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Front cover photography: Large avalanches like the January 2021 »twin avalanche« in the upper Soča Valley that reach the valley floor will be unavoidable in the Alps in the future, as climate warming actually triggers them, contrary to expectations (photograph: Jure Tičar).
Fotografija na naslovnici: Velikim snežnim plazovom, kakršen je bil »dvojček« januarja 2021 v Zgornjem Posočju, ki dosežejo dolinsko dno, se v Alpah tudi v prihodnosti ne bomo izognili, saj jih otoplitev podnebja, nepričakovano, celo povzroča (fotografija Jure Tičar).

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REMOTE SENSING ANALYSIS TO MAP INTER-REGIONAL SPATIO-TEMPORAL VARIATIONS OF THE VEGETATION IN ICELAND DURING 2001–2018

Haraldur Olafsson, Iman Rousta


IMAN ROUSTA

Figure: Single shrubs growing in grasslands in Hveragerði-Iceland.

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Haraldur Olafsson[1,2,3], Iman Rousta[2,3,4]

Remote sensing analysis to map inter-regional spatio-temporal variations of the vegetation in Iceland during 2001–2018

ABSTRACT: Changes in the vegetation of the Arctic and sub-Arctic regions have been used as indicators of the impact and seriousness of climate change. In this study, 342 MODIS NDVI images were used to monitor and assess the variability and long-term changes in the vegetation in Iceland in the period 2001–2018. An insignificant trend in the changes of the vegetation coverage ($R = 0.16$, p-value $= 0.05$) was obtained, however, it also resulted that the area with the low values of the NDVI (< 0.6) is decreasing, whereas the area with higher values of the NDVI (> 0.6, mostly forests) is increasing. The NDVI index during the study period rose for the area of about 3260 km^2, while it declined for 1635 km^2. The results of this study can be used for organizing the strategies preventing climate change and global warming.

KEY WORDS: Iceland, vegetation dynamics, MODIS, NDVI, anomaly analysis

Kartiranje spreminjanja vegetacije v prostoru in času v različnih regijah na Islandiji med letoma 2001 in 2018 s pomočjo daljinskega zaznavanja

Spremembe v vegetaciji arktičnih in subarktičnih pokrajin so pokazatelj vpliva in pomembnosti podnebnih sprememb. V pričujoči raziskavi smo 342 posnetkov NDVI senzorja MODIS uporabili za spremljanje in oceno spremenljivosti vegetacije in njenih dolgoročnih sprememb na območje Islandije v obdobje 2001–2018. Ugotovili smo neznačilen trend spreminjanja pokrovnosti vegetacije ($R = 0{,}16$, $p = 0{,}05$), polega tega pa smo opazili, da se površina z nizkimi vrednostmi NDVI ($< 0{,}6$) zmanjšuje, površina z visokimi vrednostmi NDVI ($> 0{,}6$, predvsem gozdovi) pa povečuje. Indeks NDVI je porasel v opazovanem obdobju na območju 3260 km^2, zmanjšal pa se je na 1635 km^2. Rezultati študije so lahko uporabni za pripravo strategij preprečevanja podnebnih sprememb in globalnega segrevanja.

KLJUČNE BESEDE: Islandija, dinamika spreminjanja vegetacije, MODIS, NDVI, analiza anomalij

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1 Introduction

Vegetation is an indispensable element of the Earth that links soil, air, water, and other components of the environment (Foley et al. 2000; Cui et al. 2009; Rousta et al. 2018; Rousta et al. 2020a; Mansourmoghaddam et al. 2021; Rousta et al. 2021). Environmental conditions and variability can define varaiety of future land cover (Zhang et al. 2019b; Shen et al. 2020; Wang et al. 2020; Chao et al. 2021). Vegetation dynamics carry valuable information about the impacts of global warming (Pettorelli et al. 2005; Olafsson and Rousta 2021), land degradation (Metternicht et al. 2010; Rousta et al. 2020c), and desertification (Symeonakis and Drake 2004; Rousta et al. 2020b). The Intergovernmental Panel on Climate Change (IPCC) highlights that the high northern latitudes are warming faster than other regions on the planet (Masson-Delmotte et al. 2018). As some researches point out, this is due to Polar Amplification (PA), a phenomenon in which effects such as decreasing sea ice and lower albedo due to reduced snow cover cause the Arctic temperatures to rise disproportionately under increased greenhouse gas emissions (Polyakov et al. 2003). The Arctic and sub-Arctic vegetation are highly sensitive to climate change, and the changes in the vegetation of this region have been used as indicators of the global impact of climate change.

With the advent of the space-borne era, using remote sensing and satellite images for assessment and monitoring of vegetation dynamics is common in research (Miao et al. 2018; Zhao et al. 2021a). Remotely sensed studies showed that since the 1980s the vegetation throughout northern latitudes has been increasing (Slayback et al. 2003; Bokhorst et al. 2009; Liu et al. 2015; Raynolds et al. 2015; Merrington 2019). One of the most widely used remotely-sensed indicators of vegetation is the Normalized Difference Vegetation Index (NDVI), which is highly sensitive to ecosystem conditions (Ollinger 2011; Lemenkova 2020a). NDVI is the normalized difference between the near-infrared (NIR) and visible red band's reflectance (Rouse et al. 1974; Tucker 1979) and has great potential for vegetation monitoring. The greater the NDVI value is, the higher is the photosynthetic capacity (Tucker 1979; Gao and Goetzt 1995; Chen and Brutsaert 1998). It can be used for detecting changes in vegetation development, such as downtrends or uptrends (Alcaraz-Segura et al. 2010; Ghafarian Malamiri et al. 2020). Over the last few decades, many scientists have established the effective role of NDVI on vegetation variability, or drought dynamics assessment, and monitoring of them (Kogan 1991; Kogan 1995; Yang et al. 1998; McVicar and Bierwirth 2001; Ji and Peters 2003; Wan, Wang and Li 2004; Zhao et al. 2021b). The AVHRR (Advanced Very High-Resolution Radiometer) derived NDVI is available since 1981, which creates an opportunity to monitor vegetation dynamics (VD) on various scales, from global or country to small regions, using time series data for different periods. The increased NDVI was found in peak parts of the Arctic, with the growth of the summer surface temperature believed to be the reason for this. In-situ measurements performed at various locations across the tundra biome during 1980–2010 have also connected the increases in sampled vegetation to summer warming (Elmendorf et al. 2012). The highest NDVI trends for the AVHRR record were observed for Iceland in the period 1982–2010 (0.008 NDVI units per year) (Epstein et al. 2012). Greenland, which was mentioned as the second with the highest increases, also had an increase of 0.005 NDVI units per year, and the rest of the northern countries experienced increases equal to 0.003 per year or less (Epstein et al. 2012). Additionally, the NDVI has decreased in certain areas, in which reduction of air temperature occurred (Bhatt et al. 2013). For example, in parts of Scandinavia, recent decreases in NDVI have been linked to winter warming events that reduced the protective snow layer (Bokhorst et al. 2009) and to unfavorable summer conditions and insect outbreaks (Bjerke et al. 2014).

Soil is an important factor that influences the processes between the land surface and atmosphere (Zhang et al. 2019a; Zhao et al. 2020; Zuo et al. 2020; Li et al. 2021; Li et al. 2022; Miao et al. 2022). In terms of world ecosystems, Iceland is unique, mostly because of its soils. The island's geology is overwhelmingly influenced by relatively recent extrusive volcanism, which forms the main parent material for its soils. On a geologic timescale, soil formation occurred about 10,000 years ago, which coincides with the end of the last glacial period (Arnalds et al. 1995). The basaltic tephra, which is the term for material of any size ejected by volcanoes, is one of the parent materials of soil types in Iceland (James, Chester and Duncan 2000; Arnalds 2008). The land-cover of Iceland is very dynamic. Erupting volcanoes produce lava flows and ash deposits, which dramatically transform landscapes. Despite the low population density (3.1 inhabitants/km^2 in 2010), it's the human influence that affects most of the countryside (Jóhannesson 2010) and its water surrounding (Mansourmoghaddam et al. 2022). Within an Icelandic context, understanding biodiversity is of special importance, as Iceland has a landscape history of which has been characterized by frequent, energetic geological processes (Thorarinsson 1967) and pressure on its ecosystems due to the land-use changes imposed after Iceland was settled by humans (Dugmore et al. 2009; Sigurmundsson et al. 2014; Bates et al. 2021). This has led to relatively low biodiversity in Iceland compared to the lands at similar latitudes (Jóhannesdóttir et al. 2017). The reduction in vegetation cover in Iceland in historical times has resulted in feedback loop. With less vegetation present to bind the soil, it becomes vulnerable to aeolian processes (Arnalds et al. 2001). This wind erosion removes useful surface nutrients, making vegetation colonization problematic (Óskarsson et al. 2004). It is reported that these processes have left large areas of Iceland barren (Arnalds et al. 2001).

In the sense of environmental sustainability, Iceland is subject to volcanic eruptions, local overgrazing, and soil erosion. Most of the vegetation is located in the coastal zone and the human settlement areas. On the other hand, the Icelandic vegetation, same as it is with the sub-arctic and arctic vegetation, is of high importance for wild and human life. Studying vegetation dynamic and their link to climate change is therefore of high importance for securing the ecological sustainability of Iceland. However, studies that focus on Iceland are rare and almost none of them focused specifically on the assessment of the vegetation evolution for the whole Iceland during recent years. Therefore, the objective of this research is to assess the spatio-temporal NDVI variations in Iceland and its main sub-regions.

2 Material and methods

2.1 Study area and data collection

Iceland is located between 63 and 67°N, and 13 and 25°W. It is the second-largest island in the Northern Atlantic, having an area of 103,000 km^2 and a population of 360,000. More than two-thirds of the population live in Reykjavík city and surrounding areas in the southwestern part of the country. Reykjavík is the capital and the largest city of Iceland. The country is volcanically and geologically active and consists of highlands, glaciers, and mountains. Iceland is a mountainous island, yet it does not have areas with high elevations. About 26% area of Iceland lies between 0–200 m, 36% between 200–600 m, 17% between 600–800 m, and 21% above 800 m. The highest mountain is 2119 m (Thorsteinsson, Olafsson and Van Dyne 1971). The climate of the country is temperate and the archipelago lies in a tundra vegetation zone.

In the present study, the country was divided into 8 main regions. The South and East regions with 9421 and 7786 km^2 have the largest share of vegetation coverage and the South East Peninsula and Reykjavik area with 894.4 and 701.6 km^2 have the smallest share of Iceland's vegetation coverage (Table 1). The south coast is wetter, windier, and warmer than the north. The snowfall in winter is more common in the north than in the south. The climate of Iceland was described in detail by Einarsson (1984) and Ólafsson et al. (2007). While the country is close to the Arctic, the coastal area remains ice-free through the winter (Figure 1). The largest parts of Iceland are covered by grasslands (about 55%, 56,250 km^2), barren land (about 28%, 28,958 km^2), and permanent snow and ice cover (about 10%, 10,496 km^2) (Table 2).

Table 1: Basic characteristics of the main regions of Iceland.

Name	Area (km^2)	Vegetated area (km^2)	Nonvegetated area (km^2)	Vegetated area (%)	Max Elevation (m)	Average Elevation (m)
South (S)	24423	9421.7	15001.3	38.6	2015	513
Southwest Peninsula (SWP)	792	701.6	90.4	88.6	610	99
Reykjavik Area (RA)	1001	894.4	106.6	89.4	1050	219
West (W)	9346	6929.4	2416.6	74.1	1717	320
West Fjords (WF)	9038	4401.0	4637.0	48.7	1012	323
Northwest (NW)	12346	7148.9	5197.1	57.9	1796	494
Northeast (NE)	21712	6980.7	14731.3	32.2	2057	580
East (E)	22074	7786.8	14287.2	35.3	2076	606

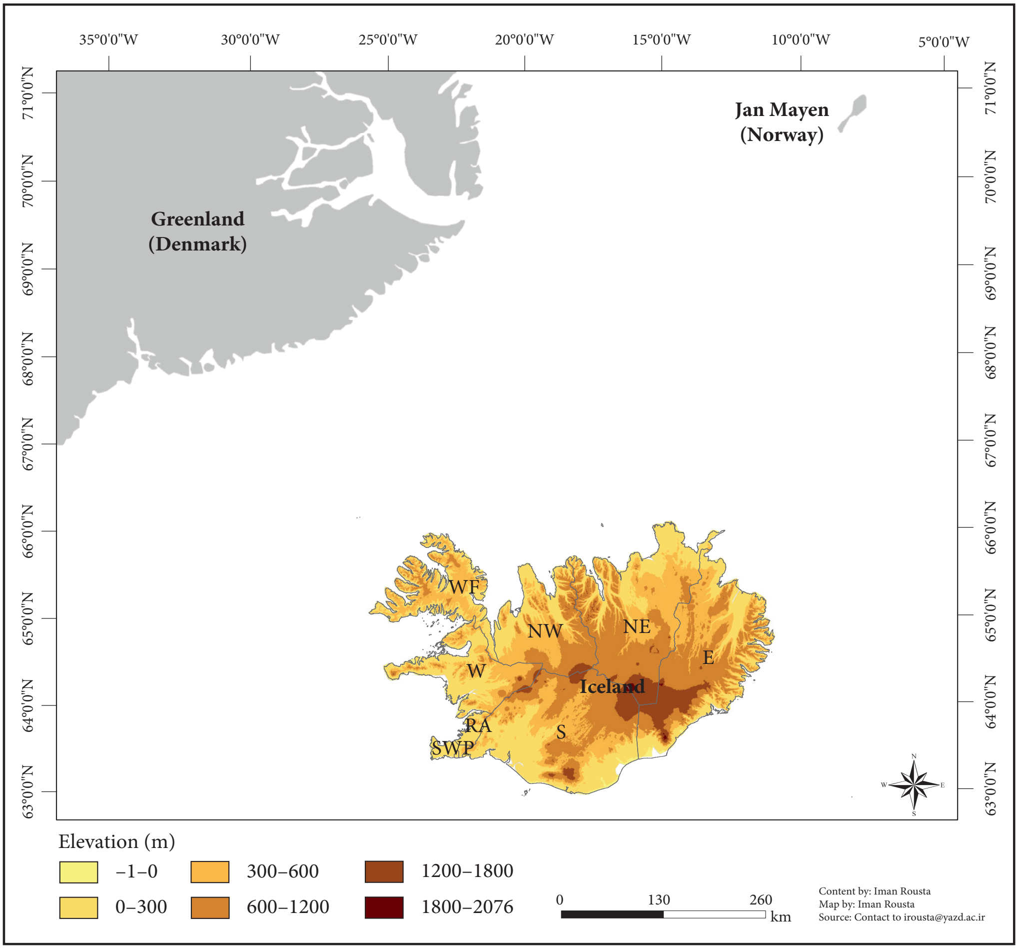

Figure 1: The map of the study area showing elevation and main regions.

Table 2: Iceland land cover types derived from MODIS (MCD12Q1) – Yearly Land Cover Type 1: Annual International Geosphere-Biosphere Programme (IGBP) (Loveland et al. 1999; Didan et al. 2015).

Land cover type	Area (km^2)	Percent of the whole area (%)
Evergreen Needleleaf Forests	9.7	0.009
Deciduous Needleleaf Forests	1.3	0.001
Deciduous Broadleaf Forests	4.8	0.005
Mixed Forests	6.1	0.006
Open Shrublands:	177.7	0.173
Woody Savannas	1.4	0.001
Savannas	2,953.5	2.867
Grasslands	56,255.2	54.617
Permanent Wetlands	1,823.0	1.770
Urban and Built-up Lands	47.9	0.046
Permanent Snow and Ice	10,496.5	10.191
Barren	28,960.8	28.117
Water Bodies	2,271.7	2.206
Total	103,000.00	100.000

2.2 Methods

To explore the spatio-temporal variability of vegetation coverage in Iceland, a total of 342 NDVI images were downloaded from the Terra MODIS vegetation Indices (MOD13Q1) database from the Land Processes Distributed Active Archive Center (https://lpdaacsvc.cr.usgs.gov.appeears) (Didan 2015a). The MODIS analysis-ready 16-day composite product (MOD13Q1.006) with 250 m spatial resolution was collected for the period from 1 January 2001 to 1 November 2018. ArcGIS 10.7 software and R environment were used to perform spatial and statistical analyses. The 1 arc-second (~30 m) spatial resolution SRTM (Shuttle Radar Topography Mission) elevation data was used to visualize the terrain profile of the study area (Zandbergen 2008).

NDVI is the most commonly used vegetation index (VI) for detecting the greenness of vegetation and production patterns (Tarpley, Schneider and Money 1984; Gitelson et al. 2003; Thenkabail, Gamage and Smakhtin 2004; Dutta et al. 2015). Scientists from all over the world have been using VI for investigation of various aspects of vegetation dynamic, i.e. vegetation mapping, monitoring, phonological analysis, crop growth, yields, and many more (Running et al. 1995; Moulin et al. 1997; Dabrowska-Zielinska et al. 2002; Geerken, Zaitchik and Evans 2005; Martínez and Gilabert 2009; Moniruzzaman et al. 2021). NDVI is defined as:

$$\mathrm{NDVI} = \frac{B^{nir} - B^{red}}{B^{nir} + B^{red}}\,. \tag{1}$$

The B^{nir} and B^{red} in Eq. 1 stands for the spectral reflectance in the near-infrared band and red band, respectively. NDVI ranges between −1 and +1, with the values from −1 to 0 indicating the absence of green leaves and the values from 0 to +1 indicating the greenest areas. Moderate NDVI values from 0.2 to 0.3 represent shrub and grassland, while high NDVI values (0.6 to 0.8) indicate dense vegetation (Montandon and Small 2008; Atasoy 2018; Jovanović, Milanović and Zorn 2018; Rousta et al. 2020b). NDVI values close to 0 represent the bare ground, while negative NDVI values correspond to water bodies snow and ice (Dye and Tucker 2003; Gandhi et al. 2015).

In the present research, the NDVI data were acquired from the Terra-MODIS Vegetation Indices MOD13Q1. To calculate the vegetation coverage, the number of pixels with vegetation, that is, having the NDVI m × 250 m = 0.0625 km^2). The same procedure was used for calculating the yearly and seasonal vegetation coverages. NDVI index was defined into 7 classes (0.2–0.3, 0.3–0.4, 0.4–0.5, 0.5–0.6, 0.6–0.7, 0.7–0.8 and > 0.8) for each of 8 selected regions separately, to calculate seasonal and annual vegetation coverages, along with inter-annual and inter-seasonal vegetation anomalies.

The annual and seasonal NDVI anomalies were calculated for each pixel during 2001–2018 as:

$$NDVI_{YA} = \frac{NDVI_y - NDVI_{\bar{y}}}{Std_y}, \tag{2}$$

$$NDVI_{SA} = \frac{NDVI_s - NDVI_{\bar{s}}}{Std_s}. \tag{3}$$

Where $NDVI_{YA}$ is a yearly anomaliy and $NDVI_{SA}$ is a seasonal anomaliy for each pixel in each year, $NDVI_s$ is the average NDVI for each season and $NDVI_y$ is the average NDVI for each year, $NDVI_{\bar{y}}$ is the average yearly NDVI for the whole study period 2001–2018, $NDVI_{\bar{s}}$ is the average seasonal NDVI for the whole study period 2001–2018, and is the standard deviation of NDVI for the whole study period 2001–2018, and is the standard deviation of NDVI for each season for the whole study period 2001–2018.

The study used a linear regression to define the correlations significant at a level of 0.05, which were taken into account in further analyses. Linear regression is a statistical method to find the relationship between two variables by fitting a linear model, in which one variable acts as an explanatory variable and the other one is a dependent variable (Song et al., 2005). A linear regression model is defined as:

$$y_i = a + bx_i, \tag{4}$$

where a and b are the regression coefficients. The b coefficient can be obtained from the given pairs of (x_i, y_i). In the current study regression model was used for calculating the trend of vegetation (as the dependent variable) during the years (as the independent variable) in Iceland during 2001–2018.

3 Results

3.1 NDVI variations

In Figure 2 the average vegetation coverage (NDVI > 0.2) in Iceland for the study period is shown. The NDVI is steadily rising from the midst of February, however, it is very slow till the middle of March (12,948 km^2). From the end of March, vegetation coverage starts to increase rapidly to reach 33,524 km^2 only one month later (at the end of April). The uptrend is continued in the next months and the maximum coverage is reached in the period from the middle of July to late August, having an average value of 66,858 km^2. After the end of August, the coverage of green vegetation decreases rapidly. Therefore, it can be stated that the average growing season (GS) in Iceland starts around 23rd March and ends at the end of August (Figure 2).

Figure 3 shows the time series of the annual average vegetation coverage in Iceland for the study period. There is an insignificant decreasing trend in the NDVI coverage for the study area in 2001–2018, however substantial interannual variability is also visible. In the years 2003, 2004, and 2017 the maxima in the annual average vegetation coverage were observed (being 43,229, 42,106, and 42,255 km^2, respectively), while in 2008, 2009, 2013, 2014, and 2015 the minima occurred (33,233, 33,962, 34,645, 34,051 and 34,398 km^2, respectively).

In Figure 4 the similar time series as in Figure 3 are shown, but for individual classes of the NDVI. There is a decreasing trend in the NDVI for the ranges between 0.2–0.5, and an increasing trend in the NDVI from the range of 0.6–1. However, no long-term trend for NDVI for the range 0.5–0.6 was observed (Figure 4 and Table 3).

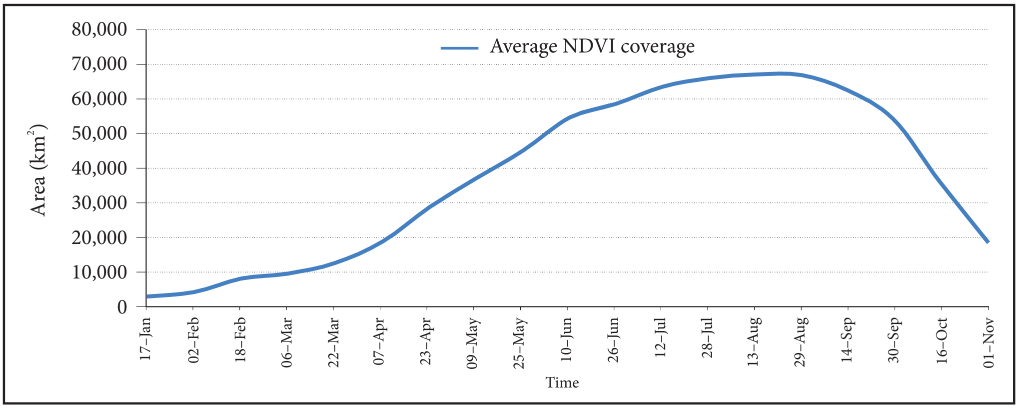

Figure 2: The average value of the NDVI coverage (> 2) in Iceland for the period 2001–2018.

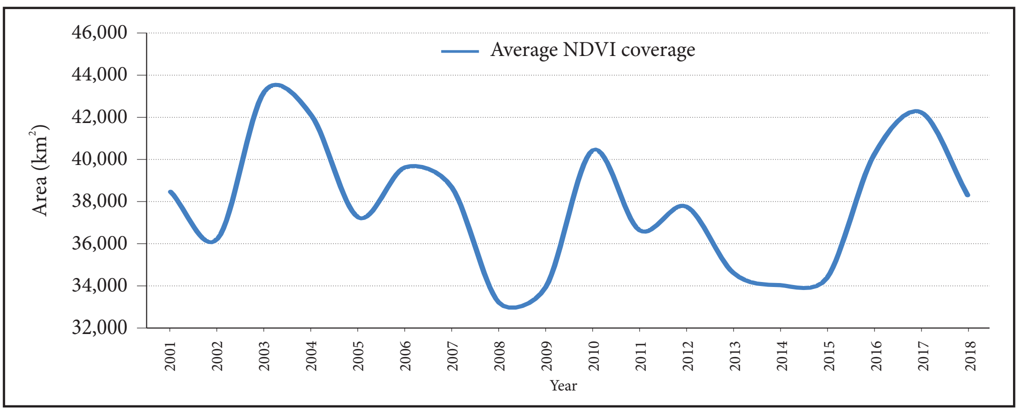

Figure 3: The time series of average annual vegetation coverage (NDVI > 0.2) in Iceland.

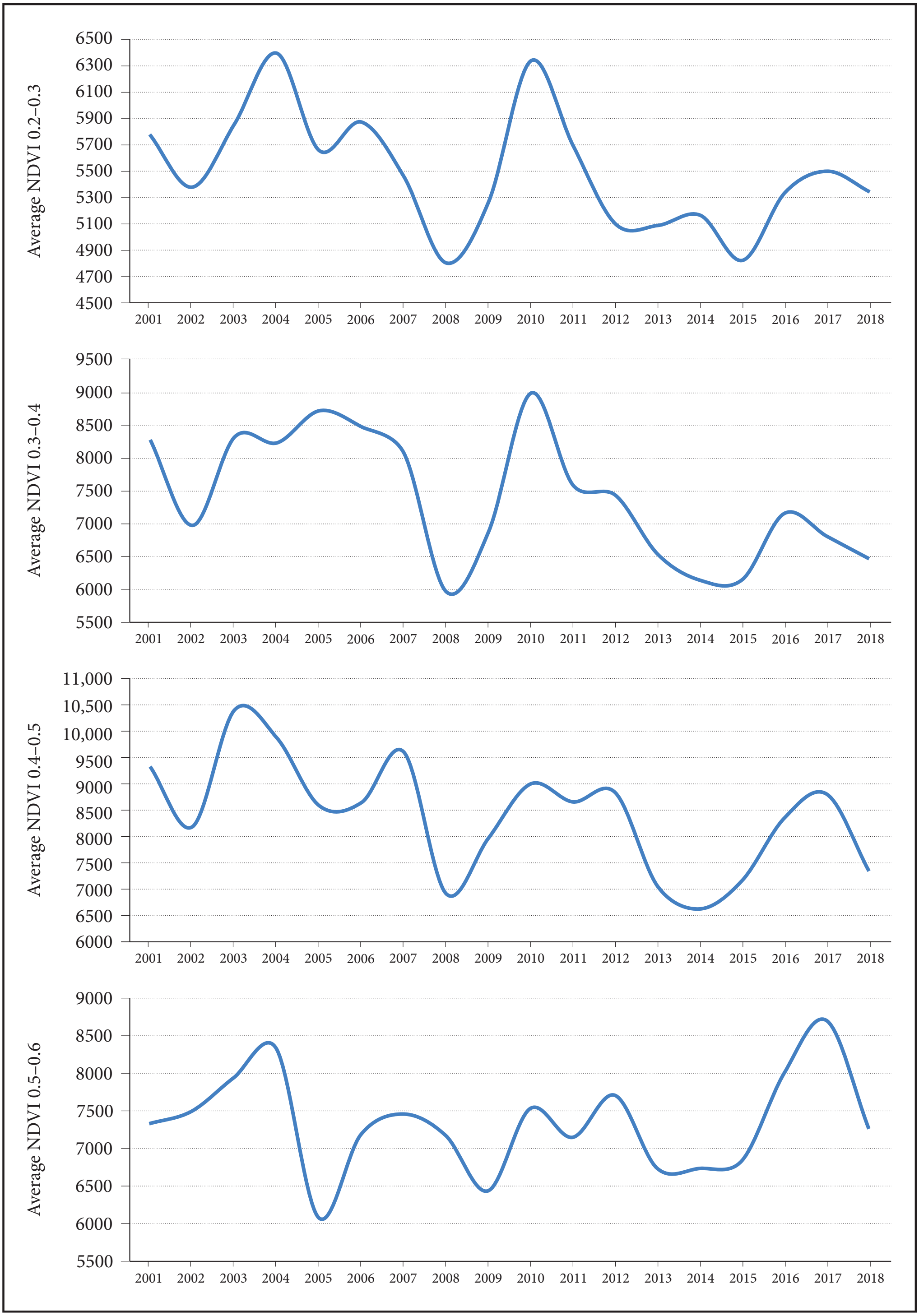

Figure 4: The time series of the average annual coverage of the vegetated areas with different ranges of NDVI values in Iceland. (p. 112–113)

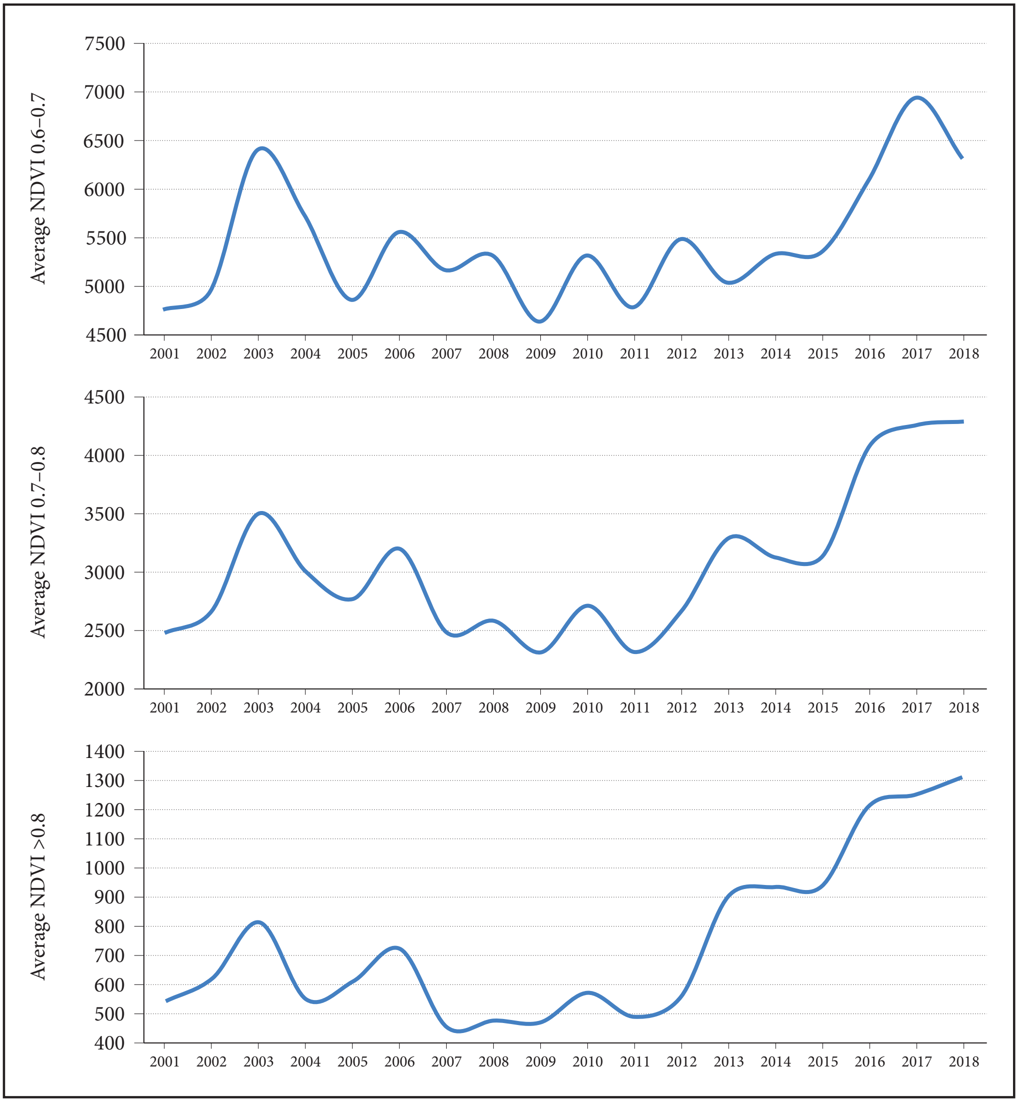

Table 3: The trend of different NDVI classes in Iceland in the period 2001–2018.

NDVI Categories	Correlation
Average NDVI 0.2–0.3	–0.46*
Average NDVI 0.3–0.4	–0.59*
Average NDVI 0.4–0.5	–0.55*
Average NDVI 0.5–0.6	0.05
Average NDVI 0.6–0.7	0.43
Average NDVI 0.7–0.8	0.59*
Average NDVI 0.8–0.9	0.70*
Average NDVI 0.9–1	0.80*

Note: * denotes significance at $p = 0.05$

3.2 Regional variability

Table 4 presents both the seasonal and annual percentage of area covered by vegetation in the regions of Iceland. The Southwest Peninsuls (SWP) and Rekjavik Area (RA) regions have the highest vegetation coverage, with an average annual value of 77.1 and 67.3%, respectively. The Northeast (NE) and East (E) regions have the lowest values, 26.9%, and 31.3%, respectively, followed closely by the South region with an annual value of only 33.6%. In winter very low percentage of the area is covered by vegetation, except in the Southwest peninsula. (Table 4 and Figure 5).

Table 4: The average seasonal and annual percentage of areas covered by vegetation (NDVI > 0.2) in the regions of Iceland in the period 2001–2018.

Period	S	SWP	RA	W	WF	NW	NE	E
Winter	2.2	36.8	4.5	2.8	0.0	0.1	0.2	1.6
Spring	31.5	85.1	78.2	60.5	23.6	40.2	16.7	17.9
Summer	53.6	94.0	95.5	92.1	77.4	80.9	51.3	57.4
Fall	47.1	92.5	90.8	83.5	61.5	66.7	39.3	48.2
Year	33.6	77.1	67.3	59.7	40.6	47.0	26.9	31.3

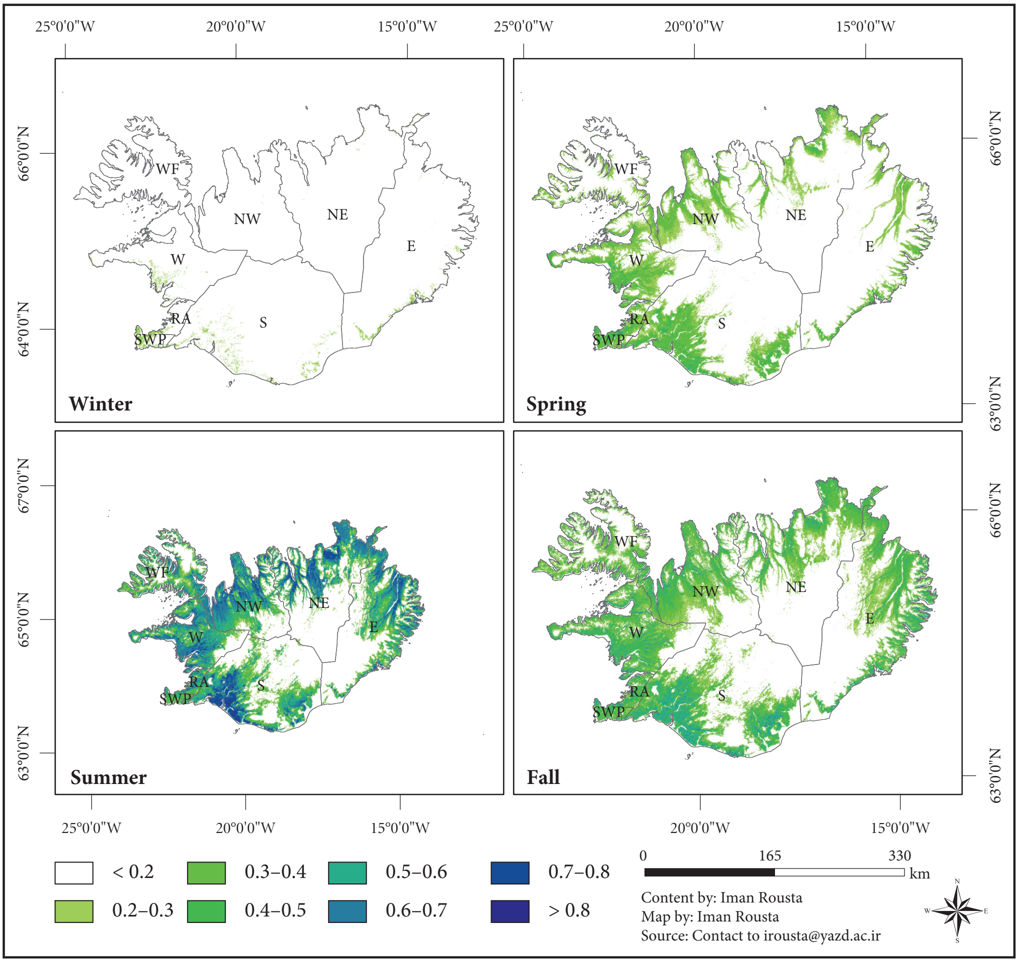

Figure 5: Average seasonal vegetation coverage in Iceland in the period 2001–2018.

In Table 5 information about the variability and trend of the NDVI during the study period for each of 8 regions of Iceland is provided. The highest average maximum NDVI values are found in the West, the South (0.66), and the East (0.63) regions. The lowest average maximum values are observed in the Northeast and Northwest (0.58) and the West Fjords (0.56). A small and insignificant downtrend in the maximum values in the East, and slightly higher, but also insignificant, uptrends in the Northeast, Reykjavik, Northwest, and West were found. A positive and statistically significant trend was found in the average maximum NDVI in the South. The average NDVI values represent mainly the proportion of mountains in the respective region, with the highest values observed for the Northeast, East, and West Fjords. The downtrends of average NDVI were observed for all the regions except the Southwest peninsula and the Northeast. The highest negative trend values were obtained for Reykjavik, the South, and the West regions, however, all of them were statistically non-significant. The standard deviation of the mean NDVI values is the smallest for Reykjavik and the Southwest Peninsula regions (about 0.1 std). The increasing trend of the standard deviation of the NDVI is significant in Reykjavik. Figure 6 shows the maximum annual NDVI for every region of Iceland for the whole study period (2001–2018). It was observed that the highest mean was in the South region (0.75), while the lowest was in the West Fjords (0.63).

Table 5: The descriptive NDVI statistics for the regions of Iceland for the period 2001–2018.

Name	Avg. Max NDVI	Avg. Max NDVI Trend	Avg. NDVI	Avg. NDVI Trend	Avg. Std NDVI	Avg. Std NDVI Trend
South	0.66	0.55*	0.20	–0.26	0.19	0.01
Southwest Peninsula	0.60	–0.08	0.34	0.07	0.10	0.24
Reykjavik Area	0.62	0.19	0.34	–0.21	0.10	0.58*
West	0.66	0.19	0.29	–0.22	0.14	0.50
West Fjords	0.56	–0.01	0.19	–0.13	0.14	0.00
Northwest	0.58	0.29	0.23	–0.14	0.15	0.14
Northeast	0.58	0.44	0.13	0.04	0.17	0.07
East	0.63	–0.14	0.15	–0.15	0.17	0.04

Note: * denotes significance at $p = 0.05$

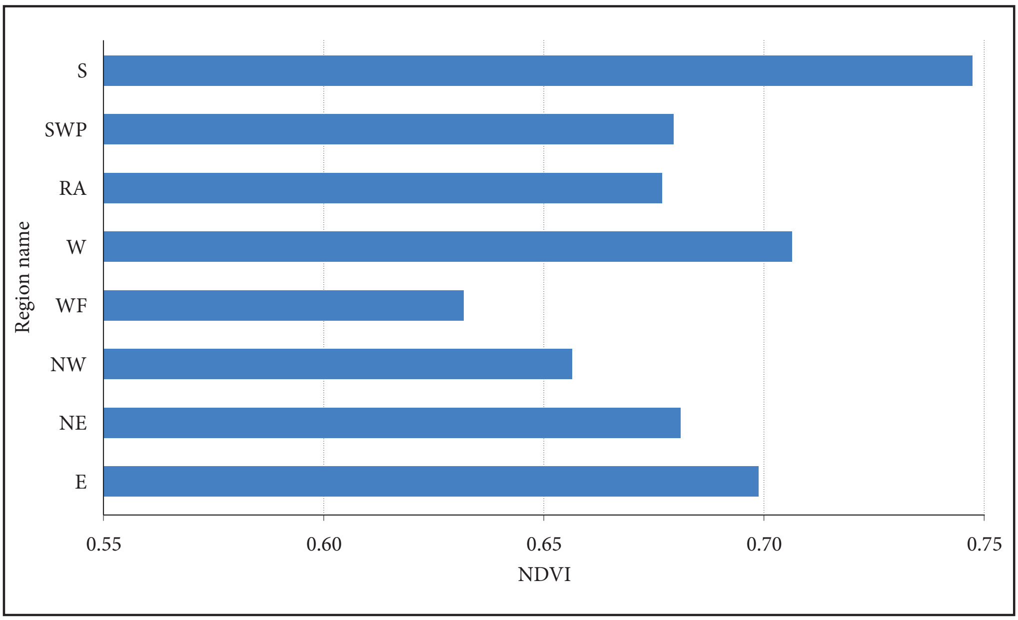

Figure 6: Maximum annual NDVI for the regions of Iceland for the period 2001–2018.

Assessment of the vegetation coverage trends in Iceland (Table 6) indicates that a reduction in NDVI in all regions was occurring in the winter season, however, it was significant only in Reykjavik (–0.5). It is worth noting that rather high values were observed also for the Northwest, West, and West Fjords regions (–0.4), but they were insignificant. In the spring, a negative non-significant trend occurred in most regions. In the summer, a strong and significant average NDVI uptrend can be noticed in the Southwest peninsula, while in other regions much weaker and non-significant trends occurred. In the fall, positive non-significant trends in the West, Northwest, and the West fjords can be noticed, while in other regions only minor changes occurred.

Table 6: Trends of the seasonal average NDVI values in regions of Iceland in the period 2001–2018.

Season	S	SWP	RA	W	WF	NW	NE	E
Winter	–0.3	–0.3	–0.5*	–0.4	–0.4	–0.4	–0.2	–0.2
Spring	–0.3	–0.1	–0.3	–0.2	–0.2	–0.2	0.0	–0.2
Summer	0.2	0.5*	–0.3	–0.1	–0.1	0.0	0.2	–0.1
Fall	0.1	0.2	–0.1	0.2	0.3	0.0	0.1	0.1

Note: * denotes significance at $p = 0.05$

Table 7 shows the percentage of the area with decreasing (change from –0.12 to –0.007 NDVI/year), stable (from –0.007 to 0.005 NDVI/year), or increasing (from 0.005 to 0.08 NDVI/year) values of the NDVI index for each region in Iceland during the study period. In all regions, no constant change of vegetation was observed on more than 80% of the lands. The WF and E regions had the highest share of land with a decrease of the vegetation (2.8 and 1.8%, respectively), while the remaining regions had smaller fractions of the area, on which vegetation decreased. At the same time, the WF and E were also the regions having the largest share of the area with increasing vegetation (5.6 and 3.7%, respectively), while in the remaining regions vegetation index rose on about 2–3% of the area. In general, an increase in the NDVI index was observed on about 3260 km^2, whereas a decrease on 1635 km^2 (Table 7 and Figure 7).

Table 7: The percentage of the area with decreasing, stable, or increasing vegetation of each region in Iceland during 2001–2018.

Trend (NDVI/year)	S	SWP	RA	W	WF	NW	NE	E
from –0.12 to –0.02 (Strong decrease)	0.2	0.0	0.1	0.1	0.2	0.1	0.1	0.2
from –0.02 to –0.007 (Decrease)	1.5	0.5	1.2	1.3	2.6	1.0	1.0	1.6
from –0.007 to –0.002 (No change)	8.1	3.3	7.3	6.6	12.3	5.6	6.9	9.4
from –0.002 to 0.005 (No change)	87.4	94.9	88.2	88.9	79.3	90.8	89.6	85.0
from 0.005 to 0.08 (Increase)	2.8	1.3	3.2	3.1	5.6	2.4	2.5	3.7

3.3 Location of the areas with the most extreme changes

Several areas with relatively large changes in the annual average of the NDVI index have been detected. Such areas appear as small clusters of pixels with a uniform color. In Figure 7 three additional locations relative to pre-2013 locations indicated by Raynolds et al. (2015) were marked by the boxes. The first one is located along the shorelines of artificial lake Hálslón in eastern Iceland (Figure 7, box a). The lake began to be filled in the fall of 2006 and due to variability of the lake water level, a reduction in vegetation along its shoreline was observed (Aradóttir et al. 2013). A second location is the extended riverbed of Skaftá River (Figure 7, box b). The river flooded in the fall of 2015 and for the second time in the summer of 2018, causing a substantial level of destruction of vegetation (Óskarsdóttir 2016). The third one is a landslide in Hítardalur, in western Iceland, which is covering about 2 km^2, including a small lake that was formed due to a dammed river (Dabiri et al. 2019). Although the landslide fell as late as at the end of the study period, in July 2018, it appeared in Figure 7 (box c) as a cluster of pixels with a downtrend.

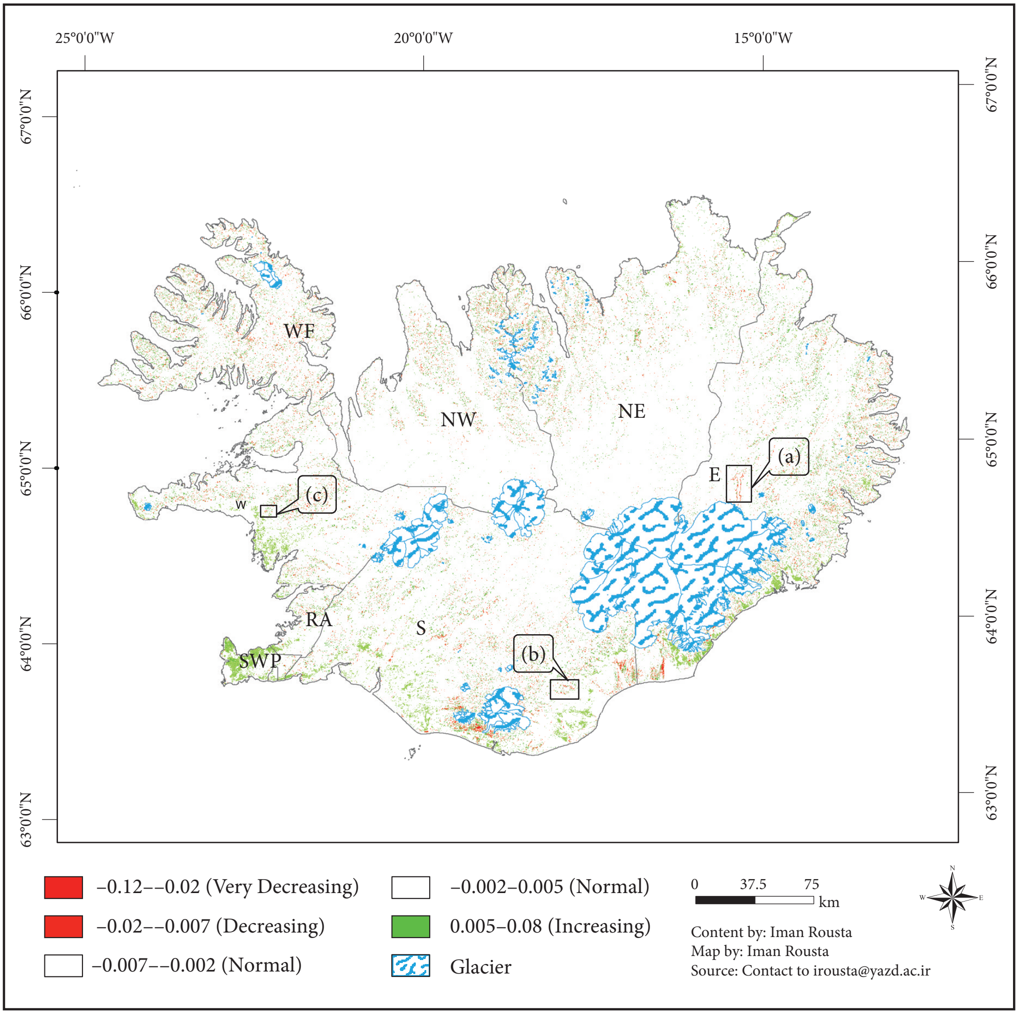

Figure 7: The map of the values of the NDVI index trends (NDVI/year) in Iceland during 2001–2018. (a) shorelines of artificial lake Hálslón, (b) Skaftá River, (c) landslide in Hítardalur.

4 Discussion

Not many studies on the regional, seasonal and annual spatial vegetation dynamics of Iceland were undertaken up to now. Our study is the first study that has assessed the vegetation variation in the whole of Iceland and its sub-regions using remote sensing. In the recent works dealing with the vegetation dynamics over the studied area, only a part of the country was analyzed (Lemenkova 2020b; Bates et al. 2021). In the case of study made for the whole country, vegetation variation and the inter-regional differences were not studied, and additionally, they employed satellite images having a lower spatial resolution, and analyzes were done for a shorter period (Raynolds et al. 2015). The satellite images used by Raynolds et al. (2015) were not trustable, and the next version (V006), which was unavailable at that time, could solve the uncertainties. Raynolds et al. (2015, 9495) said: »Version 6 of the MODIS Vegetation Indices products will correct this problem, but is not yet available«. It occurred that the MODIS NDVI images are useful for monitoring vegetation dynamics in Iceland and the method used in the study can be used for other regions and countries.

The results of this study indicated that the maximum vegetation coverage in Iceland occurs from the middle of July to late August, with an average area of 66,858 km^2 covered in vegetation (NDVI ≥ 0.2), which is about 65% of the country's territory. Also, the results showed that the growing season starts on average from late March and lasts up to the end of August.

Raynolds et al. (2015) in their study showed that a reduction in NDVI occurred in Iceland in the period from 2002 to 2013. The present study dealt with the period 2001–2018 and the results are in line with the results of the Raynold's team in the case of moderate decreasing trend and the high spatial variability of trends for the different regions of Iceland.

In the study, significant downtrends for the lower values of the NDVI were found, whereas, for higher values, positive uptrends were spotted. The reason for this effect is probably due to the growth of both planted, as well as natural forests, which again is in line with results presented in Raynolds et al. (2015). The total area of forests in Iceland has indeed increased from a total of 298 km^2 in the year 2000 to ~514 km^2 in 2020 (estimated value), whereas the area of other wooded lands increased from a total of 1344 km^2 in 2000 to ~1495 km^2 in 2020 (estimated value) (MacDicken 2015). A forest growing on grassland will most likely increase the NDVI for that area. As some of the new forests in Iceland do indeed grow on grasslands, they may simultaneously contribute to a reduction of the areas with a low value of the NDVI and an increase of the areas with higher NDVI value. The high positive trend in the maximum annual NDVI index value in the southern part of Iceland is in line with the widespread afforestation of that region (Fries 2017). The other studies about northern latitude's vegetation variations, indicate that there is a great increase in vegetation coverage between 45°N and 70°N (Myneni et al. 1997; Huang et al. 2017).

Substantial interannual variability in all of the analyzed classes of the NDVI values was found. This observation requires to be explored further in connection with the actual state of the atmosphere, especially with temperatures and precipitation.

The percentage of land covered by vegetation is by far the highest in the Southwest peninsula and the Reykjavik area (these are the smallest regions of the 8 main regions of Iceland). This is primarily due to the fact that both regions are located mostly at terrain having lower elevation. On the other hand, fieldwork showed that the high-density vegetation of that area is established after reclamation through the use of inorganic fertilizers and birch trees, which is consistent with the result of the Nyirenda (Nyirenda 2020) as well as the Reykjavik area has the most dense site of reforestation in the whole country (Fries 2017). In three regions, the West fjords, the Northeast, and the South, anomalously low vegetation coverage was spotted. The West fjords had much less vegetation coverage than the West even though their mean elevation is similar. Similarly, the Northeast had less vegetation coverage than the East, and the South had less vegetation than the Northwest, although their mean elevations are similar. The explanation for the West fjords having less vegetation than the West lies undoubtedly in a relatively cold climate in the West fjords (Einarsson 1984). As for the other regions with low-vegetation coverage, the explanation lies in the fact that the South and the Northeast are located in volcanically active zones, in which every few years eruptions occur, which in turn results in large areas with progressing erosion, even at relatively low altitudes (Arnalds, Ólafsson and Dagsson-Waldhauserova 2014; Lemenkova 2020b).

Only minor changes in the vegetation coverage in Iceland during the study period were observed, with the trend of changes significantly smaller than the inter-annual variability, which in turn must be considered as substantial. The total vegetation coverage was almost 67,000 km^2 (about 65% of the Iceland area), which is quite high for an island located in high latitudes, with a high elevation and a high share of land covered by glaciers and lakes.

5 Conclusion

Climate change and global warming can affect all areas around the world. It is predicted that the impact of climate change will be more severe for regions with higher latitudes (King et al. 2018; Anderson, Bayer and Edwards 2020), such as Iceland. Vegetation variations are surface phenomena, which could be a good indicator of climate change. The present study attempted to identify and analyze the spatio-temporal variations of the NDVI in both Iceland and its 8 sub-regions using remotely-sensed satellite images. It was found that MODIS NDVI images can be useful for monitoring the vegetation variations in the studied area.

The NDVI retrieved from remote sensing for the period 2001–2018 showed considerable inter-annual variability and a minor, statistically insignificant, decrease in the vegetation coverage in Iceland. In the late summer, 65% of Iceland is covered with vegetation (NDVI > 0.2). The areas with low NDVI (NDVI < 0.6) had a decreasing trend, whereas for the areas with high NDVI (NDVI > 0.6) an increase in the vegetation coverage was observed. In general, an increase in the NDVI was observed in the area of about 3260 km^2, whereas a decrease in the NDVI index was observed in the area of 1635 km^2, which is in line with an increase in forested areas in Iceland.

Vegetation coverage is influenced by such atmospheric parameters as temperature, precipitation, relative humidity, etc. On the other hand, all of these atmospheric parameters are influenced by atmospheric patterns and teleconnections. Therefore, to have a more accurate assessment of inter-seasonal, inter-annual, and inter-regional vegetation variations in the studied area, the atmosphere dynamics should be studied simultaneously with the vegetation variations. Up to now, one paper, in which the relationships between the atmospheric circulations and teleconnections with vegetation dynamics of Iceland (Olafsson and Rousta 2021) has already been published.

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