: A Rapidly Evolving Tool for Ecological Management. *BioScience*, *Volume 60, Issue, Pages 47–59,* https://doi.org/10.1525/bio.2010.60.1.9

Nelson, T., Wulder, M., and Niemann, K. O., (2001). Spatial resolution implications of digitizing aerial photohraphy for environmental applications. *Imaging Science Journal. 49 (4): 223-232*. doi.org/10.1080/13682199.2001.11784386

Noorollahi, Y. (2005). *APPLICATION OF GIS AND REMOTE SENSING IN EXPLORATION AND ENVIRONMENTAL MANAGEMENT OF NÁMAFJALL GEOTHERMAL AREA, N-ICELAND.* https://orkustofnun.is/gogn/unu-gtp-report/UNU-GTP-2005-01.pdf

Olafsson H. & Rousta I. (2021). Influence of atmospheric patterns and North Atlantic Oscillation (NAO) on vegetation dynamics in Iceland using Remote Sensing. *European Journal of Remote Sensing, 54:1, 351-363,* DOI: 10.1080/22797254.2021.1931462

Ottósson, J. G., Sveinsdóttir, A. and og Harðardóttir, M. (edit.). (2016). *Vistgerðir á Íslandi. Fjölrit Náttúrufræðistofnunar nr. 54. 299*

Pavri, F. & Farrell, D. (2021) Arctic landscape transitions: ice cap and terrestrial margins across Hofsjökull, Iceland, *Physical Geography, 42:5, 472-488*, DOI: 10.1080/02723646.2020.1839212

Piao, S., Fang, J., Zhou, L., Ciais, P. & Zhu, B. (2006). Variations in satellite-derived phenology in China´s temperate vegetation. Global Change Biology, 12, 672-685.

Pickett, S. T. A. (1980). Non-equilibrium coexistence of plants. BULLETINOFTHET ORREYBOTANICALCLUB VOL. 107, No. 2, p https://www.jstor.org/stable/pdf/2484227.pdf

Pinto, A. T., José A. G., Pedro., and João P. H. (2019). "From Archived Historical Aerial Imagery to Informative Orthophotos: A Framework for Retrieving the Past in Long-Term Socioecological Research. *Remote Sensing 11, no. 11: 1388.* https://doi.org/10.3390/rs11111388

Poortinga, A., Visser, S. M., Riksen, M. J. P. M. & Stroosnijder, L. (2011). Beneficial effects of wind erosion: Concepts, measurements, and modelling. *Aeolian Res. 3, 81–86*

Prevéy, J., M. Vellend, N. Rüger, R. D. Hollister, A. D. Bjorkman, I. H. Myers-Smith, S. C. Elmendorf, K. Clark, E. J. Cooper, B. Elberling, et al. 2017. Greater temperature sensitivity of plant phenology at colder sites: Implications for convergence across northern latitudes. *Global Change Biology* 23 (7):2660–71. doi:https://doi.org/10.1111/gcb.13619.

Raynolds, M., Magnusson, B., Magnusson, S and Magnusson, S. (2015). Warming, Sheep and Volcanoes: Land Cover Changes in Iceland Evident in Satellite NDVI Trends. *Remote Sensing, 7(8):9492-9506* 10.3390/rs70809492

Raynolds M. K., Josefino C. A., Comiso B., Walker, D. A., and Verbyla C. (2008). Relationship between satellite-derived land surface temperatures, arctic vegetation types, and NDVI. *Remote Sensing of Environment 112.. 1884–1894.* https://www.geobotany.org/library/pubs/RaynoldsMK2008_rse_112_1884_p11.pdf

Richardson, A.D., Keenan, T.F., Migliavacca, M., Ryu Y, Sonnentag, O., Toomey, M. (2013). Climate change, phenology, and phenological control of vegetation feedbacks to the climate system. *Agricultural and Forest Meteorology, 169, 156 -173.*

Riihimaki, H., Heiskanen, J. And Luoto, M. (2017). The effect of topography on arctic-alpine aboveground biomass and NDVI patterns. Earth Observation and Geoinformation. Vol. 56, p. 44-53. https://doi.org/10.1016/j.jag.2016.11.005

Rist, A., Roth, L. & Veit, H. (2020). Elevational ground/air thermal gradients in the Swiss inner Alpine Valais, Arctic, Antarctic, and Alpine Research, 52:1, 341-360, DOI: 10.1080/15230430.2020.1742022

Runnström, M. C., Ólafsdóttir, R., Blanke, J., & Berlin, B. (2019). Image Analysis to Monitor Experimental Trampling and Vegetation Recovery in Icelandic Plant Communities. *Environments*, *6*(9), 99. MDPI AG. http://dx.doi.org/10.3390/environments6090099

Stehman, S. (1992). Comparison of systematic and random sampling for estimating the accuracy of maps generated from remotely sensed data. *PE & RS-Photogrammetric Engineering and Remote Sensing*, *58*(9), 1343-1350.

Thapa, K., & Bossler, J. (1992). Accuracy of spatial data used in geographic information systems. Photogrammetric Engineering & Remote Sensing, vol. 58, no. 6, pp. 835–841.

Thompson, W. L., White,g. C. and Gowan, C. (1998). Monitoring Vertebrate Populations, *Academic Press, Pages 43-73*, doi.org/10.1016/B978-012688960-4/50002-2.

Titshall, L.W., O'Connor, T.G., and Morris, C.D., (2000). Effect of long-term exclusion of fire and herbivory on the soils and vegetation of sour grassland. *African Journal of Range and Forage Science, 17, 70–80.*

UNESCO. (1973). International classification and mapping of vegetation. *UNESCO Ecology and Conservation Series 6. pp. 1-93.* UNESCO, Paris.

Urban, D.L., O'Neill, R.V. and Shugart Jr., H.H. (1987). Landscape Ecology. A Hierarchical Perspective. Can Help Scientists Understand Spatial Patterns? *Bioscience, 37, 119-127.* https://doi.org/10.2307/1310366

Walker, D. A., Raynolds, M. K., Daniëls, F. J.A., Einarsson, E., Elvebakk, A., Gould, W. A., Katenin, A. E., Kholod, S., Markon,C., Melnikov, E., Moskalenko, N.,Talbot, S. and Yurtsev, B. A. (2005). The Circumpolar Arctic vegetation map. *Journal of Vegetation Science 16: 267-282* https://onlinelibrary.wiley.com/doi/epdf/10.1111/j.1654-1103.2005.tb02365.x

Westhoff, V., Van Der Maarel, E. (1978). The Braun-Blanquet Approach. In: Whittaker, R.H. (eds) *Classification of Plant Communities. Classification of Plant Communities, vol 5-1.* Springer, Dordrecht. https://doi.org/10.1007/978-94-009-9183-5_9

White, M.A., de Beurs, K.M., Didan, K. et al. (2009). Intercomparison, interpretation, and assessment of spring phenology in North America estimated from remote sensing for 1982-2006. Global Change Biology, 15, 2335-2359.

Zhou, Y. (2020). Relative Contribution of Growing Season Length and Amplitude to Long-Term Trend and Interannual Variability of Vegetation Productivity over Northeast China. *Forests*, *11(1), 112*.

Appendix A. Summary of classification

Vegetation changes within two transects were analyses by comparing aerial photographs from two different years, 2004 and 2019. The table shows a summary of the changes detected (km^2) within each transect.

Austurdalur (2.5 km^2)	*2004*	*2019*	*Change*
Heathland	-	-	-
Grassland	0.04 km^2 (1 %)	0.05 km^2 (2%)	0.6%
Moss-heath	0.53 km^2 (21%)	0.6 km^2 (24%)	3%
Sand / Gravel	1,75 km^2 (70%)	1,69 km^2 (67%)	-2%
Glacier	0.19 km^2 (8%)	0.17 km^2 (7%)	-1%
Total	2.5 km^2 (100%)	2.5 km^2 (100%)	

Tindur (2 km^2)	*2004*	*2019*	*Change*
Heathland	0.08 km^2 (4%)	0.04 km^2 (2%)	-2%
Grassland	-	-	-
Moss-heath	0.81 km^2 (40%)	0.96 km^2 (47%)	7%
Sand / Gravel	0.98 km^2 (48%)	0.92 km^2 (45%)	-3%
Glacier	0.17 km^2 (8%)	0.12 km^2 (6%)	-2%
Total	2 km^2 (100%)	2 km^2 (100%)	

Appendix B. Summary of vegetation cover distribution according to elevation zones (pixel size 2x2).

Vegetation cover changes was analysed in relation to elevation. Elevation was sliced into 200 meter elevation zones and the table shows the vegetation cover distribution within each zone for each study site.

			Vegetation type				
Study site	Year	Elevation zone (m)	Heath-land	Grass-land	Moss-Heath	Sand/ Gravel	Glacier
Austurdalur	2004	300 -500		3 880	47 781	34 252	
		500 -700		6 230	70504	79 437	
		700 -900			9 666	115 293	
		900 -1100			2215	131 384	
		1100-1300			70	66 220	46 136
		1300-1400			2346	10 313	2358
Total			0	10 110	132 582	436 899	48 494
Austurdalur	2019	300 -500		2 930	53 721	29 606	
		500 -700		8 370	73 139	74 857	
		700 -900			15 090	109 794	
		900 -1100			4682	128 547	
		1100-1300			242	71 314	40 844
		1300-1400			3512	9229	2242
Total			0	11 300	150 386	423 347	43 086

			Vegetation type				
Study site	Year	Elevation zone (m)	Heath-land	Grass-land	Moss-Heath	Sand/ Gravel	Glacier
Tindur	2004	300 -500	8 166		80 432	18095	
		500 -700	10 194		55 835	19 901	
		700 -900			29 397	49 527	
		900 -1100			19 958	73 228	
		1100 -1300			40 034	78 307	41 244
		1300- 1400				19 077	410
Total			18 360	0	225 656	258 135	41 654

Tindur	2019	300 -500	8 285		66 472	23 930	
		500 -700	2 039		48 921	49 310	
		700 -900			46 540	37 692	
		900 -1100			29 146	54 321	
		1100 -1300			45 271	84 570	29 710
		1300- 1400			2 982	19 465	128
Total			10 324	0	239 332	269 288	29 838

Appendix C. Summary of accuracy assessment

Reference data was collected in the field to evaluate the classification performed in the study. The ground truth creates a link between the aerial photography data and the real surface of the Earth. The tables below show the accuracy assessment calculated for each of the transects.

REFERENCE TINDUR

	No	**Heathland**	**Grassland**	**Moss-heath**	**Sand/gravel**	**Glacier**	**total**	**User´s accuracy**
MAP	**Heathland**	2	2	0	0	0	4	50%
	Grassland	0	0	0	0		0	0%
	Moss-heath	2	0	9	1	0	12	75%
	Sand/gravel	0	0	1	3	0	4	75%
	Glacier	0	0	0	0	0	0	0%
	Total	4	2	10	4	0	20	0
	Producer´s accuracy	50%	0%	90%	75%	0%	0%	Total 70%

*Kappa = 0.52

REFERENCE TINDUR

	No	**Heathland**	**Grassland**	**Moss-heath**	**Sand/gravel**	**Glacier**	**total**	**User´s accuracy**
MAP	**Heathland**	0	0	0	0	0	0	0%
	Grassland	5	0	0	0	0	5	0%
	Moss-heath	3	0	8	1	0	12	67%
	Sand/gravel	0	0	1	2	0	3	67%
	Glacier	0	0	0	0	0	0	0%
	Total	8	0	9	3	0	20	
	Producer´s accuracy	0%	0%	89%	67%	0%		Total 50%

*Kappa = 0.29