Supplementary Material

to

The use of remote sensing for studying environmental changes in a palsa mire zone of Northern Finland in the period 1985-2024

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1. Study area at the background of geographical features

The study area, covering 402 km², is characterised by diverse topography. The lowest-lying parts, at elevations of approximately 105 m a.s.l., are located in the bottoms of depressions, while the highest hills reach 445 m a.s.l. (Figure S1). Most of the area (80%) consists of terrain with slope gradients below 5°, areas with slopes of 5–15° account for 19%, whereas steeper slopes exceeding 15° occur on only 1% of the area (Figure S2). The analysis of aspect indicates a predominance of east-facing slopes, which account for 31% of the area. Another major group consists of west-facing slopes, representing 27%, followed by north-facing slopes, which cover 24%. South-facing slopes occupy only 18% of the area (Figure S3).The geological structure of the analysed area is dominated by metamorphic rocks (quartz feldspar paragneisses occupy 54.9% of the area and biotite paragneisses - 14.2%) as well as quarts diorites and granodiorites (14.4% and 11.5%, respectively) (Figure S4). The investigated area is covered with sediments from the last glaciation, upon which endogleyic podzols have developed covering almost 80% of the territory (Figure S5), with the rest of the area featuring histosols (peat soils) and leptosols (initial soils). Peatlands are a characteristic element of the landscape, occupying approximately 16% of the area (Figure S6). Palsa mires, characteristic of marginal permafrost zones, have been documented within the study area (Seppälä, 2006). These mires form characteristic mounds composed of peat, mineral soil, and permanently frozen cores (Pissart, 2002; Seppälä, 2011). In response to climate change, progressive degradation of palsa mires has been observed in northern Finland (Leppiniemi et al., 2025). In addition to the mires, lakes are numerous in the study area, occupying 4.3% of the land surface. The hydrographic network is also formed by small watercourses, the largest of which, the Vetsijoki, flows from south to north through the central part of the area.

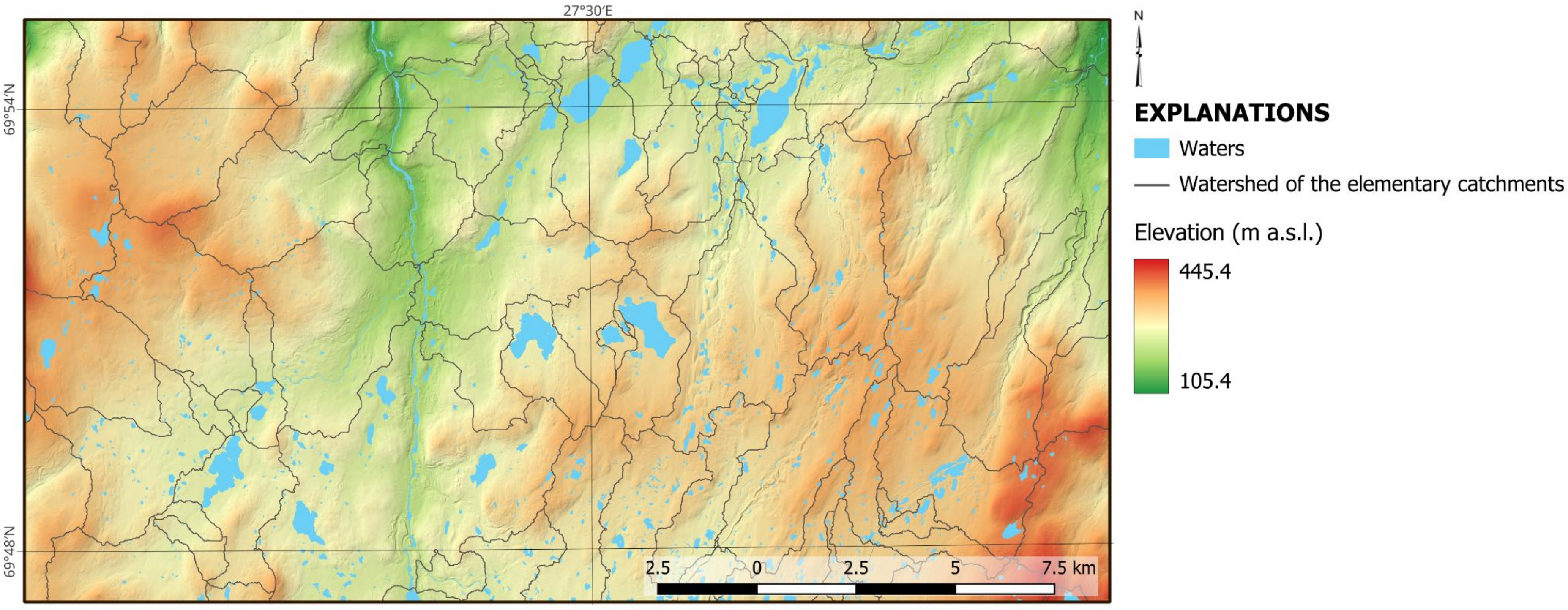

Figure S1. Hypsometric map of the study area in northern Finland (prepared based on National Land Survey of Finland, 2025)

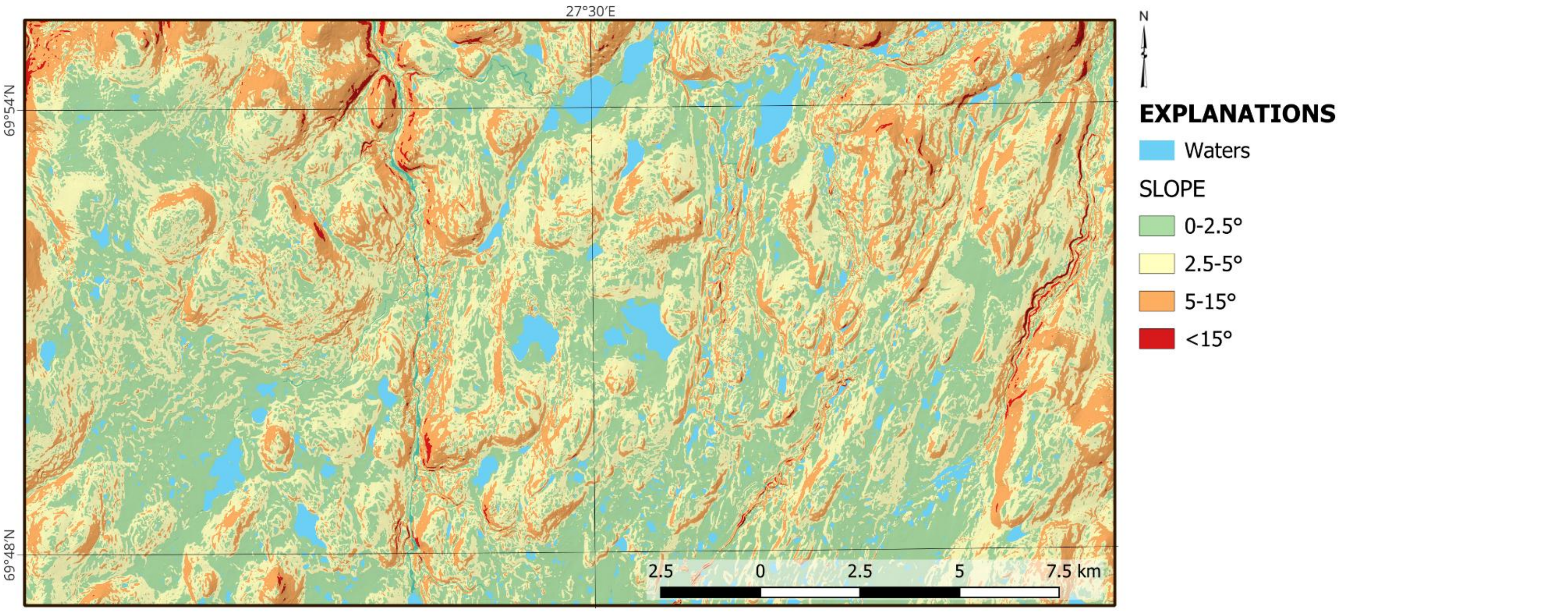

Figure S2. Terrain slope of the study area in northern Finland (prepared based on National Land Survey of Finland, 2025)

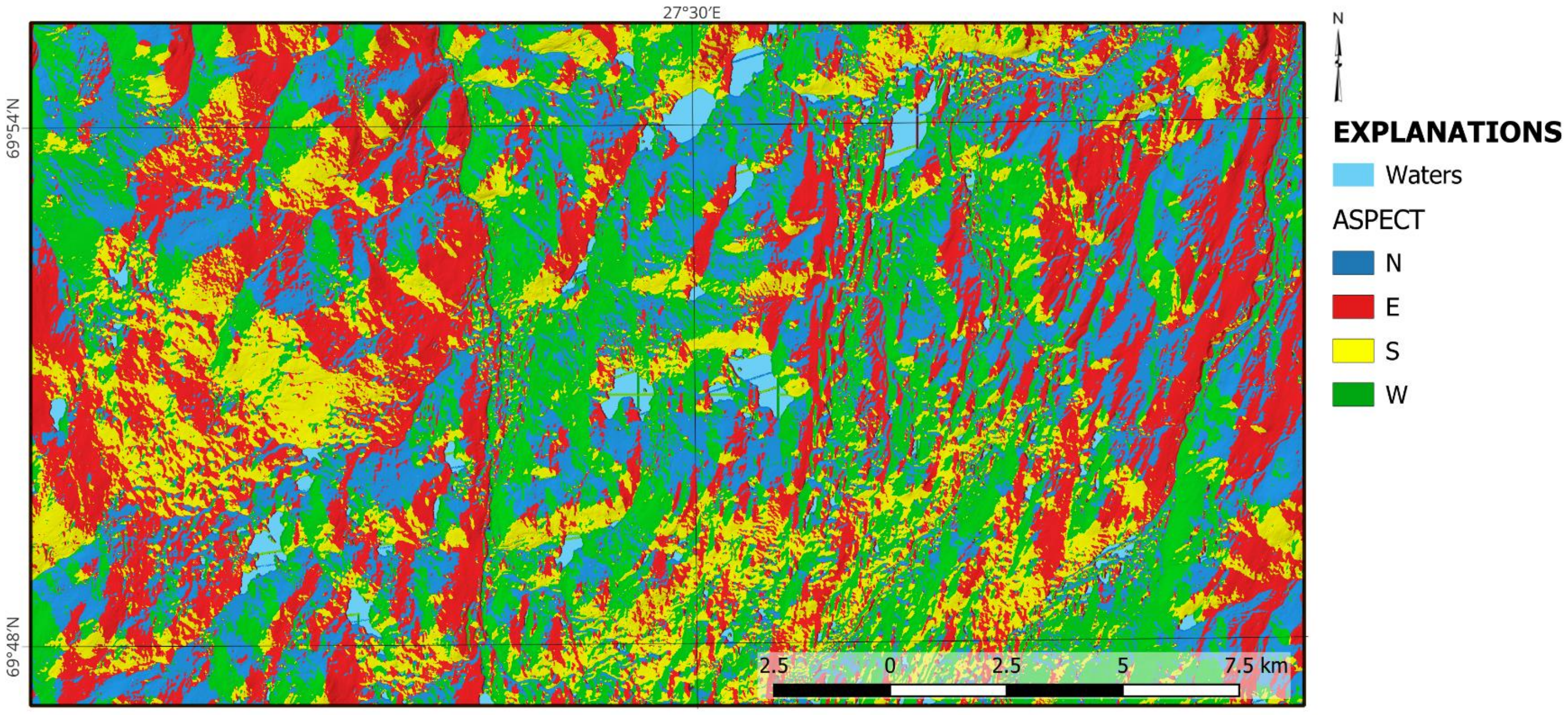

Figure S3. Aspect of the study area in northern Finland (prepared based on National Land Survey of Finland, 2025)

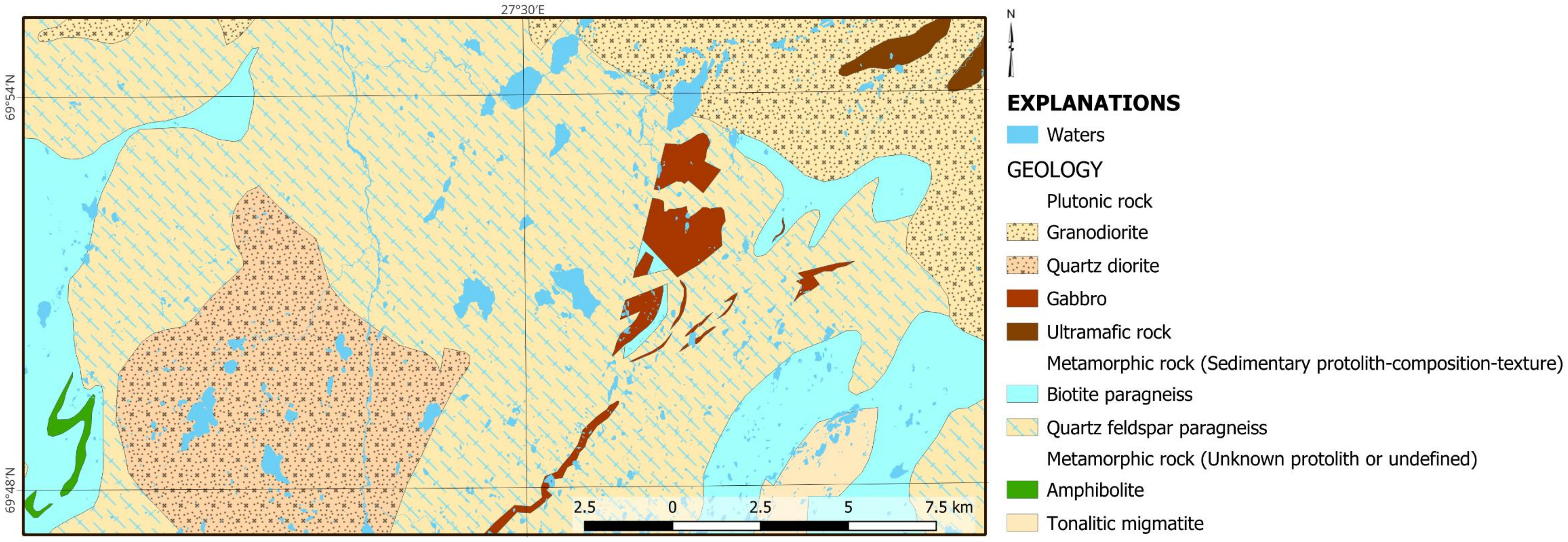

Figure S4. Geological features of the study area in northern Finland (prepared based on Geological Survey of Finland GTK, 2025)

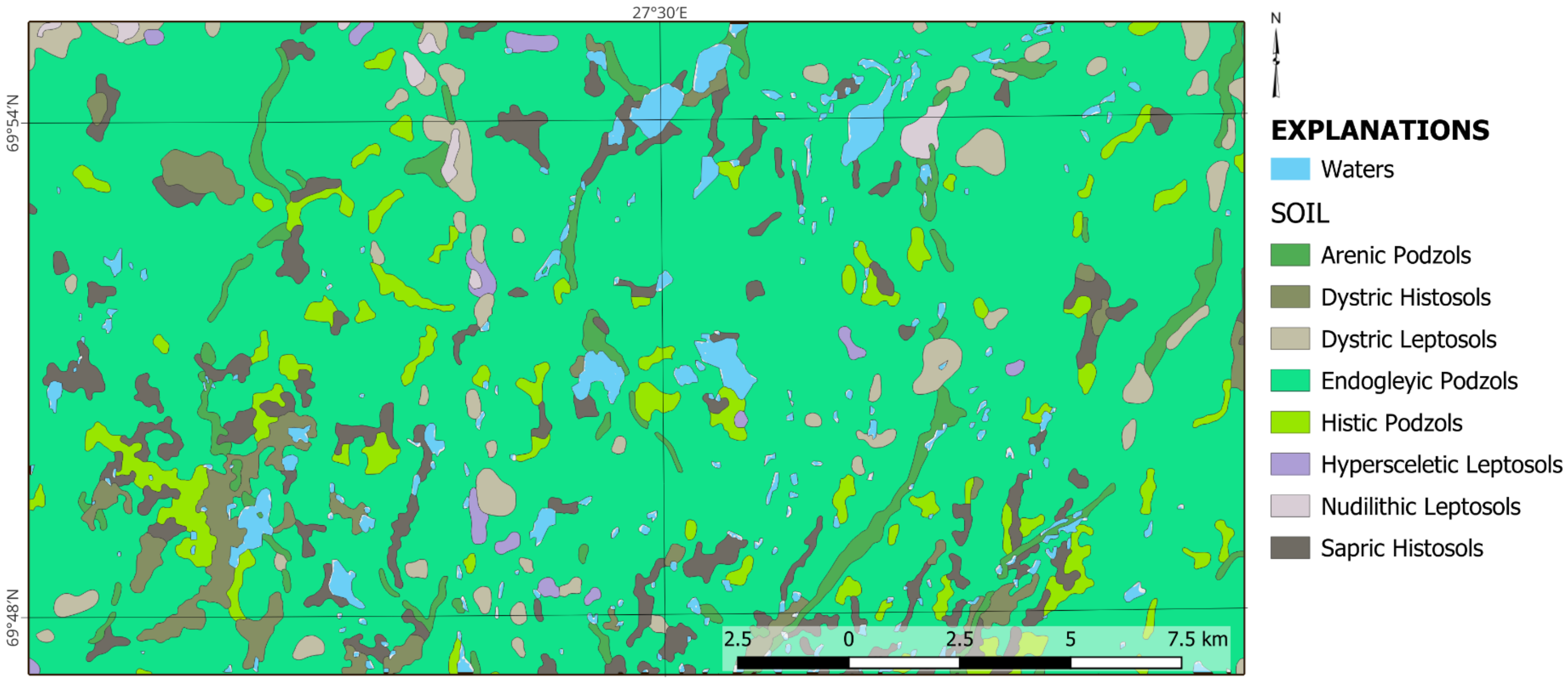

Figure S5. Soil map of the study area in northern Finland (prepared based on Lilja et al., 2017)

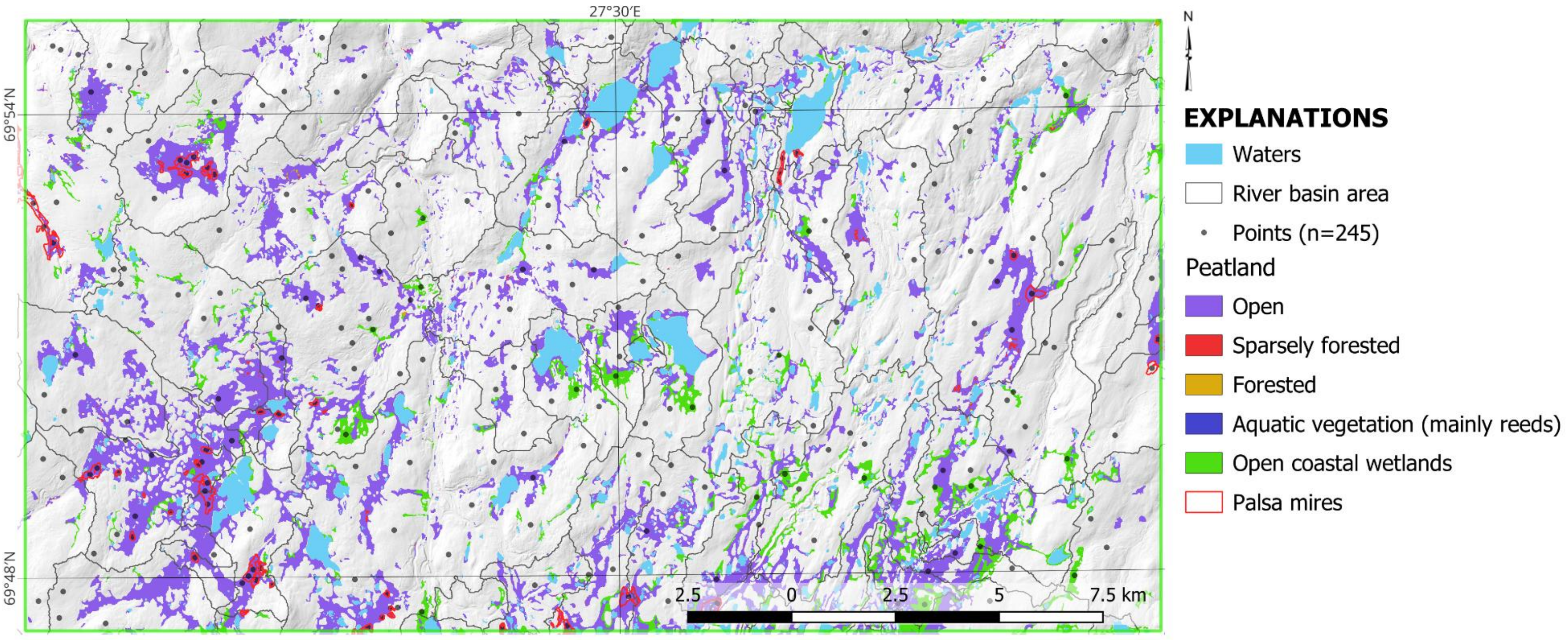

Figure S6. Land cover within peatlands in the study area in northern Finland (prepared based on Leppiniemi et al. (2025) and Finnish Environment Institute (SYKE), 2025)

2. Methods

2.1. Satellite and GIS data characteristics

Table S1. List of Landsat satellite images used in the study and a summary of thermal and precipitation classifications for the months from which the analysed satellite images originate (month classification based on climate data for Kevo station prepared based on Finnish Meteorological Institute, 2025)

No.	ID Landsat data	Date of satellite imagery	Thermal classification of years at Utsjoki Kevo station	Precipitation classification of years at Utsjoki Kevo station
1	LT05_L1TP_193011_19850712_20200918_02_T1	12.07.1985	Normal	Extremely dry
2	LT05_L1TP_191011_19850714_20200918_02_T1	14.07.1985	Normal	Extremely dry
3	LT05_L1TP_194011_19880625_20200917_02_T1	25.06.1988	Normal	Very dry
4	LT05_L1TP_194011_19880828_20200917_02_T1	28.08.1988	Normal	Very moist
5	LT05_L1TP_193011_19900608_20200915_02_T1	08.06.1990	Normal	Extremely dry
6	LT05_L1TP_191011_19910629_20200915_02_T1	29.06.1991	Normal	Moist
7	LT05_L1TP_192011_19930625_20200914_02_T1	25.06.1993	Anomalously cold	Very dry
8	LM02_L1TP_209011_19790419_20210616_02_T1	11.07.1993	Normal	Dry
9	LT05_L1TP_191011_19940707_20200913_02_T1	07.07.1994	Normal	Normal
10	LT05_L1TP_193011_19960811_20201008_02_T1	11.08.1996	Slightly warm	Very moist
11	LT05_L1TP_194011_19980621_20200909_02_T1	21.06.1998	Very cold	Extremely moist
12	LT05_L1TP_193011_19980630_20201008_02_T1	30.06.1998	Very cold	Extremely moist
13	LE07_L1TP_193011_20000713_20200918_02_T1	13.07.2000	Normal	Very dry
14	LE07_L1TP_193011_20000729_20200917_02_T1	29.07.2000	Normal	Very dry
15	LE07_L1TP_192011_20000807_20200918_02_T1	07.08.2000	Normal	Normal
16	LE07_L1TP_192011_20010623_20200917_02_T1	23.06.2001	Warm	Very dry
17	LE07_L1TP_192011_20020813_20200916_02_T1	13.08.2002	Normal	Very dry
18	LT05_L1TP_193011_20050703_20200902_02_T1	03.07.2005	Normal	Very moist
19	LT05_L1TP_191011_20050705_20200902_02_T1	05.07.2005	Normal	Very moist
20	LT05_L1TP_191011_20060825_20200831_02_T1	25.08.2006	Warm	Moist
21	LT05_L1TP_193011_20070623_20200830_02_T1	23.06.2007	Normal	Normal
22	LT05_L1TP_194011_20090806_20200827_02_T1	06.08.2009	Slightly warm	Very moist
23	LT05_L1TP_191011_20110620_20200822_02_T1	20.06.2011	Warm	Extremely moist
24	LC08_L1TP_192011_20130531_20200913_02_T1	31.05.2013	Anomalously warm	Extremely dry
25	LC08_L1TP_192011_20140721_20200911_02_T1	21.07.2014	Warm	Extremely dry
26	LC08_L1TP_191011_20150818_20200908_02_T1	18.08.2015	Very cold	Moist
27	LC08_L1TP_194011_20160724_20200906_02_T1	24.07.2016	Slightly warm	Moist
28	LC08_L1TP_193011_20160818_20200906_02_T1	18.08.2016	Warm	Very moist
29	LC08_L1TP_194011_20170727_20200903_02_T1	27.07.2017	Normal	Extremely moist
30	LC08_L1TP_194011_20170828_20200903_02_T1	28.08.2017	Normal	Moist
31	LC08_L1TP_193011_20180824_20200831_02_T1	24.08.2018	Normal	Extremely moist
32	LC08_L1TP_193011_20180909_20200830_02_T1	09.09.2018	Slightly warm	Extremely moist

33	LC08_L1TP_194011_20190615_20200828_02_T1	15.06.2019	Slightly cool	Normal
34	LC08_L1TP_191011_20190712_20200827_02_T1	12.07.2019	Slightly cool	Extremely dry
35	LC08_L1TP_193011_20200610_20200825_02_T1	10.06.2020	Slightly warm	Normal
36	LC08_L1TP_194011_20200617_20200823_02_T1	17.06.2020	Slightly warm	Normal
37	LC08_L1TP_191011_20200730_20200908_02_T1	30.07.2020	Normal	Extremely moist
38	LC08_L1TP_194011_20200804_20200914_02_T1	04.08.2020	Normal	Normal
39	LC08_L1TP_194011_20210807_20210811_02_T1	07.08.2021	Normal	Dry
40	LC09_L1TP_192011_20220601_20230414_02_T1	01.06.2022	Warm	Very dry
41	LC09_L1TP_191011_20220626_20230409_02_T1	26.06.2022	Warm	Very dry
42	LC08_L1TP_193011_20220702_20220708_02_T1	02.07.2022	Warm	Moist
43	LC09_L1TP_193011_20230611_20230611_02_T1	11.06.2023	Warm	Extremely dry
44	LC08_L1TP_193011_20230619_20230623_02_T1	19.06.2023	Warm	Extremely dry
45	LC09_L1TP_192011_20230620_20230620_02_T1	20.06.2023	Warm	Extremely dry
46	LC08_L1TP_192011_20230628_20230711_02_T1	28.06.2023	Warm	Extremely dry
47	LC08_L1TP_194011_20230712_20230718_02_T1	12.07.2023	Normal	Dry
48	LC08_L1TP_191011_20230808_20230812_02_T1	08.08.2023	Very warm	Extremely moist
49	LC08_L1TP_191011_20240623_20240708_02_T1	23.06.2024	Very warm	Very moist
50	LC08_L1TP_194011_20240714_20240719_02_T1	14.07.2024	Very warm	Dry
51	LC09_L1TP_193011_20240715_20240715_02_T1	15.07.2024	Very warm	Dry
52	LC09_L1TP_194011_20240722_20240722_02_T1	22.07.2024	Very warm	Dry
53	LC08_L1TP_193011_20240723_20240801_02_T1	23.07.2024	Very warm	Dry
54	LC09_L1TP_193011_20240731_20240731_02_T1	31.07.2024	Very warm	Dry
55	LC09_L1TP_194011_20240807_20240807_02_T1	07.08.2024	Anomalously warm	Very dry
56	LC08_L1TP_193011_20240808_20240814_02_T1	08.08.2024	Anomalously warm	Very dry
57	LC09_L1TP_192011_20240809_20240809_02_T1	09.08.2024	Anomalously warm	Very dry
58	LC09_L1TP_194011_20240823_20240823_02_T1	23.08.2024	Anomalously warm	Very dry

Table S2. Spectral indices characteristics (calculated based on Landsat data (USGS, 2025a))

Abbreviation	Spectral Index	Application of index	Indicator Pattern	Bands Landsat 4/5	Bands Landsat 8/9	Literature
NDVI	Normalized Difference Vegetation Index	Assessing vegetation health and density	[(NIR-VIS)/(NIR+VIS)]	[(B04 − B03) / (B04 + B03)]	[(B05 − B04)/(B05 + B04)]	Rouse et al., 1974
NDWI	Normalized Difference Water Index	Detection of surface water and soil moisture	[(GREEN − NIR)/(GREEN + NIR)]	[(B02 − B04) / (B02 + B04)]	(B03 − B05) / (B03 + B05)	McFeeters, 1996
MNDWI	Modified Normalized Difference Water Index	Enhanced water body detection	[(GREEN − SWIR)/(GREEN + SWIR)]	[(B02 – B05) / (B02 + B05)]	[(B03 − B6)/(B03 + B6)]	Xu, 2006
NDMI	Normalized Difference Moisture Index	Vegetation and soil moisture	[(NIR – SWIR1)/(NIR + SWIR1)]	[(B04 − B05) / (B04 + B05)]	[(B05 − B06)/(B05 + B06)]	Gao, 1996
LST	Land Surface Temperature	Ground temperature	Derived from thermal IR band + correction	Band 06 + emissivity correction	Band 10 + emissivity correction	Jimenez and Sobrino, 2003

Table S3. Environmental data characteristics

Dataset [unit]	Abbreviation	Access/Source
Digital Elevation Model [m a.s.l.]	DEM	https://www.maanmittauslaitos.fi/en/maps-and-spatial-data/datasets-and-interfaces/product-descriptions/elevation-model-2-m
Aspect (calculated based on DEM) [°; direction]	ASPECT	https://www.maanmittauslaitos.fi/en/maps-and-spatial-data/datasets-and-interfaces/product-descriptions/elevation-model-2-m
Slope (calculated based on DEM) [°]	SLOPE	https://www.maanmittauslaitos.fi/en/maps-and-spatial-data/datasets-and-interfaces/product-descriptions/elevation-model-2-m
Soil classes and palsa mires	SOIL	(Leppiniemi et al., 2025; Lilja et al., 2017)
Cartographic Depth to Water Index (DTW2) [cm]	DTW	https://opendata.luke.fi/en/dataset/urn-nbn-fi-att-770f345e-58d4-45e5-b4e7-3fdbd858872f
Distance to water object (rivers and lakes) [m]	distance_hydro	https://ckan.ymparisto.fi/dataset/suomen-maannostietokanta

2.2. Data exploration using statistical methods

The initial stage of the analysis involved conducting an exploratory data analysis aimed at assessing the quality of the dataset and identifying preliminary patterns prior to the application of statistical methods.

2.2.1. RS data completeness

The first stage of the study involved an inventory of available satellite imagery. Based on the adopted criteria, 58 scenes were selected (growing season, absence of ice cover and snow cover), which unevenly cover the entire study period from 1985 to 2024 (Figure S7). This nonlinear structure of the dataset results directly from the evolution of the Landsat programme and the associated increase in the frequency of Landsat image acquisition over time. A marked increase in the number of available scenes occurred after 2013, reaching its maximum in 2023–2024. This is attributable to the simultaneous operation of the Landsat 8 and Landsat 9 missions and the optimisation of the global data acquisition strategy, namely the Long-Term Acquisition Plan (USGS, 2025b). For the purposes of further analyses, the dataset was divided into three sub-periods: P1: 1985–1998, P2: 2000–2011, and P3: 2013–2024. It was assumed that the number of images from periods P1 (n = 12), P2 (n = 11), and P3 (n = 35) was sufficient to perform statistical analyses. In the subsequent stages of the analysis, after selecting images for which information was available for all 245 test points, that is, images not affected by cloud cover, it was confirmed that the number of source data was sufficient for statistical analysis. However, it should be noted that the analysed subsets are unbalanced (Figure S7).

Critical data gaps were identified for individual years between 1985 and 2012, for example 1992, 1999, and 2008 (Figure S8). Due to the mathematical requirements of the statistical methods applied, which require complete data matrices without missing values, a rigorous scene selection criterion was adopted. Only those scenes for which valid values of all RS indices could be obtained for each of the 245 measurement points were included in the subsequent analyses (Figure S8). Consequently, the occurrence of cloud cover or cloud shadows over even a small number of points resulted in the exclusion of the entire scene from the modelling process. This approach was intended to ensure the highest possible consistency and reliability of the statistical results. At the same time, the high proportion of missing values observed for some periods justified the need to apply methods robust to data incompleteness in the subsequent stages of the analysis.

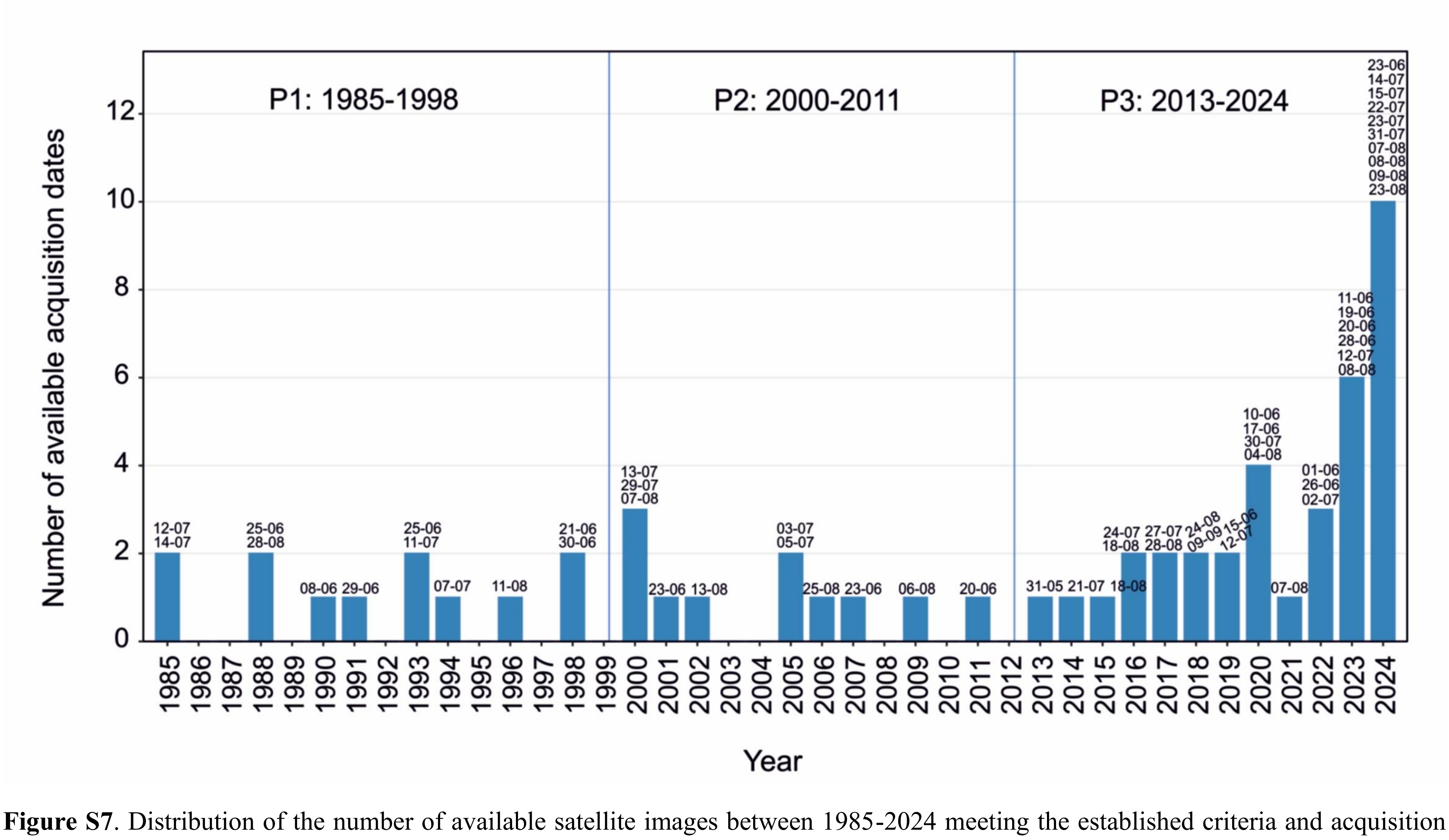

Figure S7. Distribution of the number of available satellite images between 1985-2024 meeting the established criteria and acquisition dates for Landsat imagery. Values above the bars indicate specific image acquisition dates for a given year

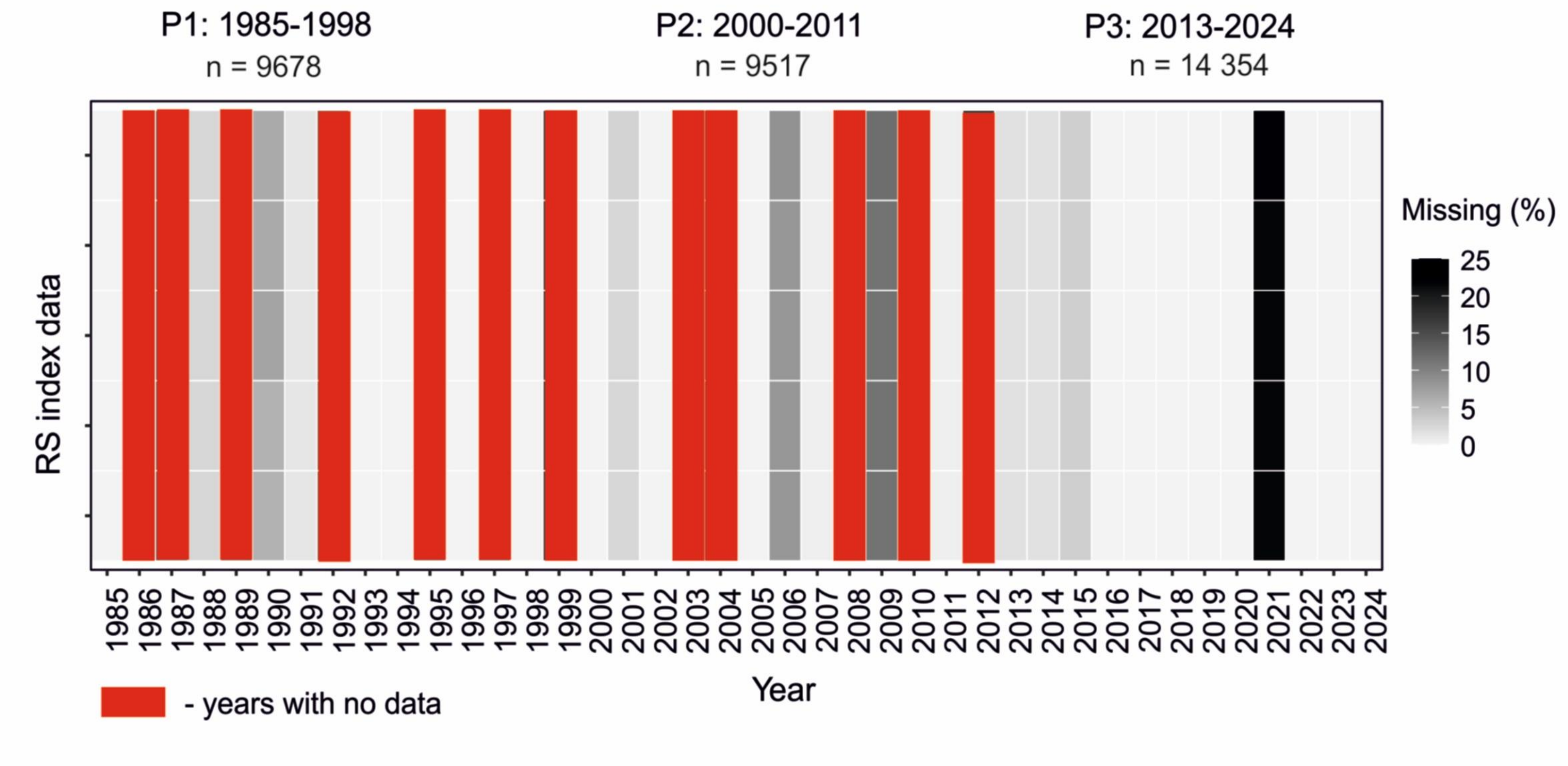

Figure S8. Percentage of missing RS indices, which were calculated based of selected Landsat satellite images in the years 1985-2024

2.2.2. Internal data structure

In the next stage, the distribution of spectral index values was examined for 245 points located within the study area, with reference to three categories defined on the basis of soil types and the spatial distribution of palsa mires (Figure S6). For the analyses, a division into three groups was adopted, provisionally referred to as "soil categories": mineral soils (class 0; n=149), non-palsa organic soils (class 1; n=48), and palsa mires (class 2; n=48) (Figure S9). The pronounced differences in the medians and interquartile ranges of the NDVI, NDWI, NDMI, MNDWI, and LST indices confirmed that the soil category is a key factor differentiating the spectral response of satellite-derived indices. This analysis demonstrated that the remote sensing data exhibit a clear internal structure that is strongly correlated with the division into soil categories. Despite the unequal sample sizes of the individual categories, the RS index values exhibit an ordered, non-random trend. The specificity of the spectral signatures for the respective classes suggests that the data structure is organised along a primary gradient differentiating moisture conditions and vegetation status from land surface temperature.

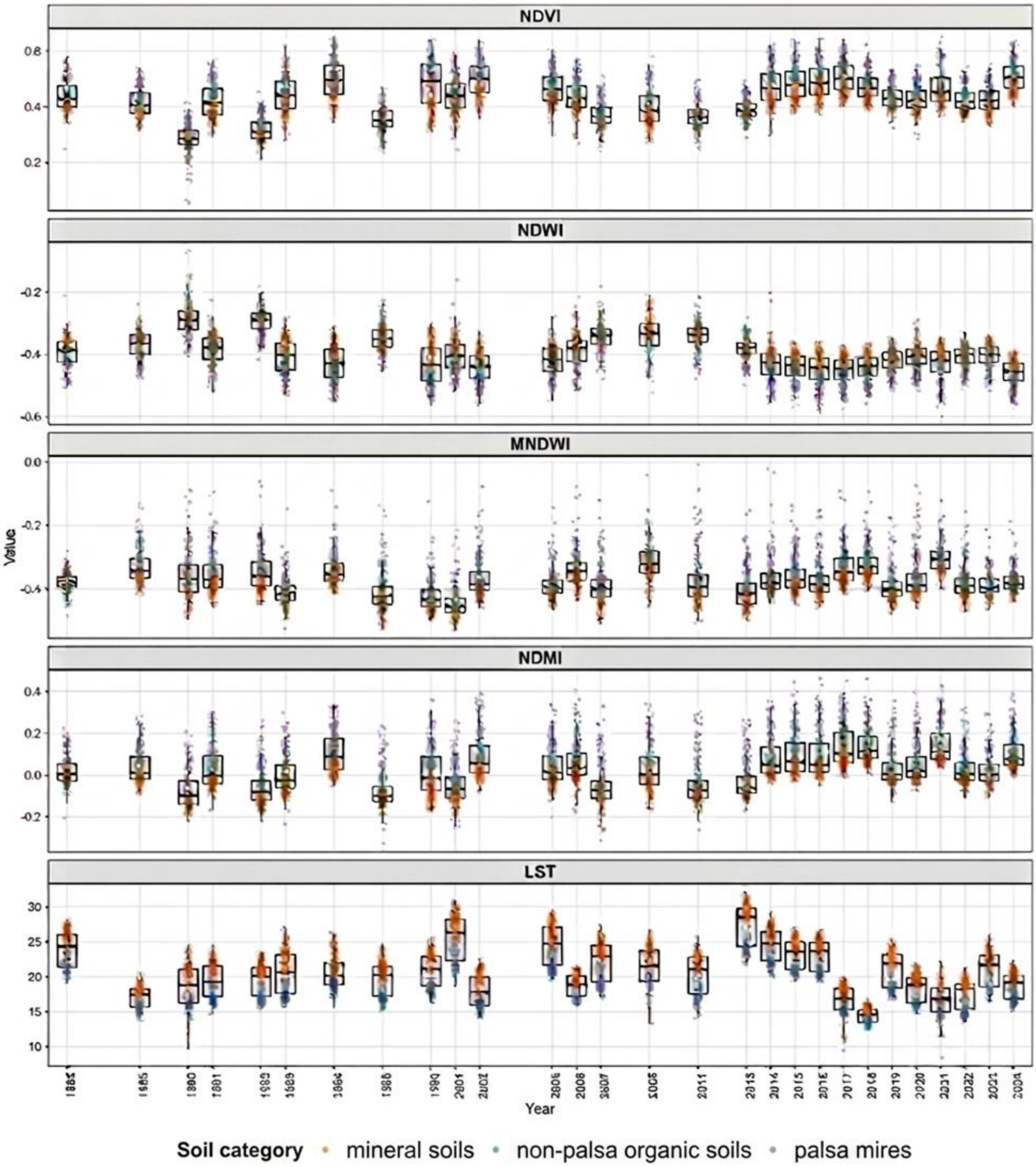

Figure S9. Average values of remote sensing indexes NDVI, NDWI, MNDWI, NDMI and LST for years 1985-2024 for 245 points distributed in the in the study area of the Northern Finland with division of three soil categories (calculated based on Landsat data *(USGS, 2025a)*)

2.2.3. Distribution and Redundancy of Environmental Data

The set of environmental data included in the statistical analysis comprised both continuous and categorical variables. Due to their differing characteristics, this required a stepwise approach to analysis and dimensionality reduction. The variables included elevation (DEM), wetness conditions (TWI), depth to groundwater (DTW05, DTW1, DTW2, DTW4, DTW10), distance to the nearest water body or watercourse (distance_hydro), distance to the boundary of the elementary catchment divide (distance_catchment), slope (SLOPE), and aspect (ASPECT). In the first step continuous environmental variables were inspected for distributional properties, skewness, and potential outliers. Strongly right-skewed variables (DTW, slope, distance_catchment, distance_hydro) were log-transformed log (x + 1) prior to multivariate analyses, whereas all other continuous variables (DEM, TWI) were subsequently z-score standardized to ensure comparability. Based on collinearity screening, the final predictor set retained for modelling included SOIL_reclass, DEM, DTW2, distance_hydro, and ASPECT_reclass. Only one DTW-derived variable (DTW2) was retained to represent hydrological position, because alternative DTW metrics were strongly intercorrelated. TWI was excluded from the main models because they showed substantial overlap with DTW-based predictors, whereas distance_catchment was not retained in order to keep the predictor set parsimonious and ecologically interpretable (Figure S10). Moreover, a high degree of interdependence was found between the environmental variables and the values of the spectral indices (Figure S11), confirming the rationale for performing Redundancy Analysis (RDA). This made it possible to determine what proportion of the shared variance was explained by environmental factors.

In turn, the observed regularity (Figure S9) and the strong correlation within the group of RS indices itself (Figure S12) ultimately justify the use of PCA transformation to reduce the dimensionality to a single synthetic principal axis. Because the RS indices do not describe independent aspects of the environment, but instead form a coherent pattern of covariation, the application of PCA allowed the strongly correlated indices to be reduced to an overarching ordering gradient. At the same time, the data structure defined in this way provided the basis for RDA, aimed at verifying the statistical significance of the effects of individual environmental variables on the observed spectral variability.

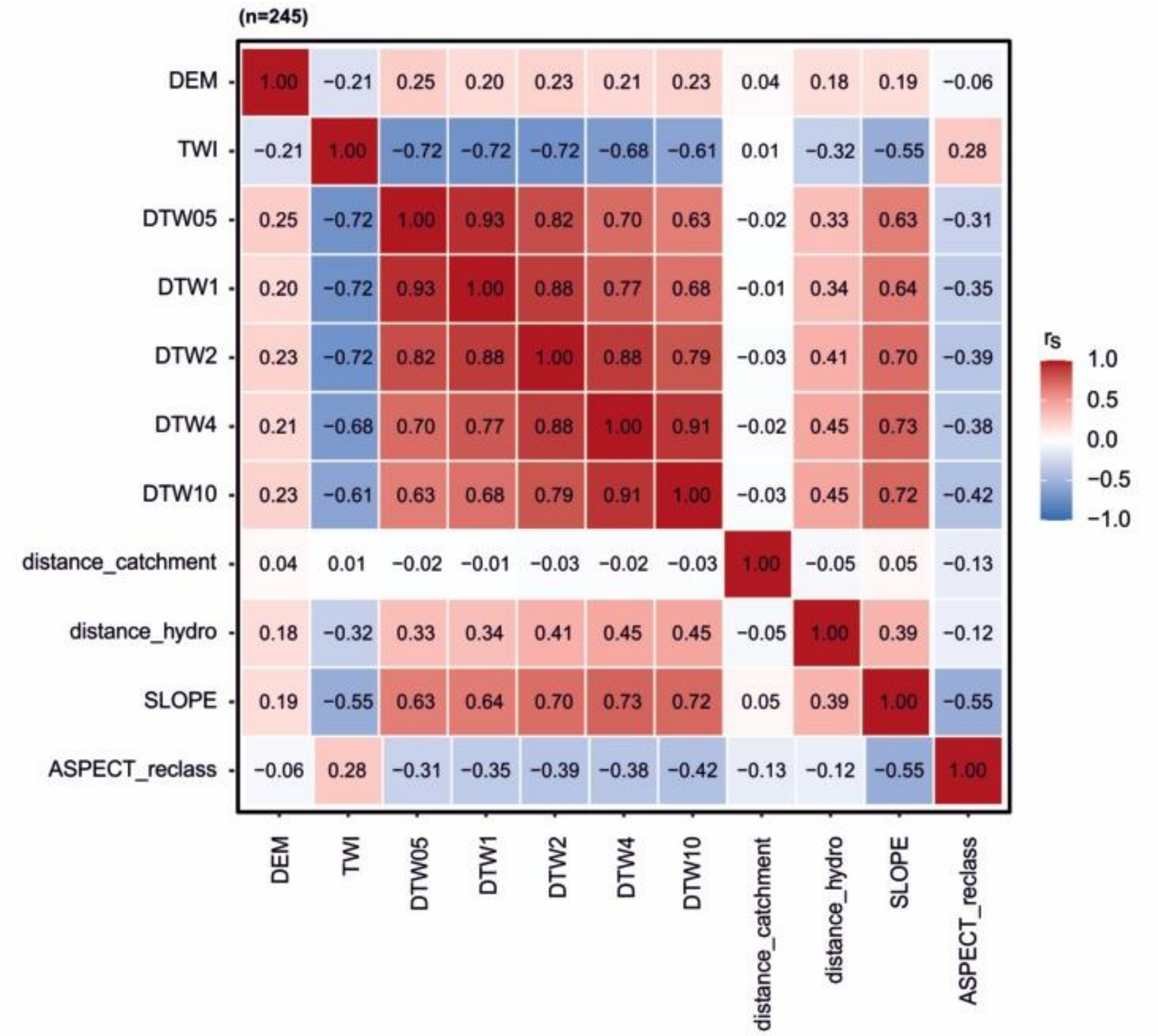

Figure S10. Correlations of Spearman rank between all available environmental factors calculated for the period 1985–2024

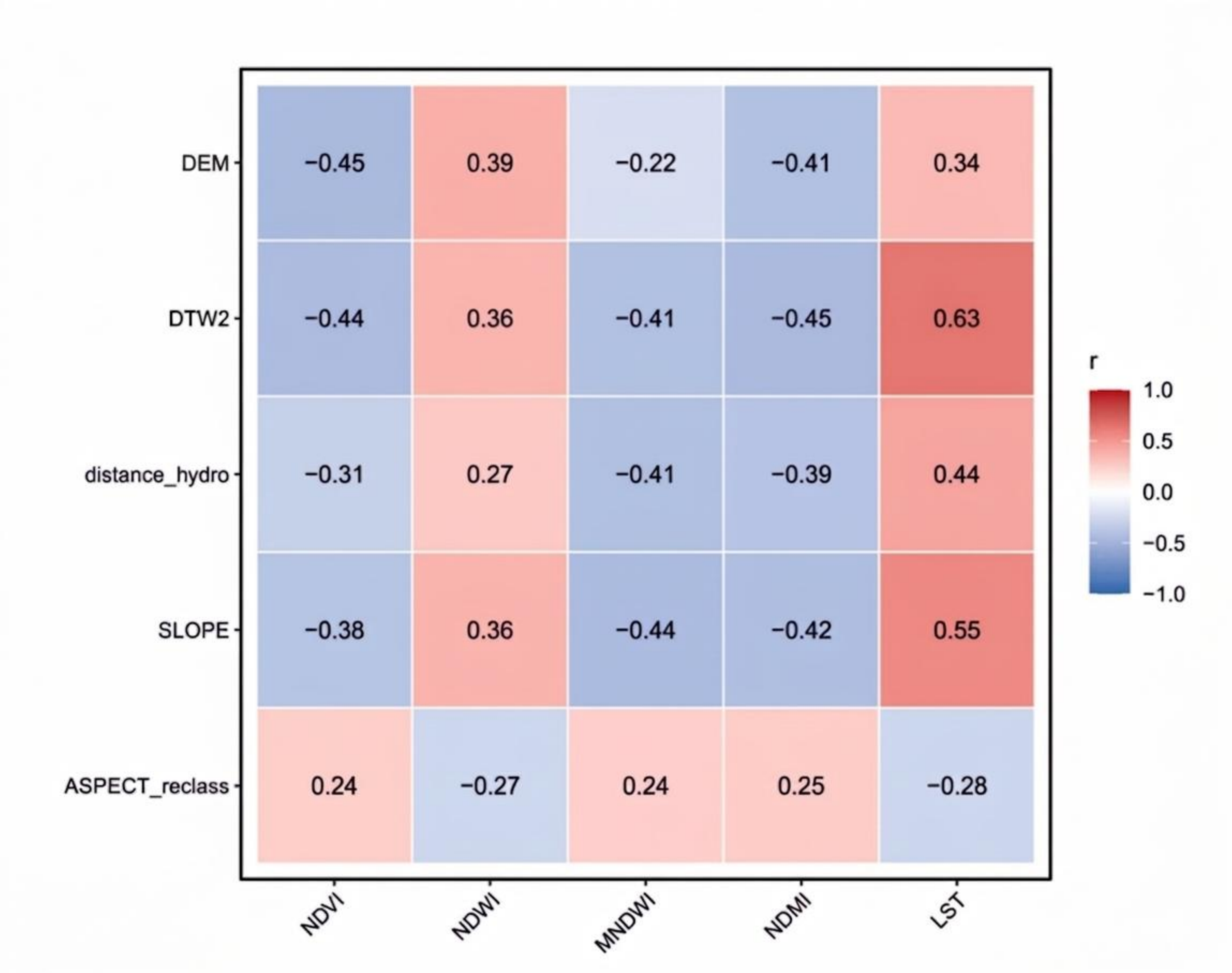

Figure S11. Correlations of Spearman rank between environmental factors and the values of remote sensing indicator values for the period 1985–2024

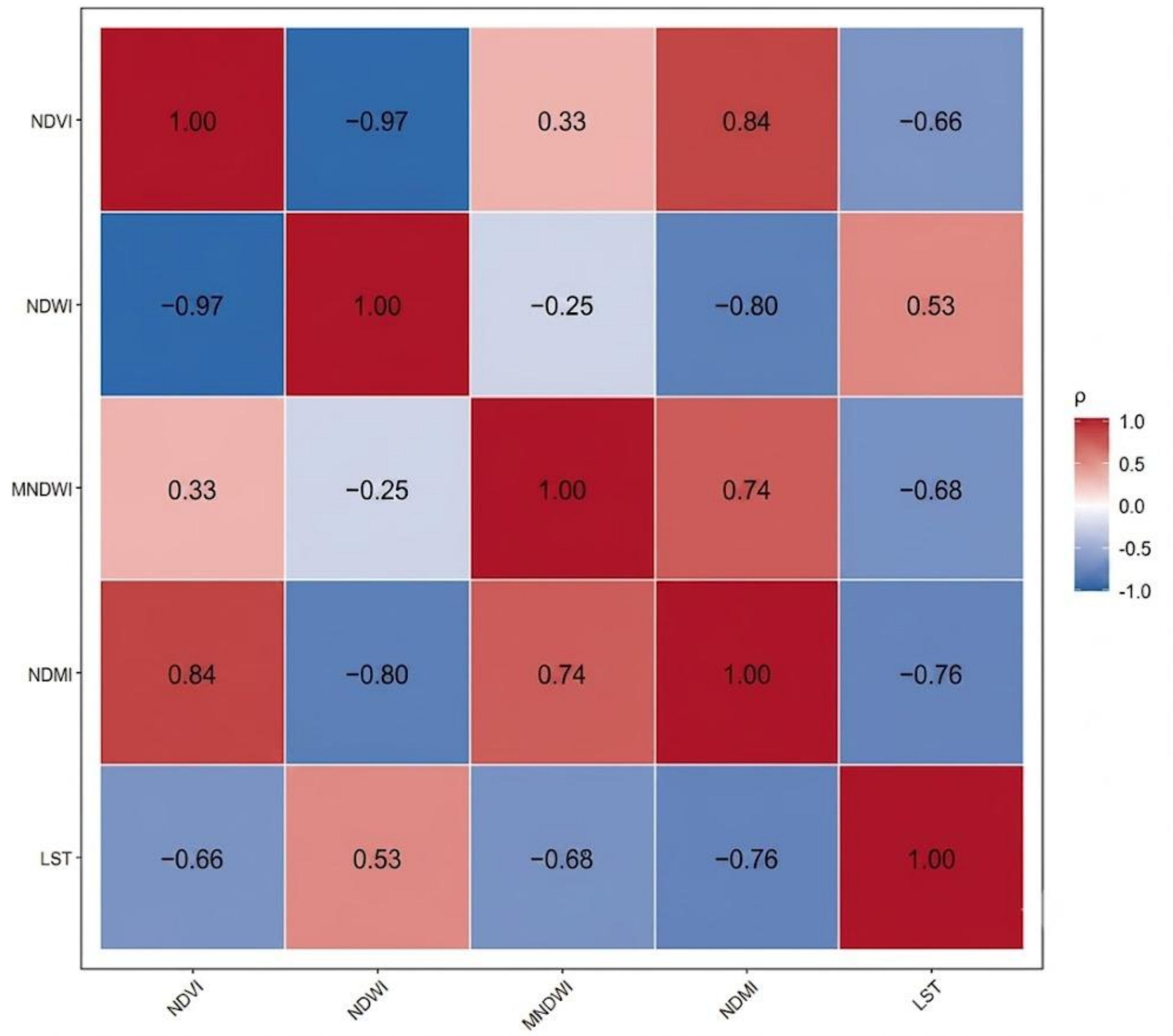

Figure S12. Correlations of Spearman of the values of remote sensing indices for the period 1985–2024

3. Results

3.1. Climate conditions and temporal changes of air temperature, precipitation and snow depth

Changes in climatic conditions were presented for the period 1970–2024 based on data from the Utsjoki-Kevo meteorological station [69°45′21″N, 27°00′44″E], located in northern Finland approximately five kilometres north-west of the boundary of the study area.

The mean annual air temperature over the analysed period showed a clear increasing trend (Figure S13). Particularly high mean annual air temperatures were recorded in the last decade of the analyzed period, especially after 2010. In 2020, 2022, and 2024, the mean annual temperatures exceeded -0.5°C, whereas in the 1970s and 1980s, years with temperatures falling below -2.0°C occurred relatively frequently (e.g., in 1985, the mean annual temperature was -3.6°C). The highest mean annual air temperature was recorded in 2024, reaching 0.9°C. Annual precipitation totals showed a slight upward trend between 1970 and 2024 (Figure S13), while the number of precipitation days showed a downward trend (Figures S13 and S15). The lowest annual precipitation totals occurred in 1980 (263 mm) and 1990 (294 mm), whereas the highest annual precipitation total occurred in 1999 (597 mm) (Figure S15).

In the summer months analyzed using satellite data (June, July, and August), it can be observed that an upward trend in air temperatures is visible across all of them (FigureS14). Of these, July constituted the warmest month, with an average temperature of 13.5°C between 1970 and 2024, followed by August (11.2°C) and June (10.1°C) (Table S4). During these months, the highest mean monthly temperature occurred in August 2018 (18.1°C), and the lowest in June 1993 (6.3°C). On a multi-year scale, July and August constitute the warmest months of the year and are characterized by the some of the lowest standard deviation values of air temperature compared to the other months (1.7°C in July and 1.4°C in August). The coldest months were January and February (with mean temperatures of -13.7°C and -12.7°C, respectively). Concurrently, for the winter and transitional months, the standard deviation of temperatures during the analyzed period was the highest (reaching 4.4°C in February and 3.8°C in January). Among the extreme values, a record-low mean monthly temperature occurred in February 1985 (−22.8°C) (Table S4). Furthermore, the results indicate a shortening of the snow cover duration over the analyzed years of 1970–2024 by approximately 0.002 days per year (Figure S16).

The thermal classification of individual years and months for the 1985–2024 period (analyzed in this study using remote sensing indices) was conducted based on the method proposed by Lorenc (1994), utilizing temperature standard deviation values relative to the mean (Table S5). Mean annual and monthly air temperatures for the period 1970–2024 were adopted as baseline values, assuming that long-term mean values are more representative. Over the period 1985–2024, years ranged from anomalously cold to very warm. Normal years occurred 15 times, warm to very warm years occurred 18 times, and cold to anomalously cold years occurred 7 times (Table S6). The year 2024 was very warm, whereas 1985 was anomalously cold. Considering the values for the months from June to August, months classified as very warm, anomalously warm, and extremely warm occurred several times after 2002.

The classification of precipitation for individual years and months was carried out for the period 1985–2024, based on the method proposed by Kaczorowska (1962), using the multi-year average annual precipitation sum from the years 1970–2024, treated as normal precipitation. Individual years were classified based on the percentage difference relative to the normal precipitation value (Table S7). In the analysed period 1985–2024, years ranged from very dry to very moist. Normal years occurred 16 times, moist years 9 times, very moist years 6 times, dry years 8 times, and one year was classified as very dry (1990). Monthly precipitation showed greater interannual variability, ranging from extremely dry to extremely moist months (Table S8).

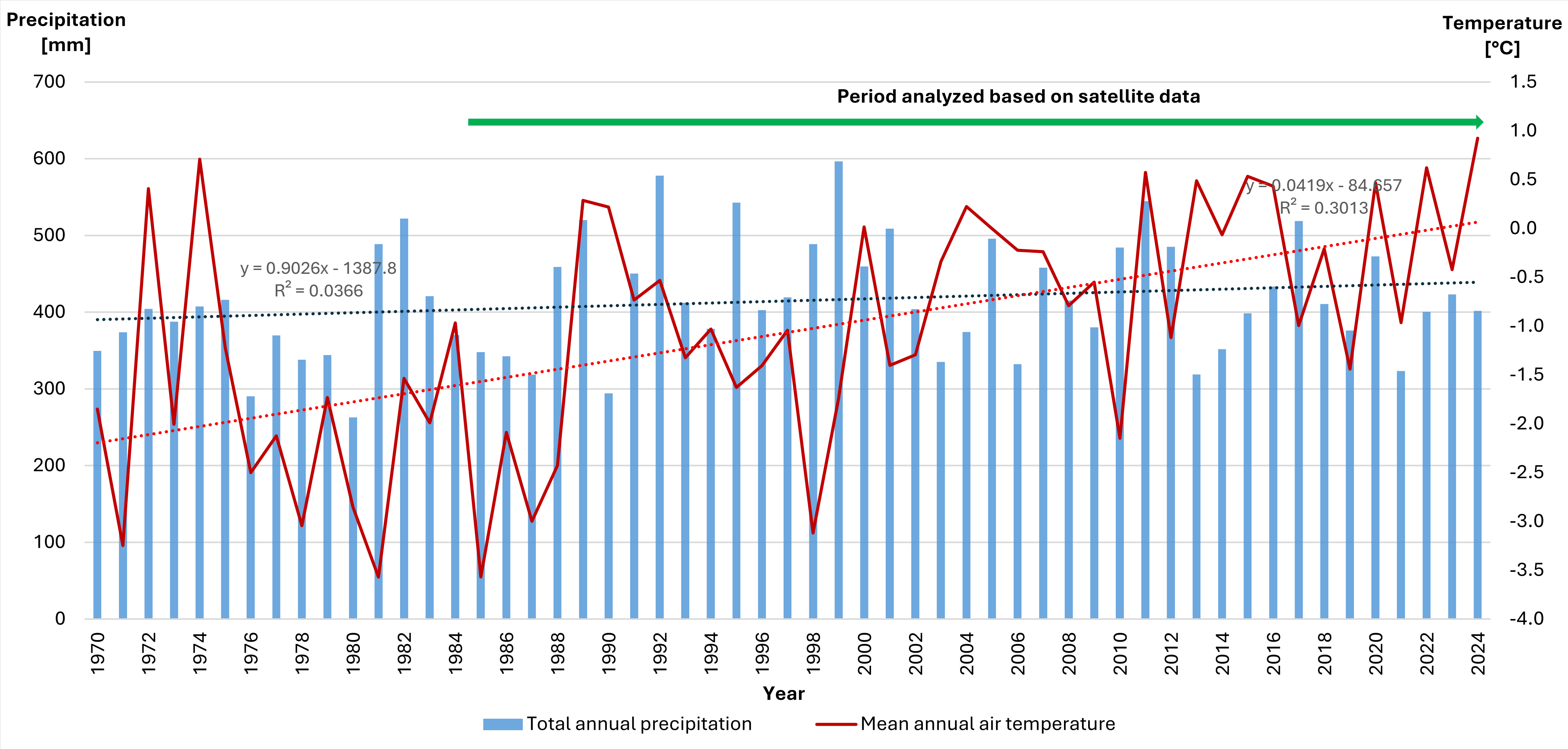

Figure S13. The course of mean annual air temperatures and total annual precipitation in the years 1970–2024 at Utsjoki Kevo station in northern Finland. Trend lines are shown as dashed lines (blue for precipitation and red for air temperature) (calculated based on data from Finnish Meteorological Institute, 2025)

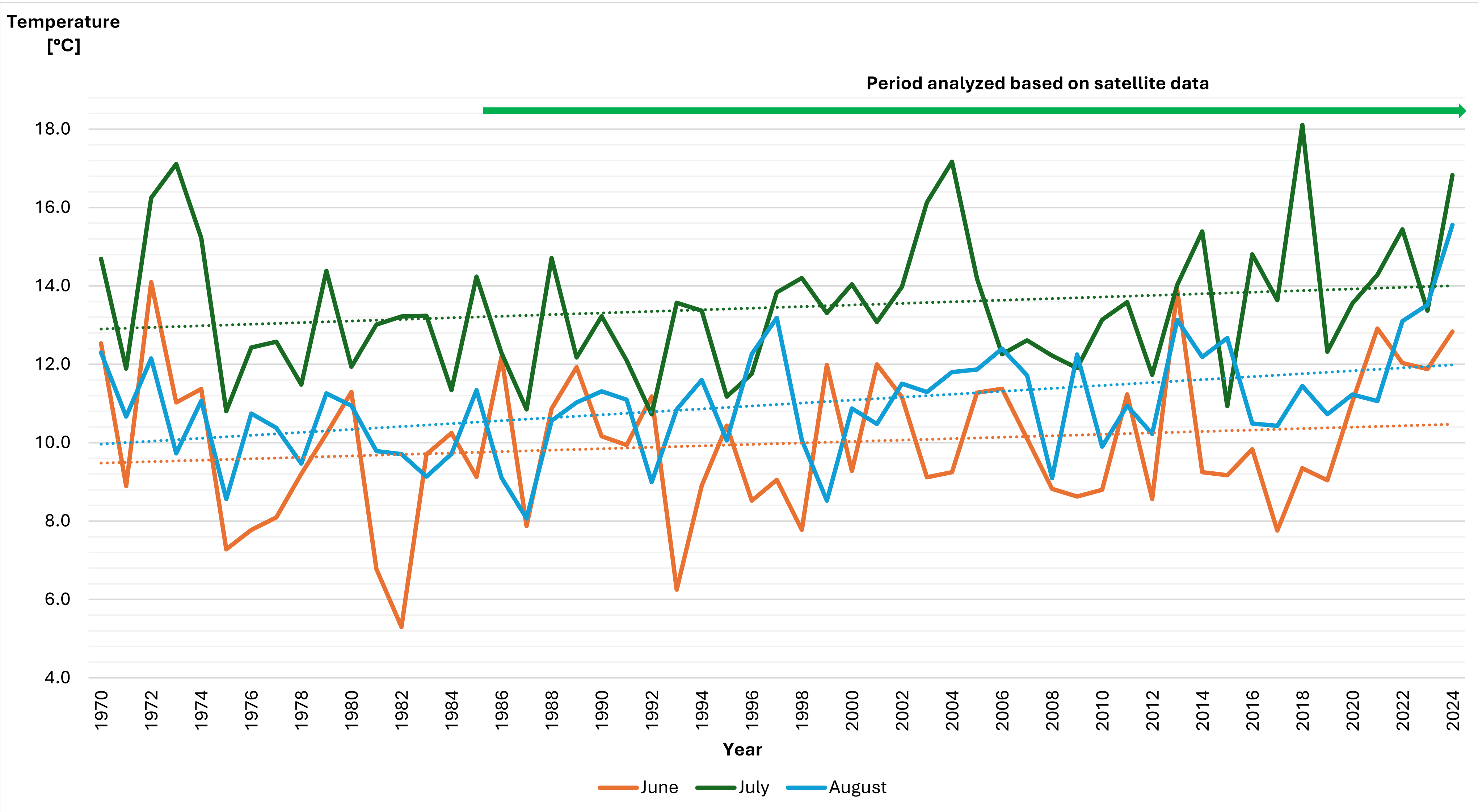

Figure S14. Average monthly air temperatures in June, July and August in the years 1970-2024 at Utsjoki Kevo station in northern Finland. Trend lines are shown as dashed lines (calculated based on data from Finnish Meteorological Institute, 2025)

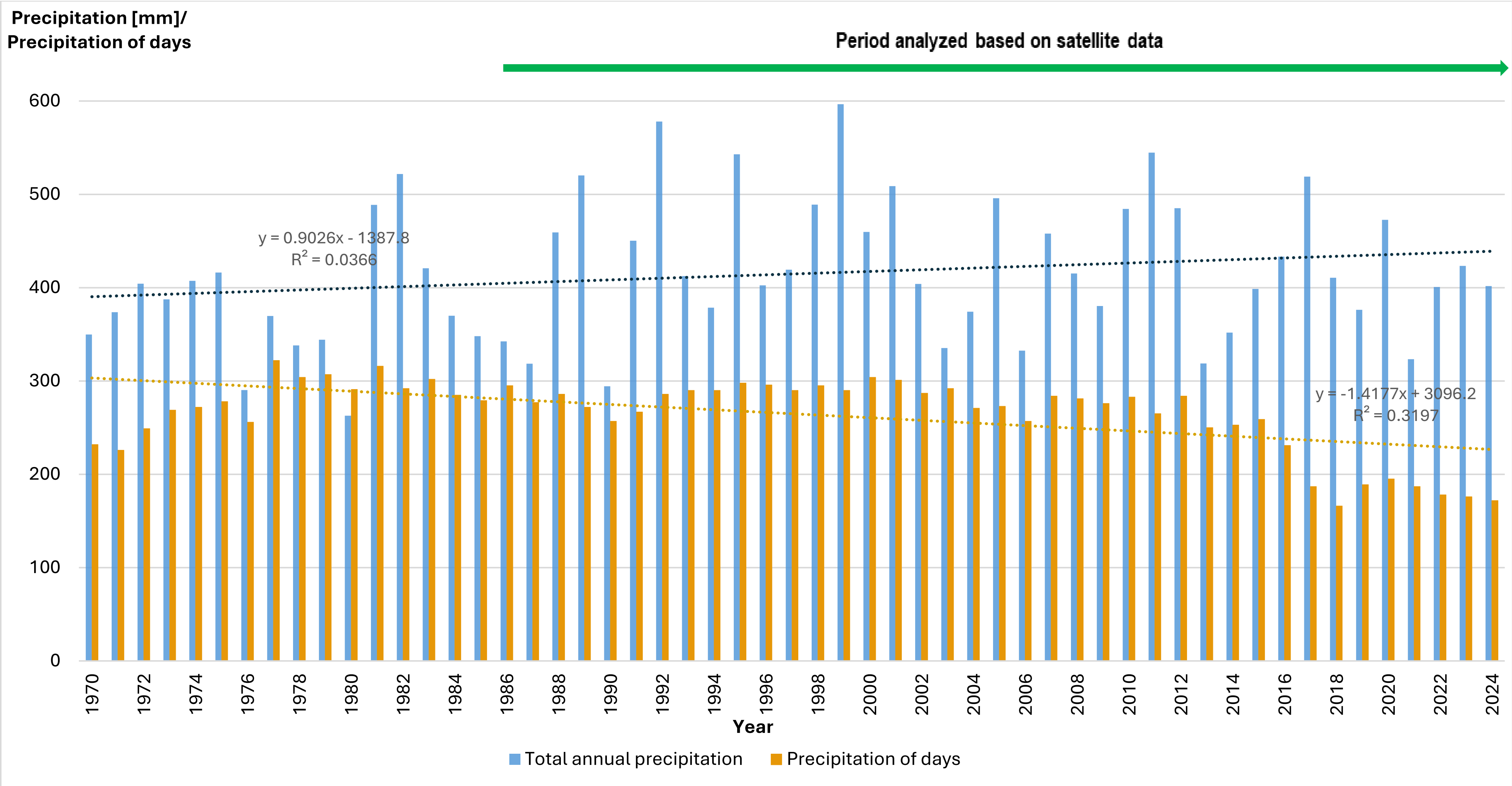

Figure S15. Annual precipitation and number of days with precipitation in the years 1970–2024 at Utsjoki Kevo station in northern Finland. Trend lines are shown as dashed lines (calculated based on data from Finnish Meteorological Institute, 2025)

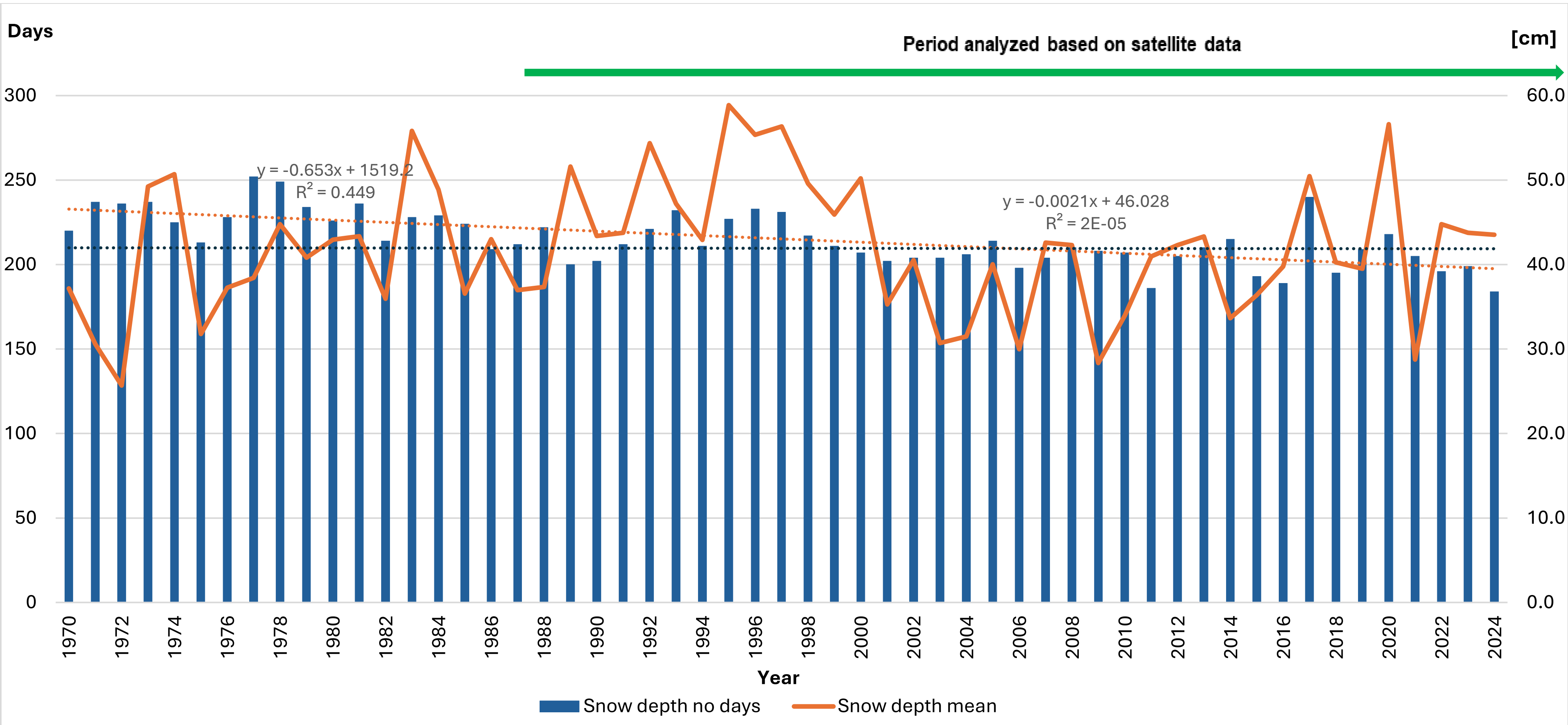

Figure S16. Number of days with snow and mean annual snow depth in the years 1970–2024 at Utsjoki Kevo station in northern Finland. Trend lines are shown as dashed lines (calculated based on data from Finnish Meteorological Institute, 2025)

Table S4. Characteristics of monthly and annual air temperatures and precipitation totals at the Utsjoki Kevo station in 1985–2024 and annual values in three time periods: 1985–1998; 2000–2011; 2013–2024 (calculated based on data from Finnish Meteorological Institute, 2025)

Month	Monthly mean						
	Air temperature						Precipitation
	Mean [°C]	Standard deviation	Minimum [°C]	Year	Maximum [°C]	Year	Mean [mm]
I	-13.7	3.8	-22.1	2003	-8.2	2008	26
II	-12.7	4.4	-22.8	1985	-3.7	1990	24
III	-7.8	3	-14.3	2001	-2.9	2007	20
IV	-2.0	2.2	-6.6	1997	1.7	2011	21
V	4.1	1.7	0.7	1996	8.2	2016	29
VI	10.1	1.7	6.3	1993	13.9	2013	50
VII	13.5	1.7	10.7	1992	18.1	2018	71
VIII	11.2	1.4	8.1	1987	15.6	2024	58
IX	6.3	1.5	2.5	1993	9.3	2024	38
X	-0.2	2.2	-8.4	1992	4.7	1987	36
XI	-7.3	3.3	-14.2	1998	-1.7	2018	26
XII	-11.5	4	-20.3	1985	-4.7	2007	28
I-XII$_{1985-2024}$	-0.8	1.1	-3.6	1985	0.9	2024	426
I-XII$_{1985-1998}$	-1.5	1.1	-3.6	1985	0.3	1989	425
I-XII$_{2000-2011}$	-0.5	0.7	-2.1	2010	0.6	2011	433
I-XII$_{2013-2024}$	-0.1	0.7	-1.4	2019	0.9	2024	402

Table S5. Thermal classification according to Lorenc (1994)

Color scale	Class number	Type of period	Temperature range
	1	Extremely warm	$T > T_{mean} + 2,5\delta$
	2	Anomalously warm	$T_{mean} + 2,0\ \delta < T \leq T_{mean} + 2,5\ \delta$
	3	Very warm	$T_{mean} + 1,5\ \delta < T \leq T_{mean} + 2,0\ \delta$
	4	Warm	$T_{mean} + 1,0\ \delta < T \leq T_{mean} + 1,5\ \delta$
	5	Slightly warm	$T_{mean} + 0,5\ \delta < T \leq T_{mean} + 1,0\ \delta$
	6	Normal	$T_{mean} - 0,5\ \delta \leq T \leq T_{mean} + 0,5\ \delta$
	7	Slightly cool (slightly frosty)	$T_{mean} - 1,0\ \delta \leq T < T_{mean} - 0,5\ \delta$
	8	Cool (frosty)	$T_{mean} - 1,5\ \delta \leq T < T_{mean} - 1,0\ \delta$
	9	Very cold (very frosty)	$T_{mean} - 2,0\ \delta \leq T < T_{mean} - 1,5\ \delta$
	10	Anomalously cold (anomalously frosty)	$T_{mean} - 2,5\ \delta \leq T < T_{mean} - 2,0\ \delta$
	11	Extremely cold (extremely frosty)	$T < T_{mean} - 2,5\ \delta$

Explanations: T – average air temperature in a month, period or year, T_{mean} – average long-term air temperature in the same period, δ – standard deviation; The names in parentheses refer to the months of the winter half-year (October-March)

Table S6. Thermal classification of months and years at Utsjoki Kevo station in the period 1985–2024 based on values from the base period 1970–2024 (calculated based on data from Finnish Meteorological Institute, 2025)

Year/ Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	**I-XII**
1985													
1986													
1987													
1988													
1989													
1990													
1991													
1992													
1993													
1994													
1995													
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2017													
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2019													
2020													
2021													
2022													
2023													
2024													

Table S7. Percipitation classification according to Kaczorowska (1962)

Color scale	Class number	Type of period	Percipitation range
	1	Extremely dry	$P < 50$
	2	Very dry	$50 \leq P < 75$
	3	Dry	$75 \leq P < 90$
	4	Normal	$90 \leq P \leq 110$
	5	Moist	$111 \leq P \leq 125$
	6	Very moist	$126 \leq P \leq 150$
	7	Extremely moist	$P > 150$

Explanations: P - reference percentage, i.e. how many percent of the standard (long-term average) is the current precipitation

Table S8. Classification of precipitation in months and years at Utsjoki Kevo station in the period 1985–2024 based on values from the base period 1970–2024 (calculated based on data from Finnish Meteorological Institute, 2025)

Year/ Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	**I-XII**
1985													
1986													
1987													
1988													
1989													
1990													
1991													
1992													
1993													
1994													
1995													
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2019													
2020													
2021													
2022													
2023													
2024													

3.2. Analysis of remote sensing indices with connection to environmental factors

Table S9. Pairwise differences in temporal slopes

Index	Contrast	Estimate	SE	z ratio	Adjusted p
NDVI	mineral soils - other organic soils	-0.000668	0.000165	-4.06	<0.001
NDVI	mineral soils - palsa mires	-0.000545	0.000164	-3.32	0.003
NDVI	other organic soils - palsa mires	0.000122	0.000202	0.60	0.818
NDWI	mineral soils - other organic soils	0.000330	0.000126	2.61	0.024
NDWI	mineral soils - palsa mires	0.000332	0.000126	2.64	0.023
NDWI	other organic soils - palsa mires	0.000002	0.000155	0.01	1.000
MNDWI	mineral soils - other organic soils	-0.000055	0.000123	-0.45	0.895
MNDWI	mineral soils - palsa mires	-0.000241	0.000123	-1.96	0.123
MNDWI	other organic soils - palsa mires	-0.000186	0.000152	-1.22	0.439
NDMI	mineral soils - other organic soils	-0.000494	0.000188	-2.63	0.023
NDMI	mineral soils - palsa mires	-0.000676	0.000187	-3.61	<0.001
NDMI	other organic soils - palsa mires	-0.000182	0.000231	-0.79	0.709
LST	mineral soils - other organic soils	-0.019901	0.008541	-2.33	0.052
LST	mineral soils - palsa mires	-0.011000	0.008514	-1.29	0.400
LST	other organic soils - palsa mires	0.008901	0.010491	0.85	0.673

SE - standard error of the estimated contrast, z ratio - test (=estimate/SE), Adjusted p - the p-value after multiple-comparison correction, differences were considered statistically significant when the adjusted p-value < 0.05; Positive estimates indicate a less negative or more positive trend in the first group named in the contrast.

Table S10. Post hoc pairwise comparisons in estimated marginal means at the average year. Positive estimates indicate higher values in the first group named in the contrast

Index	Contrast	Estimate	SE	z ratio	Adjusted p
NDVI	mineral soils - other organic soils	-0.0397	0.0061	-6.50	<0.001
NDVI	mineral soils - palsa mires	-0.0738	0.0061	-12.09	<0.001
NDVI	other organic soils - palsa mires	-0.0341	0.0075	-4.54	<0.001
NDWI	mineral soils - other organic soils	0.0210	0.0054	3.87	<0.001
NDWI	mineral soils - palsa mires	0.0653	0.0054	12.00	<0.001
NDWI	other organic soils - palsa mires	0.0442	0.0067	6.61	<0.001
MNDWI	mineral soils - other organic soils	-0.0342	0.0053	-6.42	<0.001
MNDWI	mineral soils - palsa mires	-0.0792	0.0053	-14.88	<0.001
MNDWI	other organic soils - palsa mires	-0.0451	0.0066	-6.88	<0.001
NDMI	mineral soils - other organic soils	-0.0644	0.0085	-7.61	<0.001
NDMI	mineral soils - palsa mires	-0.1674	0.0085	-19.77	<0.001
NDMI	other organic soils - palsa mires	-0.1030	0.0104	-9.89	<0.001
LST	mineral soils - other organic soils	3.6468	0.1727	21.12	<0.001
LST	mineral soils - palsa mires	3.9478	0.1727	22.86	<0.001
LST	other organic soils - palsa mires	0.3010	0.2125	1.42	0.332

SE - standard error of the estimated contrast, z ratio - test (=estimate/SE), Adjusted p - the p-value after multiple-comparison correction, values < 0.05 were considered statistically significant; Positive estimates indicate higher values in the first group named in the contrast

Figure S17. Variability of satellite indexes NDVI, NDWI, MNDWI, NDMI, LST in the points distributed in the study area of Norther Finland (n = 245) - mean values of indices for three time intervals P1: 1985–1998; P2: 2000–2011; P3: 2013–2024, with division of three categories of soils (calculated based on Landsat data (USGS, 2025a))

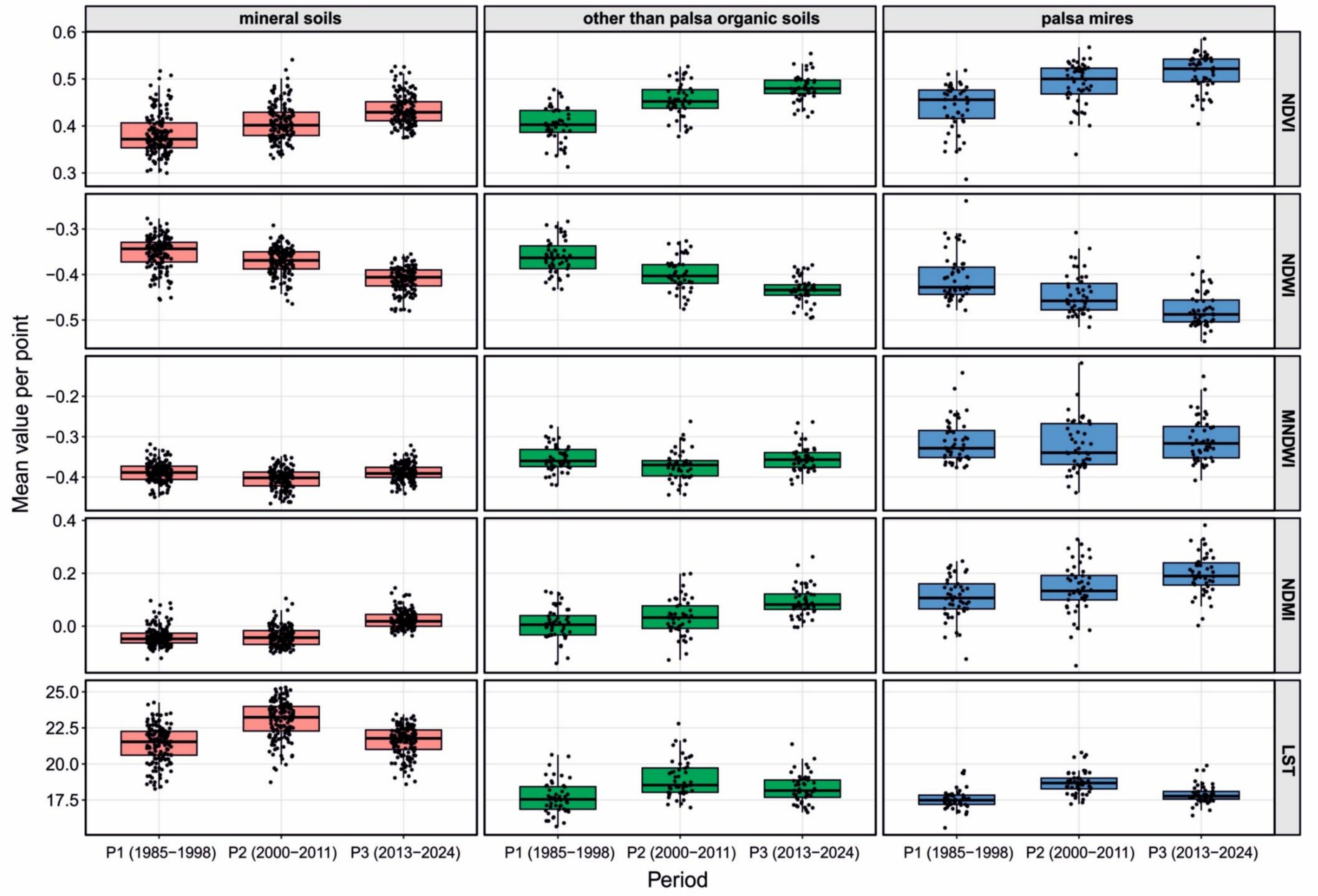


Figure S18. Values of remote sensing indexes NDVI, NDWI, MNDWI, NDMI and LST for three soil category (MS, OOS and PM) and for three study periods (P1, P2, P3) for 245 points distributed in the in the study area of the Northern Finland (calculated based on Landsat data *(USGS, 2025a)*)

Table S11. Differences among soil-environment categories within each study period based on point-level mean values of remote sensing indices

Index	Period	H	p	MS vs OOS (adj. p)	MS vs PM (adj. p)	OOS vs PM (adj. p)
NDVI	P1 (1985-1998)	51.38	<0.001	0.003	<0.001	0.003
NDVI	P2 (2000-2011)	97.54	<0.001	<0.001	<0.001	0.010
NDVI	P3 (2013-2024)	115.48	<0.001	<0.001	<0.001	0.018
NDWI	P1 (1985-1998)	44.80	<0.001	0.101	<0.001	<0.001
NDWI	P2 (2000-2011)	83.94	<0.001	<0.001	<0.001	<0.001
NDWI	P3 (2013-2024)	88.31	<0.001	<0.001	<0.001	<0.001
MNDWI	P1 (1985-1998)	108.46	<0.001	<0.001	<0.001	0.002
MNDWI	P2 (2000-2011)	93.11	<0.001	<0.001	<0.001	0.002
MNDWI	P3 (2013-2024)	117.39	<0.001	<0.001	<0.001	0.003
NDMI	P1 (1985-1998)	109.79	<0.001	<0.001	<0.001	<0.001
NDMI	P2 (2000-2011)	121.30	<0.001	<0.001	<0.001	<0.001
NDMI	P3 (2013-2024)	136.74	<0.001	<0.001	<0.001	<0.001
LST	P1 (1985-1998)	164.99	<0.001	<0.001	<0.001	0.787
LST	P2 (2000-2011)	164.88	<0.001	<0.001	<0.001	0.689
LST	P3 (2013-2024)	168.38	<0.001	<0.001	<0.001	0.276

Point-level mean values were calculated separately for each study period and compared among soil-environment categories using Kruskal–Wallis tests followed by Dunn post hoc tests with Holm adjustment. MS = mineral soils; OOS = other organic soils; PM = palsa mires. Adjusted p-values < 0.05 were considered statistically significant.

Table S12. Differences among soil categories within each study period, derived from Dunn post hoc tests

period	group1	group2	n1	n2	statistic	p	p.adj	p.adj.signif
P1 (1985-1998)	mineral soils	other than palsa organic soils	149	48	2.689265982	0.007160934	0.007160934	**
P1 (1985-1998)	mineral soils	palsa mires	149	48	6.869411809	6.45E-12	1.93E-11	****
P1 (1985-1998)	other than palsa organic soils	palsa mires	48	48	3.398728034	6.77E-04	0.0010155	**
P2 (2000-2011)	mineral soils	other than palsa organic soils	149	48	3.395256997	6.86E-04	0.001028463	**
P2 (2000-2011)	mineral soils	palsa mires	149	48	7.226466922	4.96E-13	1.49E-12	****
P2 (2000-2011)	other than palsa organic soils	palsa mires	48	48	3.115020651	0.00183932	0.00183932	**
P3 (2013-2024)	mineral soils	other than palsa organic soils	149	48	4.198951966	2.68E-05	4.02E-05	****
P3 (2013-2024)	mineral soils	palsa mires	149	48	7.704252217	1.32E-14	3.95E-14	****
P3 (2013-2024)	other than palsa organic soils	palsa mires	48	48	2.850035076	0.004371441	0.004371441	**
P1 (1985-1998)	mineral soils	other than palsa organic soils	149	48	-1.226963859	0.219836175	0.219836175	ns
P1 (1985-1998)	mineral soils	palsa mires	149	48	-6.572591023	4.94E-11	1.48E-10	****
P1 (1985-1998)	other than palsa organic soils	palsa mires	48	48	-4.346339494	1.38E-05	2.08E-05	****
P2 (2000-2011)	mineral soils	other than palsa organic soils	149	48	-1.595752006	0.110544172	0.110544172	ns
P2 (2000-2011)	mineral soils	palsa mires	149	48	-6.757169354	1.41E-11	4.22E-11	****
P2 (2000-2011)	other than palsa organic soils	palsa mires	48	48	-4.196565038	2.71E-05	4.06E-05	****
P3 (2013-2024)	mineral soils	other than palsa organic soils	149	48	-2.298022211	0.021560525	0.021560525	*
P3 (2013-2024)	mineral soils	palsa mires	149	48	-7.144157373	9.05E-13	2.72E-12	****
P3 (2013-2024)	other than palsa organic soils	palsa mires	48	48	-3.940220297	8.14E-05	1.22E-04	***
P1 (1985-1998)	mineral soils	other than palsa organic soils	149	48	5.793503327	6.89E-09	1.03E-08	****
P1 (1985-1998)	mineral soils	palsa mires	149	48	9.692020686	3.26E-22	9.78E-22	****
P1 (1985-1998)	other than palsa organic soils	palsa mires	48	48	3.169745933	0.001525723	0.001525723	**
P2 (2000-2011)	mineral soils	other than palsa organic soils	149	48	6.540114176	6.15E-11	9.22E-11	****
P2 (2000-2011)	mineral soils	palsa mires	149	48	10.0259307	1.17E-23	3.52E-23	****
P2 (2000-2011)	other than palsa organic soils	palsa mires	48	48	2.834193547	0.00459415	0.00459415	**
P3 (2013-2024)	mineral soils	other than palsa organic soils	149	48	6.693475743	2.18E-11	3.27E-11	****
P3 (2013-2024)	mineral soils	palsa mires	149	48	10.06770362	7.67E-24	2.30E-23	****
P3 (2013-2024)	other than palsa organic soils	palsa mires	48	48	2.74346479	0.006079457	0.006079457	**
P1 (1985-1998)	mineral soils	other than palsa organic soils	149	48	4.858177273	1.18E-06	1.78E-06	****
P1 (1985-1998)	mineral soils	palsa mires	149	48	9.948744691	2.55E-23	7.66E-23	****
P1 (1985-1998)	other than palsa organic soils	palsa mires	48	48	4.138959479	3.49E-05	3.49E-05	****
P2 (2000-2011)	mineral soils	other than palsa organic soils	149	48	5.725542078	1.03E-08	1.55E-08	****
P2 (2000-2011)	mineral soils	palsa mires	149	48	10.29004877	7.81E-25	2.34E-24	****
P2 (2000-2011)	other than palsa organic soils	palsa mires	48	48	3.711238196	2.06E-04	2.06E-04	***
P3 (2013-2024)	mineral soils	other than palsa organic soils	149	48	6.27095577	3.59E-10	5.38E-10	****
P3 (2013-2024)	mineral soils	palsa mires	149	48	10.45818659	1.34E-25	4.03E-25	****
P3 (2013-2024)	other than palsa organic soils	palsa mires	48	48	3.40448859	6.63E-04	6.63E-04	***
P1 (1985-1998)	mineral soils	other than palsa organic soils	149	48	-9.883256057	4.92E-23	7.38E-23	****
P1 (1985-1998)	mineral soils	palsa mires	149	48	-10.38451931	2.92E-25	8.75E-25	****
P1 (1985-1998)	other than palsa organic soils	palsa mires	48	48	-0.407559336	0.683597223	0.683597223	ns
P2 (2000-2011)	mineral soils	other than palsa organic soils	149	48	-9.932613256	3.00E-23	4.50E-23	****
P2 (2000-2011)	mineral soils	palsa mires	149	48	-10.37011157	3.39E-25	1.02E-24	****
P2 (2000-2011)	other than palsa organic soils	palsa mires	48	48	-0.355714332	0.722054511	0.722054511	ns
P3 (2013-2024)	mineral soils	other than palsa organic soils	149	48	-9.577947545	9.90E-22	1.48E-21	****
P3 (2013-2024)	mineral soils	palsa mires	149	48	-10.78593884	4.01E-27	1.20E-26	****
P3 (2013-2024)	other than palsa organic soils	palsa mires	48	48	-0.982174796	0.326013742	0.326013742	ns

Asterisks above comparisons indicate statistical significance: ns = not (p = 0,05), * p < 0,05, ** p < 0,01, *** p < 0,001, **** p < 0,0001. All p-values were adjusted for multiple comparisons.

Table S13. Regression coefficients for environmental predictors of point-level mean values and temporal slopes of remote sensing indices

Response	Index	Predictor	Estimate	95% CI	p-value
Mean	NDVI	DEM	-0.0131	-0.0176 to -0.0085	<0.001
		DTW2	-0.0052	-0.0112 to 0.0008	0.091
		Distance to hydro	0.0002	-0.0048 to 0.0052	0.940
		Slope	0.0063	-0.0002 to 0.0127	0.058
		Aspect	0.0000	-0.0053 to 0.0052	0.986
		Soil: other organic vs mineral	0.0346	0.0216 to 0.0476	<0.001
		Soil: palsa vs mineral	0.0696	0.0537 to 0.0854	<0.001
	NDWI	DEM	0.0093	0.0051 to 0.0134	<0.001
		DTW2	0.0036	-0.0020 to 0.0091	0.206
		Distance to hydro	-0.0004	-0.0050 to 0.0043	0.879
		Slope	-0.0035	-0.0095 to 0.0024	0.245
		Aspect	-0.0022	-0.0070 to 0.0025	0.356
		Soil: other organic vs mineral	-0.0155	-0.0275 to -0.0035	0.011
		Soil: palsa vs mineral	-0.0589	-0.0734 to -0.0443	<0.001
	MNDWI	DEM	-0.0024	-0.0066 to 0.0018	0.264
		DTW2	0.0036	-0.0020 to 0.0092	0.207
		Distance to hydro	-0.0013	-0.0060 to 0.0034	0.580
		Slope	-0.0009	-0.0069 to 0.0052	0.775
		Aspect	-0.0008	-0.0057 to 0.0041	0.741
		Soil: other organic vs mineral	0.0364	0.0242 to 0.0486	<0.001
		Soil: palsa vs mineral	0.0798	0.0650 to 0.0947	<0.001
	NDMI	DEM	-0.0132	-0.0198 to -0.0067	<0.001
		DTW2	-0.0003	-0.0090 to 0.0084	0.951
		Distance to hydro	-0.0015	-0.0088 to 0.0058	0.688
		Slope	0.0035	-0.0058 to 0.0129	0.458
		Aspect	0.0015	-0.0061 to 0.0090	0.705
		Soil: other organic vs mineral	0.0607	0.0419 to 0.0796	<0.001
		Soil: palsa vs mineral	0.1611	0.1381 to 0.1840	<0.001
	LST	DEM	0.1688	0.0357 to 0.3020	0.013
		DTW2	0.1820	0.0056 to 0.3584	0.043
		Distance to hydro	0.0558	-0.0922 to 0.2038	0.458
		Slope	-0.0332	-0.2235 to 0.1572	0.732
		Aspect	0.1689	0.0157 to 0.3220	0.031
		Soil: other organic vs mineral	-3.4889	-3.8715 to -3.1062	<0.001
		Soil: palsa vs mineral	-3.8117	-4.2772 to -3.3463	<0.001
Slope	NDVI	DEM	0.0003	0.0002 to 0.0004	<0.001
		DTW2	0.0000	-0.0001 to 0.0001	0.628
		Distance to hydro	-0.0001	-0.0002 to 0.0000	0.062
		Slope	0.0001	-0.0001 to 0.0002	0.281
		Aspect	0.0001	0.0000 to 0.0002	0.006
		Soil: other organic vs mineral	0.0008	0.0005 to 0.0010	<0.001
		Soil: palsa vs mineral	0.0006	0.0003 to 0.0009	<0.001
	NDWI	DEM	-0.0003	-0.0003 to -0.0002	<0.001
		DTW2	0.0000	-0.0001 to 0.0001	0.921
		Distance to hydro	0.0001	0.0000 to 0.0002	0.065
		Slope	0.0000	-0.0001 to 0.0001	0.917
		Aspect	-0.0001	-0.0001 to 0.0000	0.230
		Soil: other organic vs mineral	-0.0004	-0.0006 to -0.0002	<0.001
		Soil: palsa vs mineral	-0.0003	-0.0006 to -0.0001	0.008
	MNDWI	DEM	0.0000	-0.0001 to 0.0001	0.490
		DTW2	0.0001	-0.0001 to 0.0002	0.316
		Distance to hydro	0.0000	-0.0001 to 0.0001	0.760
		Slope	0.0000	-0.0001 to 0.0001	0.725
		Aspect	0.0000	-0.0001 to 0.0001	0.509
		Soil: other organic vs mineral	0.0001	-0.0001 to 0.0004	0.282
		Soil: palsa vs mineral	0.0004	0.0000 to 0.0007	0.024
	NDMI	DEM	0.0003	0.0002 to 0.0004	<0.001
		DTW2	0.0001	-0.0001 to 0.0002	0.240
		Distance to hydro	0.0000	-0.0002 to 0.0001	0.447
		Slope	0.0000	-0.0001 to 0.0002	0.912
		Aspect	0.0001	0.0000 to 0.0002	0.066
		Soil: other organic vs mineral	0.0006	0.0003 to 0.0009	<0.001
		Soil: palsa vs mineral	0.0008	0.0004 to 0.0012	<0.001
	LST	DEM	-0.0048	-0.0072 to -0.0024	<0.001
		DTW2	-0.0021	-0.0052 to 0.0011	0.207
		Distance to hydro	-0.0012	-0.0039 to 0.0014	0.364
		Slope	-0.0006	-0.0040 to 0.0029	0.752
		Aspect	-0.0036	-0.0063 to -0.0008	0.012
		Soil: other organic vs mineral	0.0168	0.0099 to 0.0238	<0.001
		Soil: palsa vs mineral	0.0069	-0.0015 to 0.0154	0.107

Estimates are shown with 95% confidence intervals (CI) and p-values. Continuous predictors were standardized prior to modelling, and coefficients for soil category are expressed relative to the reference level (*SOIL_reclass 0* =mineral soils).

Table S14. Permutation tests for environmental predictors in the redundancy analysis (RDA) models

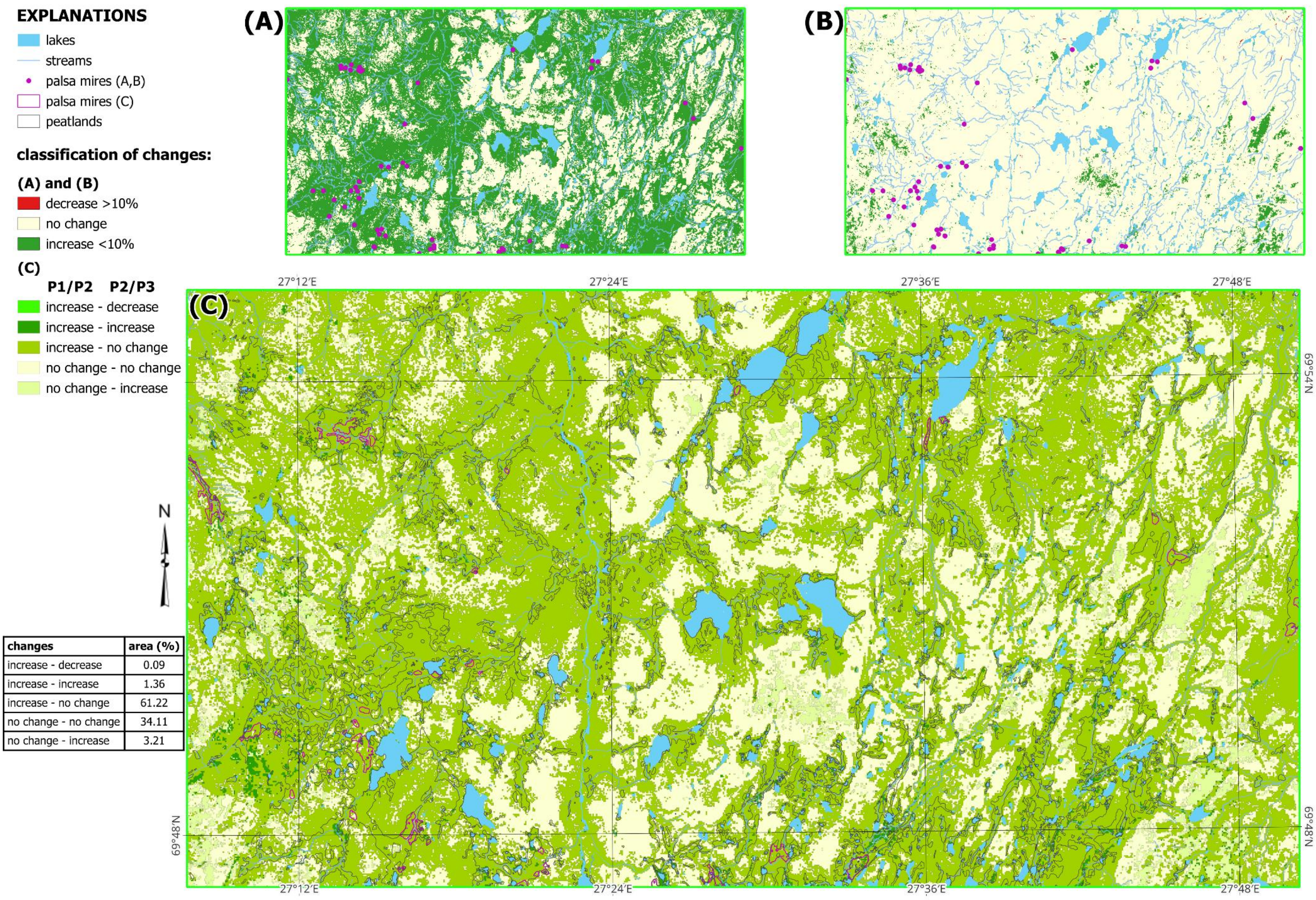
Period	Predictor	F	p-value
P1	DEM	61.80	<0.001
P1	DTW2	45.16	<0.001
P1	Distance to hydro	21.52	<0.001
P1	Slope	11.82	<0.001
P1	Aspect	3.74	0.027
P1	Soil category	48.97	<0.001
P2	DEM	58.14	<0.001
P2	DTW2	50.91	<0.001
P2	Distance to hydro	26.04	<0.001
P2	Slope	15.74	<0.001
P2	Aspect	14.37	<0.001
P2	Soil category	64.94	<0.001
P3	DEM	57.54	<0.001
P3	DTW2	72.36	<0.001
P3	Distance to hydro	35.18	<0.001
P3	Slope	19.81	<0.001
P3	Aspect	12.88	0.002
P3	Soil category	76.65	<0.001

F statistics and permutation p-values are shown for each predictor in P1, P2, and P3. Continuous predictors were standardized before analysis; soil-environment category was included as a factor.

Table S15. Eigenvalues and variance explained by the first two constrained axes in the RDA models

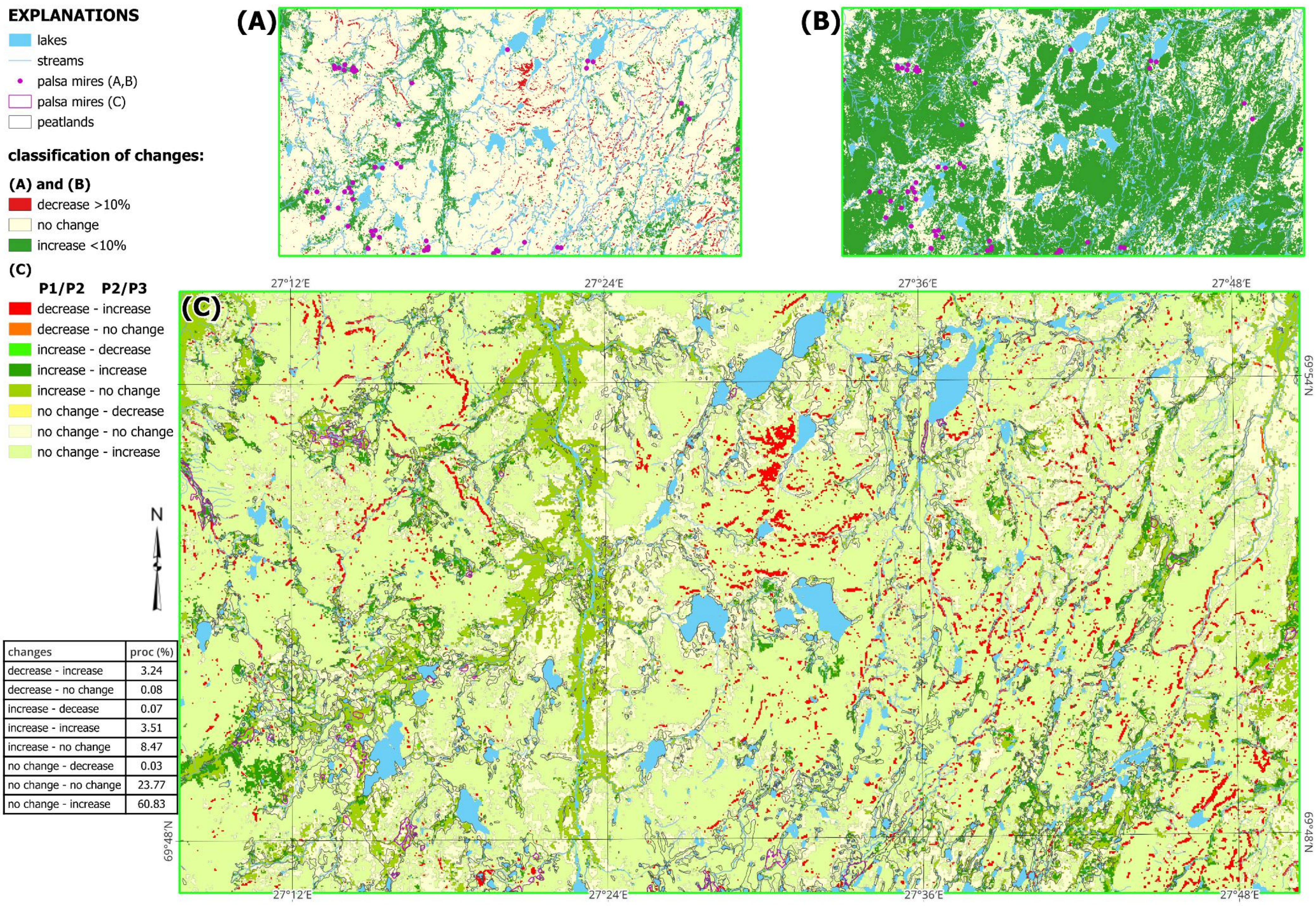
Period	Axis	Eigenvalue	Explained (%)	Cumulative (%)
P1	RDA1	2.294	89.9	89.9
P1	RDA2	0.200	7.8	97.7
P2	RDA1	2.620	93.9	93.9
P2	RDA2	0.114	4.1	98.0
P3	RDA1	2.848	95.2	95.2
P3	RDA2	0.104	3.5	98.7

Percentages refer to the proportion of constrained variance explained by each canonical axis.



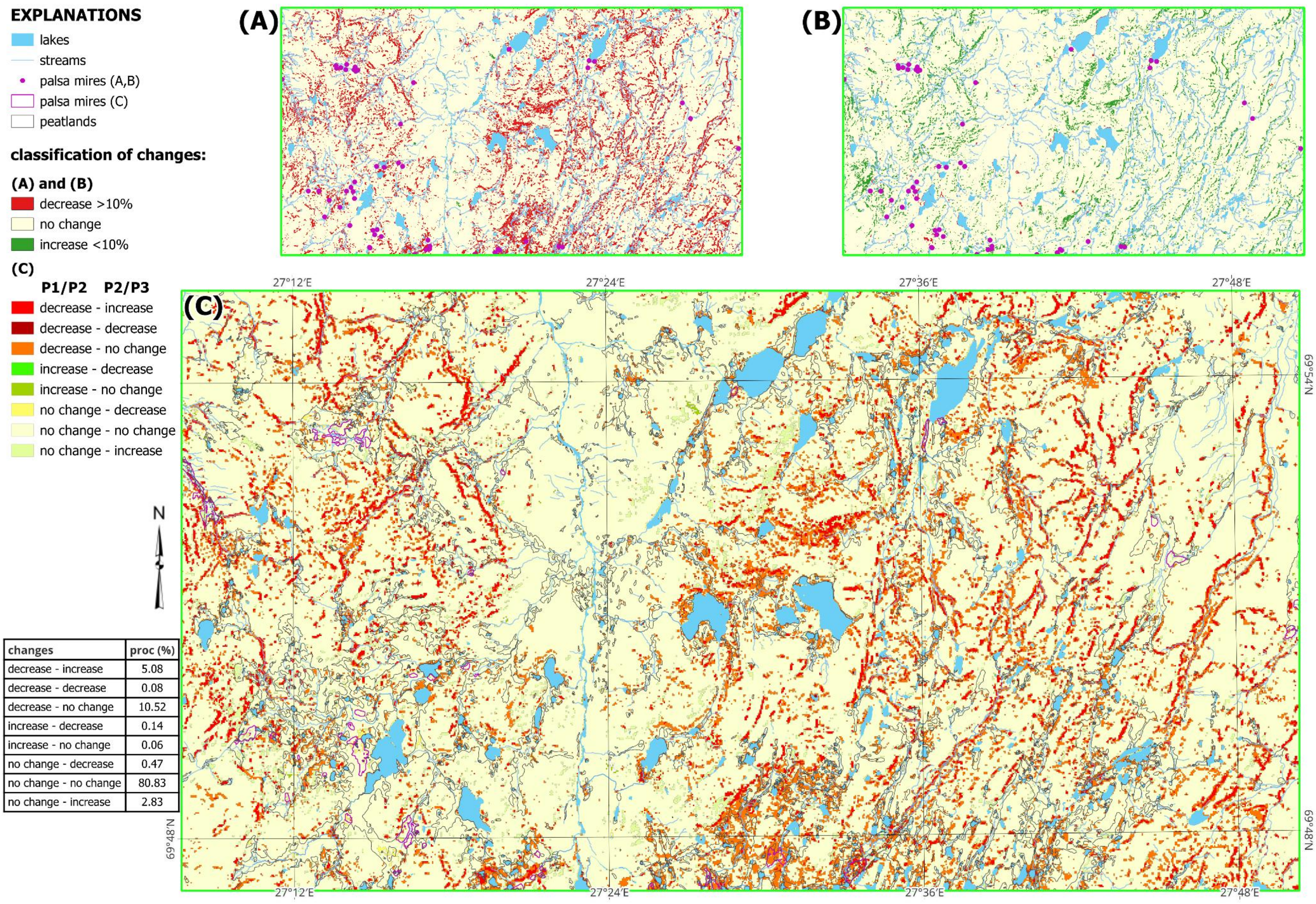
changes	area (%)
increase - decrease	0.09
increase - increase	1.36
increase - no change	61.22
no change - no change	34.11
no change - increase	3.21

Figure S19. Classification of changes in the Normalized Difference Vegetation Index (NDVI): (A) changes between P1 (1985–1998) and P2 (2000–2011); (B) changes between P2 (2000–2011) and P3 (2013–2024); (C) changes between P1/P2 and P2/P3 (calculated based on Landsat data (USGS, 2025a))



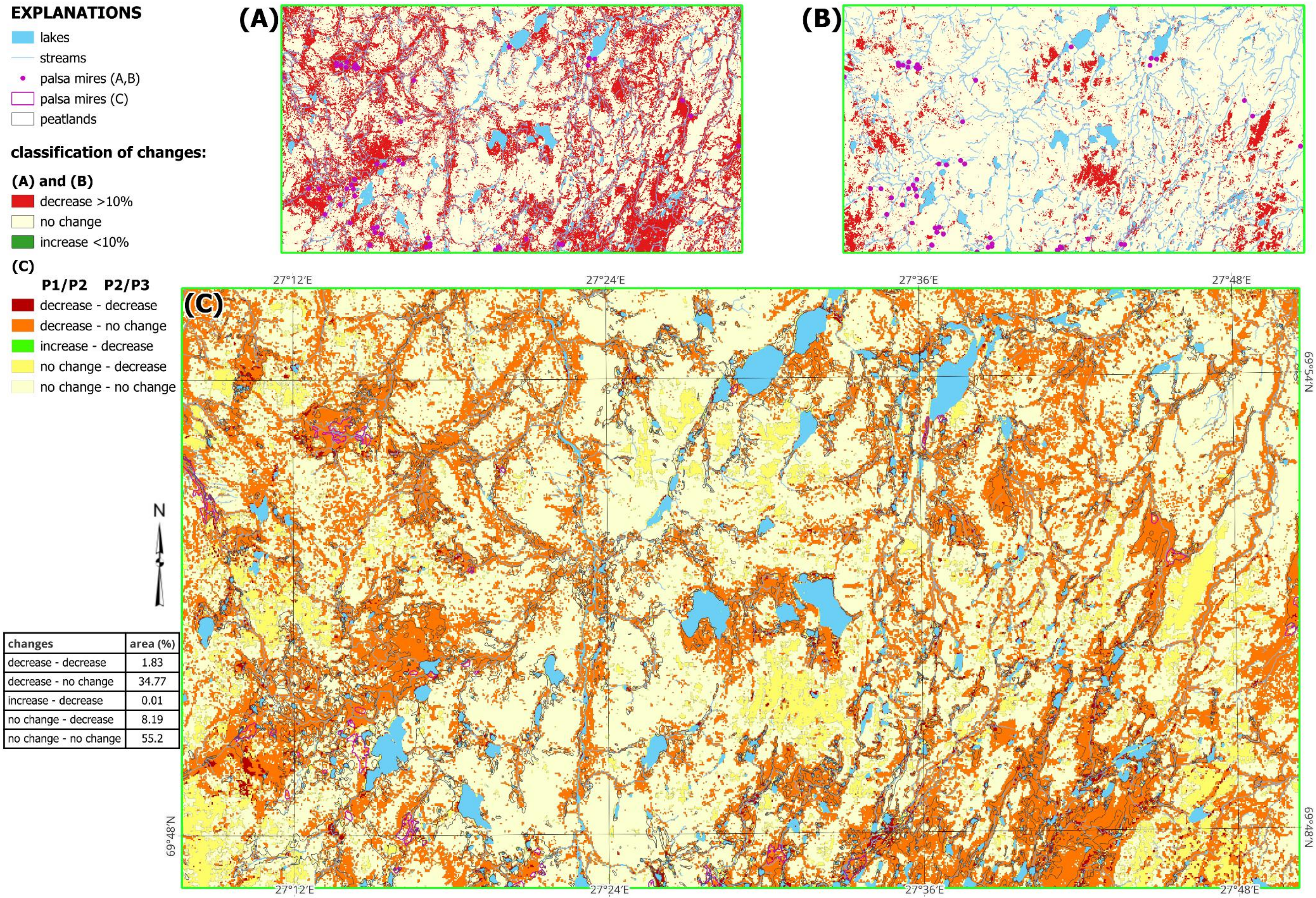
changes	proc (%)
decrease - increase	3.24
decrease - no change	0.08
increase - decease	0.07
increase - increase	3.51
increase - no change	8.47
no change - decrease	0.03
no change - no change	23.77
no change - increase	60.83

Figure S20. Classification of changes in the Normalized Difference Moisture Index (NDMI): (A) changes between P1 (1985–1998) and P2 (2000–2011); (B) changes between P2 (2000–2011) and P3 (2013–2024); (C) changes between P1/P2 and P2/P3 (calculated based on Landsat data (USGS, 2025a))



changes	proc (%)
decrease - increase	5.08
decrease - decrease	0.08
decrease - no change	10.52
increase - decrease	0.14
increase - no change	0.06
no change - decrease	0.47
no change - no change	80.83
no change - increase	2.83

Figure S21. Classification of changes in the Modified Normalized Difference Water Index (MNDWI): (A) changes between P1 (1985–1998) and P2 (2000–2011); (B) changes between P2 (2000–2011) and P3 (2013–2024); (C) changes between P1/P2 and P2/P3 (calculated based on Landsat data (USGS, 2025a))



changes	area (%)
decrease - decrease	1.83
decrease - no change	34.77
increase - decrease	0.01
no change - decrease	8.19
no change - no change	55.2

Figure S22. Classification of changes in the Normalized Difference Water Index (NDWI): (A) changes between P1 (1985–1998) and P2 (2000–2011); (B) changes between P2 (2000–2011) and P3 (2013–2024); (C) changes between P1/P2 and P2/P3 (calculated based on Landsat data (USGS, 2025a))

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