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Environmental spaces for palsas and peat plateaus are disappearing at a circumpolar scale

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Abstract. ~~The~~ anthropogenic climate change threatens northern permafrost environments. This compromises the existence of permafrost landforms, such as palsas and peat plateaus, which have been assessed to be critically endangered habitats. In this study, for the first time we integrated geospatial datasets and statistical methods, to model the distribution of palsas and peat plateaus across the Northern Hemisphere permafrost region. The models were calibrated using data from years 1950–2000. The effects of climate change on the future distribution of palsas were assessed by using moderate and high emission scenarios (Representative Concentration Pathways; RCP4.5 and RCP8.5, respectively) for two periods (2041–2060 and 2061–2080). Hotspots for palsas and peat plateaus occurred in Northern Europe, Western Siberia, and subarctic Canada. Climate change was predicted to cause an almost complete loss (-98.2 %) of suitable environmental spaces under a high emissions scenario by 2061–2080, while under a moderate emissions scenario 89.3 % were predicted to disappear. The comparison with previously published thermokarst data supported our findings regarding the recent degradation of palsa and peat plateau environments. Our results fill the knowledge gaps in the distribution of the permafrost landforms in less studied areas such as Central and Eastern Siberia. In addition, the projections provide insights into the changing geoecological conditions of the circumpolar region with important implications for greenhouse gas emissions.

1 Introduction

Northern environments are heavily affected by ~~the~~ climate change (IPCC, 2021). Because of ~~the~~ arctic amplification these environments are warming almost two to three times as fast as the global average (You et al., 2021). As ~~the~~ climate changes, permafrost (defined as ground with a temperature of 0 °C or below, for at least two consecutive years; Muller, 1943), is projected to thaw from extensive areas (Wang et al., 2022), and distinctive permafrost processes and related landforms are threatened (e.g., Liljedahl et al., 2016; Aalto et al., 2017; Borge et al., 2017; Karjalainen et al., 2020). Palsas and peat plateaus are peat hummocks with permafrost cores, which can be found primarily from regions of sporadic and discontinuous permafrost (Seppälä, 1988). They differ mainly by their extent and height (Zoltai and Tarnocai, 1971). Height of palsas varies between 0.5–10 m and their diameter exceed two meters (Washburn, 1983; Pissart, 2002). Peat plateaus have a greater extent, even over one square kilometer, but are elevated from their surroundings by only about one meter (Kershaw and Gill, 1979; Zoltai, 1972).

Permafrost peatlands, such as palsa mires and peat plateaus, are widespread, and according to Hugelius et al. (2020) nearly half of the peatlands of the Northern Hemisphere contain permafrost. Previous studies have shown that most palsas were formed in much colder climate than present (Vorren, 2017; Fewster et al., 2020). Palsas and peat plateaus are highly sensitive to further changes in climate, and many studies have reported rapid degradation of palsas (e.g., Borge et al., 2017; Mamet et al., 2017; Olvmo et al., 2020). As ~~the~~ permafrost thaws from peatlands, changes in ~~the~~ greenhouse gas fluxes are expected (Turetsky et al., 2020; Miner et al., 2022). Increasing CO2, CH4 and N2O -emissions further accelerate ~~the~~ climate change (Marushchak et al., 2011; Schuur et al., 2015; Hugelius et al., 2020).

In addition to their importance in global carbon balance, palsas and peat plateaus have an important role in the bio- and geodiversity of Northern environments. Peat controlled permafrost hummocks create topographical and hydrological variability (Seppälä, 1988; Beilman, 2001), resulting different microhabitats for many animal and plant species (Luoto et al., 2004a). For example, palsa mires are well known for their rich bird life (Järvinen and Sammalisto, 1976; CAFF, 2001). Permafrost thaw leads to the collapse of palsas and peat plateaus (Seppälä, 1982, 2006), changes in vegetation (e.g., Malmer et al., 2005; Johansson et al., 2006; Normand et al., 2017) and overall homogenization of peatlands in the end (Swindles et al., 2015). This can lead to changes in bird and invertebrate species composition and affect the functioning of the peatland ecosystem (Luoto et al., 2004a; Markkula, 2014). The European Union classified palsas critically endangered habitats in 2016, mainly because of the degradation of permafrost (Janssen et al., 2016).

Palsas in ~~the~~ Northern Europe are relatively well mapped and studied (e.g., Backe, 2014; Ottósson et al., 2016; Ruuhijärvi et al., 2022). There are mapping and monitoring studies conducted also in Canada (e.g., Tam et al., 2014; Mamet et al., 2017) and in the Western parts of Russian (e.g., Barcan, 2010; Kirpotin et al., 2011; Terentieva et al., 2016). However, only a few studies of palsas are available for Central and Eastern Siberia (Vasil'chuk et al., 2013a, 2013b, 2014). The distribution of palsas has been previously modelled mainly at local and regional scales in Northern Fennoscandia (e.g., Luoto et al., 2004b; Fronzek et al., 2006, 2011; Aalto et al., 2017) but recently also in Western Siberia (Fewster et al., 2022), and at a continental scale in North America (Fewster et al., 2020). Previous studies have shown that palsas require specific climatic conditions (e.g., Luoto et al., 2004b; Parviainen and Luoto, 2007; Aalto et al., 2017; Fewster et al., 2020, 2022). However, topography and soil properties also affect the distribution of palsas (Seppälä, 2011). Especially, the role of sufficient peat cover is crucial in marginal permafrost regions, as the thermal properties of peat protect frozen palsa cores against thawing (Kujala et al., 2008).

In this study, we provide the first predictions of suitable environmental spaces for palsas over the entire Northern circumpolar region. As the explored landforms are not found from the Southern Hemisphere (Seppälä, 2011), this study covers a major part of global palsas and peat plateau environments. Our aim is to predict the suitable environmental spaces for palsas in a relatively recent period (1950–2000) and in two future periods (2041–2060 and 2061–2080), using two Representative Concentration Pathway climate-scenarios (RCP4.5 and RCP8.5). Moreover, we compare our predictions with thermokarst data produced by Olefeldt et al. (2016) to examine whether our model results are consistent with the development of thermokarst or not. We aim to answer to the following research questions:

1) What are the suitable environmental spaces for palsas and peat plateaus in the Northern circumpolar permafrost region?
2) How are the suitable environmental spaces for palsas and peat plateaus changing in the future?
3) Are the changes in suitable environmental spaces for palsas and peat plateaus spatially consistent with observed and predicted thermokarst landscapes?

To address the questions, we used four different statistical modelling methods and their ensemble. Our results offer new insights on circumpolar palsa distribution especially for poorly mapped regions. Moreover, changes in palsas and peat plateaus can be used as an indicator of the state of sporadic and discontinuous permafrost (Lagarec, 1982; Sollid and Sørbel, 1998). The thermal state of permafrost is an important factor affecting the integrity of arctic transportation and industrial infrastructure (Hjort et al., 2022), release of greenhouse gases (Miner et al., 2022) and ecosystem stability (Goetz et al., 2007; Sim et al., 2021; Magnan et al., 2022). Moreover, future predictions of endangered landforms and habitats can be helpful in conservation actions for different plant and animal species.

2 Materials and methods

2.1 Palsa and peat plateau observations

Observations of palsas and peat plateaus (Fig. 1a) were collected mainly from available inventories and published studies. In the Scopus and Google Scholar literature search we used search terms ‘palsa’, ‘peat plateau’ and ‘permafrost peatland’ combined with state, province, or region names (e.g., ‘Sweden’, ‘Yukon’ and ‘Western Siberia’). Additional observations from less studied areas were compiled from published reports, web pages and Google Earth Pro (version 7.3) and ESRI’s ArcGIS Pro (version 2.9.32739) satellite images (the list of used references are provided in Appendix A).

Palsa observations were limited to ‘true palsas’ (Fig. 1b) whereas ‘palsa-like’ formations and ‘lithalsas’ were excluded, because of the lack of substantial peat cover on these landforms (Pissart, 2002). In this study peat plateaus were considered as a morphological class of palsas – so-called ‘palsa plateaus’, (Zoltai and Tarnocai 1975; Kershaw and Gill 1979; Seppälä 1988; see also Fewster et al. 2020, 2022). All compiled observations were verified by using satellite imagery in Google Earth Pro and ESRI’s ArcGIS Pro (Fig. 1c). The final modelling data consisted of 961 grid cells (30 arc sec resolution, ~ 1 km) occupied by palsa or peat plateau.

Statistical distribution modelling (i.e., presence-absence models) require absence observations (Brotons et al., 2004; Elith et al., 2006; Zhao et al., 2020). A random sample of 2000 grid cells from areas north of latitude 40° N was taken to compile an absence dataset. All the grid cells were checked using satellite images to ensure that there were no palsas or peat plateaus in the absence grid cells ('true absence'). In total 1496 absence observations were compiled as 504 grid cells were excluded owing to the coarse resolution of satellite images, cloud cover obscuring the view, or the cell occurred in a water body. The same person (Könönen) collected and validated both presence and absence datasets.

Compiled data were further split into model calibration (N = 2057), and evaluation (N = 400) sets. These sample sizes are expected to be large enough to give robust predictions in geomorphological distribution modelling (see Hjort and Marmion, 2008). The separate evaluation dataset was formed by taking a random sample from the whole data. The random sample was taken separately from presence and absence observations, to retain the same relative portion (i.e., prevalence) with the original dataset (ca. 40 % presence, and 60 % absence observations) (Hjort and Luoto, 2013). Observations in the evaluation were selected so that they located at least 50 km from each other. Because of this criteria, two absence observations had to be removed from the evaluation data, as they located too close (< 50 km) to presence observations (final N = 398).

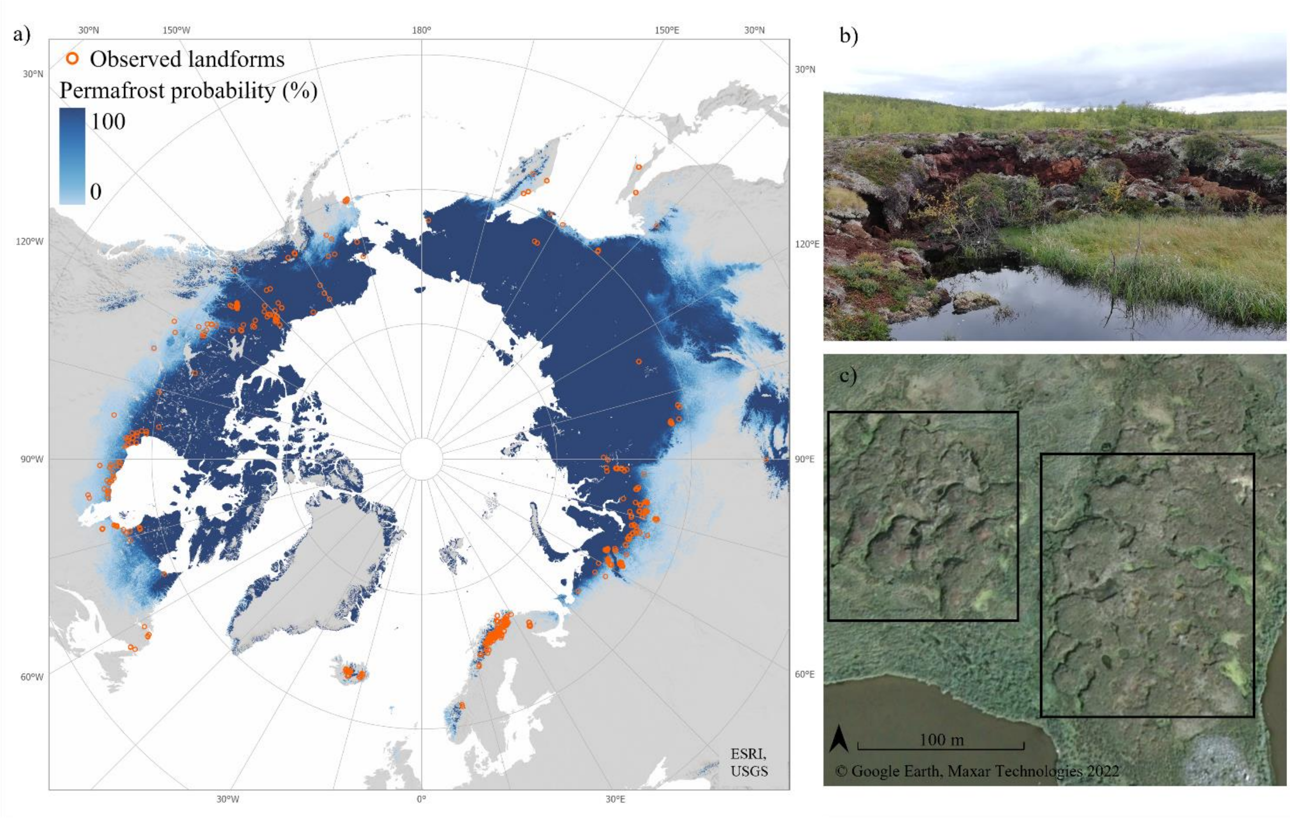

Figure 1: Distribution of the observed palsas and peat plateaus (N = 961) across the Northern Hemisphere and the probability of the permafrost occurrence (%, Ran et al., 2022) (a). A thawing palsa in Kilpisjärvi, Finland (b), and satellite image of a palsa mire in Kiruna, Sweden (68°28'N, 20°55'E), groups of palsas have been framed with black lines (c).

2.2 Environmental data

In this study, we used various geospatial datasets at a 30 arc-second (ca. 1 km) spatial resolution to describe the climatological conditions, soil properties, and topographical variation relevant to palsa mires and peat plateaus. Freezing and thawing degree-days (FDD and TDD, °C-days) were computed to describe seasonal air temperature conditions. Moreover, we used a bioclimatic variable (Bio7 in WorldClim v1.4), which describes the range of annual air temperature (Temp.range, °C, i.e., continentality) by subtracting the minimum temperature of coldest month from the maximum temperature of the warmest month, using the global circulation models (GCMs) available in WorldClim v1.4. Precipitation conditions were considered by calculating sums of liquid (Rainfall, mm) and solid (Snowfall, mm) precipitation. Snowfall was defined as the sum of precipitation for months with average air temperature below 0 °C and rainfall for months with average air temperature over 0 °C (Aalto et al., 2018).

All the environmental variables (hereafter variables) were separately computed for different time periods and RCP scenarios, using the WorldClim v1.4 data at 30 arc-second resolution (Hijmans et al., 2005). For these data, the baseline period is 1950–2000, which aligns well with the observations in our presence data. For the climate change scenarios, we used the moderate-emissions scenario RCP4.5 and the high-emissions scenario RCP8.5, and two future periods 2041–2060 and 2061–2080. Climate change projections included in the WorldClim v1.4 database (Hijmans et al., 2005) were derived from an ensemble of 18 global climate models (Taylor et al., 2012).

Variables to describe the surficial soil conditions (≤ 2 m depth) were obtained from SoilGrids250m 2.0 database (Poggio et al., 2021). Owing to the lack of high-resolution peat data we used soil organic carbon content (SOC, g kg^{-1}) to estimate it. In addition to SOC we used silt content (Silt, g kg^{-1}) and probability of bedrock within two meters from the ground surface (Bedrock, %, Shangguan et al., 2017) to describe the texture and thickness of the soil layer. Topographic Wetness Index (TWI) (Böhner and Selige, 2006) was calculated using the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) (Danielson and Gesch, 2011) to characterize the accumulation potential of ground moisture. The grid cell-wise values from each variable were extracted for the presence/absence observations. In case no value from an environmental variable was available at presence or absence location (109 cases), the value was extracted from the neighboring grid cell. If none of the neighboring grid cells had the missing value, the observation was removed from the dataset.

We compared our predictions to a circumpolar thermokarst dataset by Olefeldt et al. (2016). The dataset includes different types of thermokarst landscapes and their coverages. We utilized wetland and lake thermokarst coverages as these types can be assumed to be present in degrading palsa mires (Luoto and Seppälä, 2003; Olefeldt et al., 2016). In the dataset, thermokarst areal coverages are classified into five classes, ranging from none (0–1 %) to very high (60–100 %).

2.3 Statistical modelling

Statistical modelling was conducted using the biomod2 (version 3.5.1) package in R (version 4.1.3). We used four methods which have been previously used in distribution modelling of periglacial landforms and processes (e.g., Aalto et al., 2014, 2017; Rudy et al., 2016; Karjalainen et al., 2020;) and other permafrost characteristics, such as soil organic carbon content (Siewert, 2018; Mishra et al., 2021). By using multiple modelling techniques, the prediction uncertainties can be addressed compared to using only one method (Thuiller et al., 2009). Methods used were generalized linear model (GLM, Nelder and Wedderburn, 1972), generalized additive model (GAM, Hastie and Tibshirani, 1986), generalized boosted model (GBM, Elith et al., 2008) and random forest (RF, Elith et al., 2005) and ensemble of the former methods. Ensemble approach has been utilized previously for example to predict ground temperature (Aalto et al., 2018), soil hydrology (Cisty et al., 2014), distribution of plants species (Rissanen et al., 2021) and other periglacial landforms (Karjalainen et al., 2020).

GLMs and their semiparametric extensions GAMs, are popular in statistical modelling because they are relatively easy to use and can be utilized for different types of datasets (Hjort and Luoto, 2013). In the calibration of GLM each explanatory variable including their quadratic terms were inserted into the model to take possible curvilinear relationships into account. Variables for the final GLM were selected in a stepwise fashion using the Bayesian information criteria (BIC, Schwarz, 1978). In GAMs we used GCV.Cp smoothing algorithm to limit the degrees of freedom to three. GAM formula was generated automatically by using the 's_smoother' argument available in the biomod2. Interactions terms between environmental variables were not included in GLM or GAM.

GBM and RF are machine learning methods which build regression/classification trees to obtain robust estimates of the response (Thuiller et al., 2010). These methods include interactions between environmental variables and address potential overfitting (Elith et al., 2005). Here, we used the following parameters for the GBM models: number of trees = 8150, bag fraction = 0.5, interaction depth = 5, and shrinkage = 0.0038. For RF models we fitted 500 trees at maximum with a node size of 5. Three randomly selected variables were used at each split of a classification tree to assign observations to the nodes. In ensemble modelling, results of two or more related models are combined into a single model in attempt to improve the accuracy and predictive capabilities (Hao et al., 2019, 2020; Kit et al., 2021). In this study, the ensemble model was formed to correspond to the mean probabilities over the produced models (400 = 4 modelling techniques, 100 iterations).

The predicted probability surfaces for suitable environments were finally classified to binary distribution maps. The classification was performed by the true skill statistic (TSS) cut-off values that were estimated during each model run. From these cut-off values (100 model runs per method) the average cut-off value was computed and used for classification. Used cut-off values are presented in the supplements (Table S1). Binary maps were utilized when we calculated the areas of suitable environments. Average variable importance (VI) values (Breiman, 2001; Fisher et al., 2019) were calculated from the results of 100 modeling runs. In VI computation, the values of one variable in its turn are shuffled (i.e., a random sample is drawn from the values recorded at the modelling data grid cells) while the other variables are fixed to their mean values. Then, model predictions are produced by using these variables. Finally, VI is derived from the Pearson correlation between the predictions from the initial models (all variables having their recorded values) and from the models including the shuffled variable with the following Eq. (1) (Thuiller et al, 2009):

$$VI = 1 - \mathrm{cor}(\mathrm{initial\ model\ predictions, suffled\ model\ prediction}). \quad (1)$$

The closer a VI is to 1, the larger the influence of a given variable (Thuiller et al., 2021).

Calibrated models were evaluated in two ways (Araújo et al., 2005). First, 100-fold cross-validation was performed with the calibration data. At each validation run a random sample of 70 % (N = 1440) of observations were used to calibrate models and the remaining 30 % (N = 617) was used to validate them. Secondly, independent evaluation was conducted by using the separate evaluation data (N = 398), which was set aside before model calibration (as described in the section 2.1). Performance of the models was evaluated with two prevalence-independent statistical measures of classification accuracy, area under the receiving operating characteristic curve (AUC) and TSS (Allouche et al., 2006). Model reliability was also evaluated spatially by exploring the modelling agreement between four independent modelling methods (Luoto et al., 2010).

3 Results

3.1 Suitable environments in recent conditions

RF had the highest evaluation scores in the model evaluation (see sections 2.3 and 3.4), and thus the presented results are based on RF. RF model for the recent period 1950–2000 predicted suitable environmental conditions for an area of 1.58 million km^2. Largest continuous suitable environments located in the Western Siberia, in Canada around the Hudson Bay and Quebec, and in Northern Fennoscandia (Fig. 2). These regions and Iceland had the highest landform occurrence probabilities with only little spatial variation. Other, environments with high landform occurrence probabilities were found from the Northwest Territories of Canada, west coast of Alaska and east coast of Russia. The probability of palsa and peat plateau occurrence decreased relatively sharply outside the most suitable environments (Fig. 2).

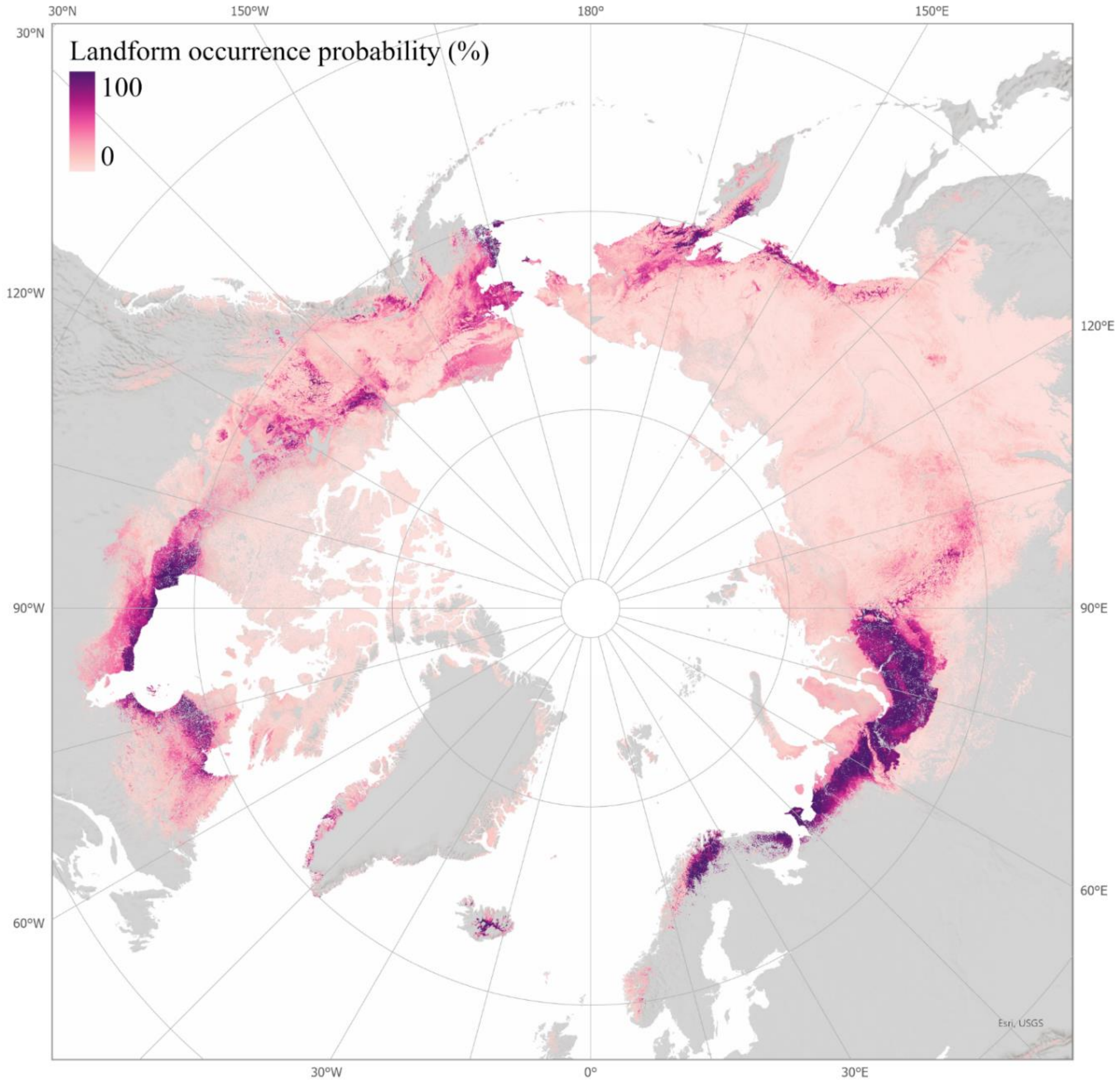

Figure 2: The probability (%) for palsa and peat plateau occurrence illustrated with a color gradient from light pink to dark purple, grey color illustrates areas outside the permafrost region and glaciers. Results of the random forest model are provided for the permafrost region (Ran et al., 2022).

Based on the variable importance (VI) values, TDD was the most important variable (VI = 0.37) to characterize the suitable environments for palsas and peat plateaus in RF models (Fig. 3a., other modelling methods in supplementary material Fig. S3). After TDD, four variables (TWI, SOC, snowfall and rainfall) had moderately equal VI values (ranging from 0.062 to 0.077). FDD, temperature range, bedrock, and silt had only a minor importance (VI < 0.021) in the RF models.

The response curve of TDD shows the optimal summer air temperatures to be around 1000 °C-days, with a steep drop in the probability of occurrence beyond ~1250 °C-days (Fig. 3b). The response of TWI shows a higher occurrence probability with higher values, indicating that palsas and peat plateaus are most likely found from flat or gently sloping basin environments with abundant soil moisture. RF model shows the highest probabilities for regions with a SOC content of over 70 g kg^{-1}. The snowfall variable shows also a clear optimum environmental space for the landforms around 200 mm, whereas the pattern is not equally clear for the rainfall (Fig. 3b). Response curves for all used modelling methods are provided in the supplementary material (Fig. S4).

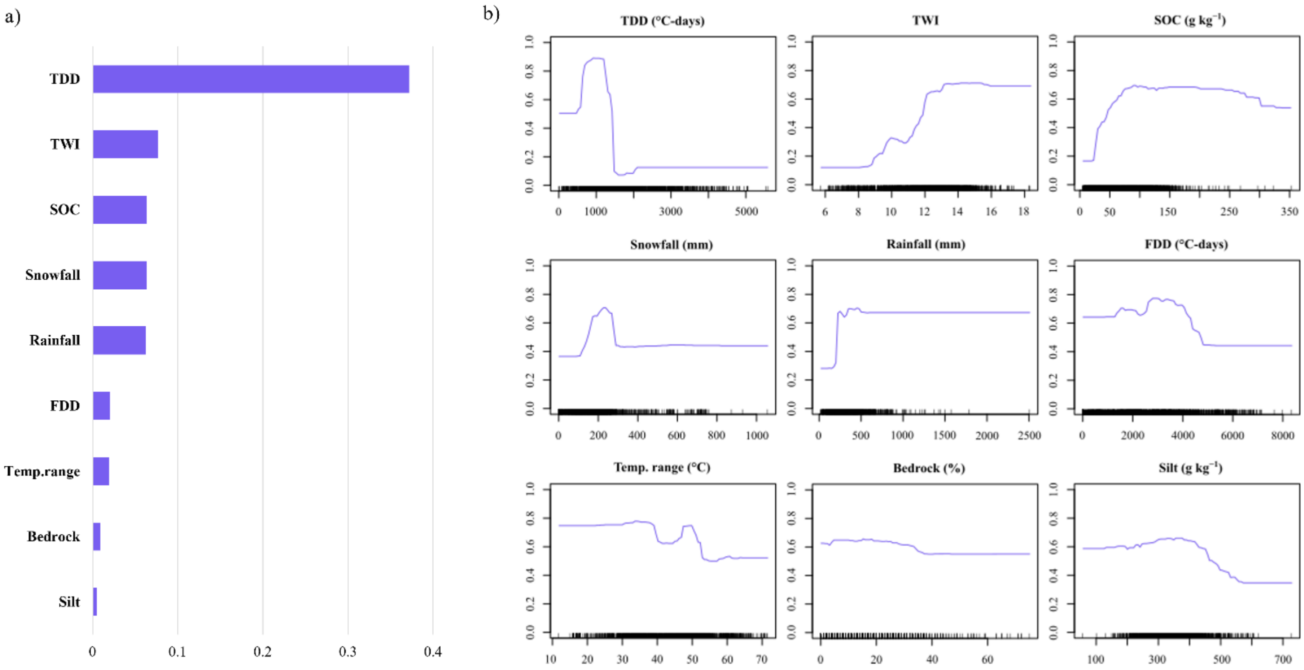

Figure 3: Variable importance values (a) and response curves (b) for the environmental variables based on the RF model.

3.2 Future changes in the circumpolar suitable environments

Our results suggest a dramatic loss of suitable environments for palsas and peat plateaus already by the mid of the 21st century (Table 1.; Table S2 in supplements). The high-emission scenario RCP8.5 predicted even larger losses by the period 2041–2060, than the moderate-emissions scenario RCP4.5 predicted by the second period 2061–2080. RCP8.5 scenario for 2061–2080 showed almost complete loss (-98,2 %) of recently suitable environments (Table 1e).

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225 **Table 1: Suitable environmental spaces (in km^2) for palsas and peat plateaus at different time periods and RCP climate change scenarios in Nordic countries (a), Western Siberia (b), Central and Eastern Siberia (c), North America (d), and entire circumpolar permafrost region (e). Areal percentage changes are given in relation to the modelled area for the period 1950–2000. Results are based on random forest modelling.**

	Suitable area (km^2)	Percentage change (%)
a) Nordic countries		
1950–2000	77 540	
RCP4.5 2041–2060	17 120	-77.9
RCP4.5 2061–2080	12 140	-84.3
RCP8.5 2041–2060	11 890	-84.7
RCP8.5 2061–2080	5 600	-92.8
b) Western Siberia		
1950–2000	562 750	
RCP4.5 2041–2060	48 270	-91.4
RCP4.5 2061–2080	14 930	-97.3
RCP8.5 2041–2060	10 110	-98.2
RCP8.5 2061–2080	10	-99.9
c) Central and Eastern Siberia		
1950–2000	305 580	
RCP4.5 2041–2060	62 550	-79.5
RCP4.5 2061–2080	30 350	-90.1
RCP8.5 2041–2060	25 140	-91.8
RCP8.5 2061–2080	1 070	-99.6
d) North America		
1950–2000	640 070	
RCP4.5 2041–2060	167 430	-73.8
RCP4.5 2061–2080	111 450	-82.6
RCP8.5 2041–2060	104 310	-83.7
RCP8.5 2061–2080	21 570	-96.6
e) Permafrost region		
1950–2000	1 587 360	
RCP4.5 2041–2060	296 110	-81.4
RCP4.5 2061–2080	169 460	-89.3
RCP8.5 2041–2060	151 990	-90.4
RCP8.5 2061–2080	28 590	-98.2

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According to our results, the suitable environments for palsas and peat plateaus will disappear almost all around the Northern Hemisphere even under the moderate climate change scenarios (Table 1; Fig. 4a). The suitable environments would disappear almost completely from Northern Fennoscandia, West Siberia, coasts of Hudson Bay, western Alaska, and eastern Siberia already by the period 2041–2060. Only in Iceland and Greenland, the modelled palsa and peat plateau environments seemed to persist without major distributional changes. In addition to these regions, the suitable environments could remain in North America in the Northwest Territories, northern Quebec, and Alaska during the period 2061–2080. In Russia, palsas and peat plateaus could be found mainly from the Yamal Nenets Autonomous Okrug and Turukhansky district (Table 1b–c; Fig. 4a). The predictions based on the RCP8.5 scenario for period 2041–2060 present similar distribution of suitable environmental spaces, compared with the RCP4.5 scenario for 2061–2080 (Fig. 4a–b). Only 1.8 % of the recently suitable environments would persist under RCP8.5 scenario in the period 2061–2080 (Table 1).

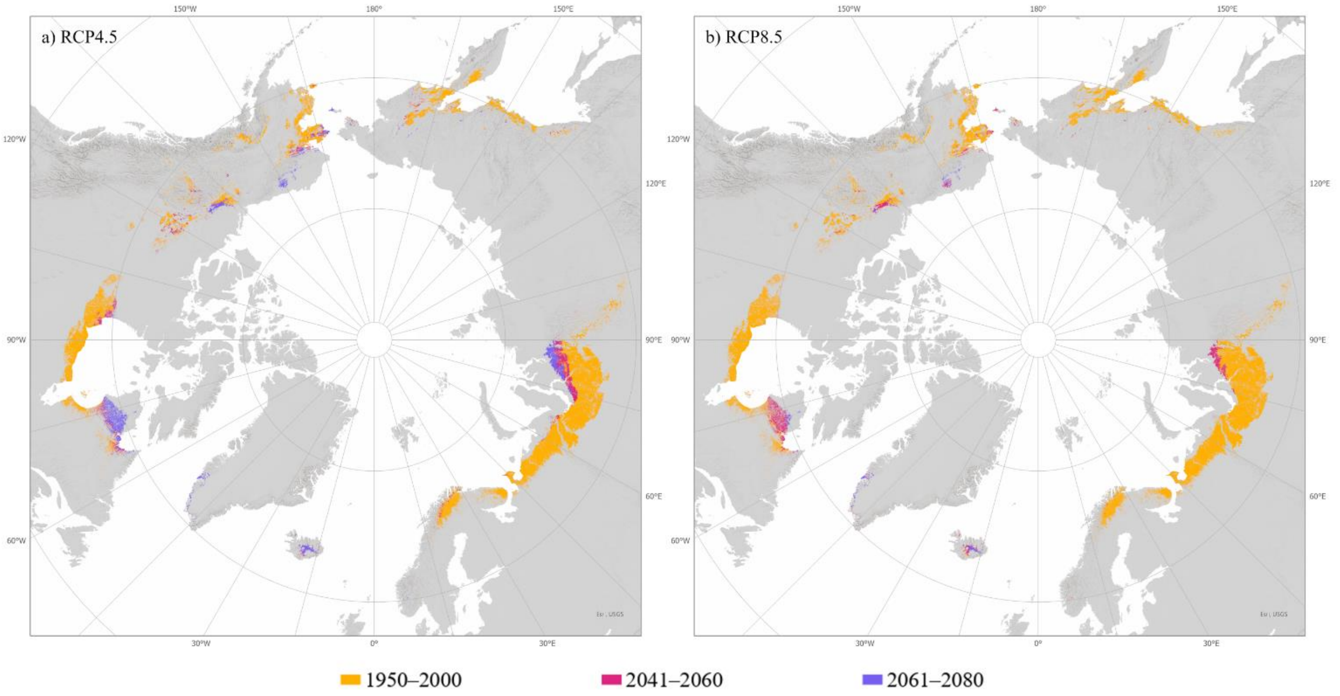

Figure 4: Predicted distributions of suitable environmental spaces for palsas and peat plateaus for different time periods under moderate (a) and high emissions (b) Representative Concentration Pathway climate change scenarios (RCP4.5 and RCP8.5). Modelling results are presented for periods 1950–2000, 2041–2060 and 2061–2080. RF model results are provided for the permafrost region (Ran et al., 2022) and for the future periods for the extent of the period 1950–2000.

3.3 Thermokarst coverage of the suitable environments

When our modelling results were compared against the thermokarst map (Olefeldt et al., 2016), areas with high or very high wetland thermokarst coverages were the first ones to become unsuitable based on our models (Fig. 4a–b & 5a). These regions located mainly at the coasts of the Hudson Bay, the Northwest Territories, west coast of Alaska and parts of Western Siberia. In turn, wide areas with none to low wetland thermokarst coverage were found from northern Quebec and Turukhansky district in Russia (Fig. 5a). These coincided well with the regions persisting as suitable environments in our climate change projections (Fig. 4a–b). The comparison with lake thermokarst presented comparable results for most of the regions with some exceptions in the Western Siberia (Fig. 5a–b).

The clearest conflict between our results and the thermokarst map located in northern Fennoscandia, where we predict major losses in suitable environmental spaces for permafrost peatlands. In contrast, Olefeldt et al. (2016) classified northern Fennoscandia to have no or low coverage of both wetland and lake thermokarst (Fig. 5a–b). Especially, lake thermokarst was rare in the area. Besides ~~the~~ northern Fennoscandia, ~~the~~ consistency between the predicted suitable environments and the thermokarst data was not so clear in the eastern parts of the Siberia.

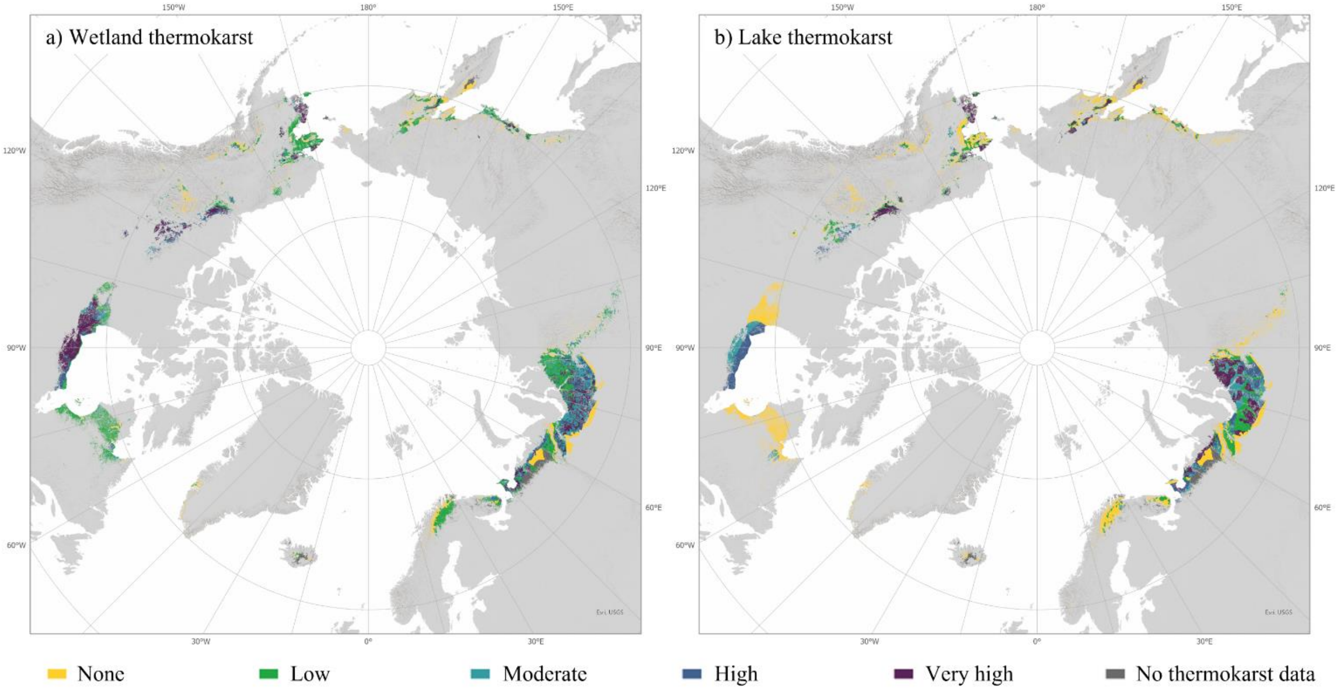

Figure 5: Suitable environmental spaces for palsas and peat plateaus (for period 1950–2000) against thermokarst classification by Olefeldt et al. (2016). Wetland (a) and lake (b) thermokarst coverages range from none (yellow) to very high (dark violet). Dark grey illustrates regions for which the thermokarst data are not available. Thermokarst coverages are classified as following, none (0–1 %), low (1–10 %), moderate (10–30 %), high (30–60 %) and very high (60–100 %). Results are provided for the permafrost region (Ran et al., 2022).

Overall, the wetland thermokarst had a closer spatial match with the projected lost and remaining suitable environmental spaces for palsas and peat plateaus in the circumpolar permafrost region. From the regions that our models predicted to become unsuitable for palsas and peat plateaus first (by 2040–2061 in RCP4.5 scenario), 36.5 % presented high or very high wetland thermokarst coverage, whereas 48.0 % had none or low coverage. This indicated conflicting spatial relationship. However, when compared to the regions that were predicted to remain suitable during the period 2040–2061 in RCP4.5 and RCP8.5 scenarios, a clear relationship was observed. These persisting palsa and peat plateau environments represented lower wetland thermokarst coverage than the degrading regions (Fig. S6).

3.4 Statistical and spatial evaluation of the models

The 100-fold cross-validation based on the split-sample approach yielded high AUC and TSS values (Fig. 6), indicating very good predictive performance of the models. RF and GBM best predicted the distribution of suitable environments, and the ensemble model performed slightly weaker. Between-model variability within the 100 modelling runs was estimated by the standard deviations. For AUC the standard deviation range was 0.003–0.006, and for TSS 0.014–0.019. Evaluation with the separate dataset resulted in lower AUC and TSS values than the cross-validation, but still indicated excellent predictive performance based on AUC values (AUC > 0.9) (Fig. 6). All models were also good (TSS > 0.5) in predicting the occurrence of landforms. In the separate evaluation data, RF and GBM had the highest TSS values, whereas the ensemble and RF models had the best AUC score. Compared to the cross-validation, larger between-model variability was observed in TSS values (sd. 0.017–0.04), whereas variability in AUC values (sd. 0.001–0.004) was smaller. GLM and GAM were the weakest models in both evaluations. Based on the evaluation metrics, response curves, and predictive maps RF was considered the best method for predicting suitable environments for palsas and peat plateaus.

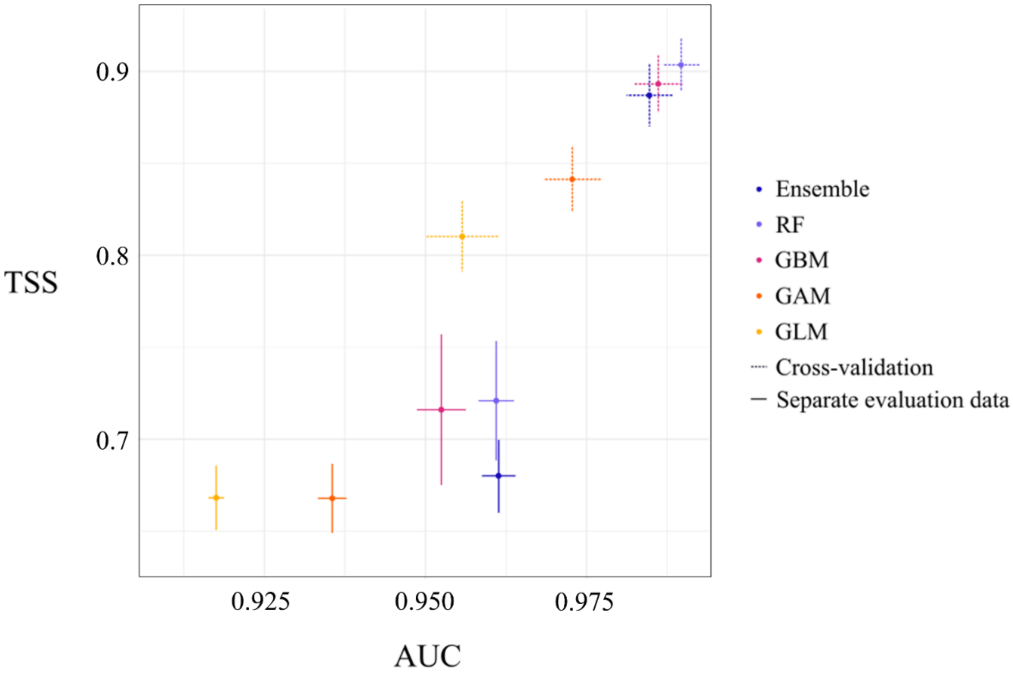

Figure 6: Statistical evaluation metrics for different modelling techniques. The averages of AUC and TSS values with one standard deviation (whiskers) are based on 100 runs of the models. Evaluation results for the 100-fold cross validation with the calibration data are presented with dashed line and for the separate evaluation data, results are presented with solid line.

The total area for which all four models predicted occurrence of palsas, and peat plateaus was 0.8 million km^2. This represents approximately 28 % of the area for which at least one model predicted occurrence of the landforms (3.1 million km^2), indicating relatively low model agreement. The highest model agreement (Fig. S7) was found in Northern Fennoscandia, Western Siberia and Northern Canada around the Hudson Bay and Quebec. Also, west coast of Alaska, regions around Kamchatka Peninsula and Iceland had a high model agreement.

4 Discussion

Our models predicted drastic loss of suitable environments for palsas and peat plateaus, indicating almost complete loss of the landforms by 2080. Previous modelling studies have shown similar trends for restricted study areas (e.g., Aalto et al., 2017; Fewster et al., 2022) and many monitoring studies have documented palsas and peat plateaus already degrading around the Northern Hemisphere (Payette et al., 2004; Borge et al., 2017; Mamet et al., 2017; Olvmo et al., 2020). Here, we presented these degradation trends for the whole northern circumpolar permafrost region. Such major changes in the permafrost peatlands as projected here, may have an influence on the future carbon cycling and potential to further accelerate the climate change (Turetsky et al., 2020; Miner et al., 2022). Moreover, the predicted permafrost degradation may have a major impact on both geodiversity and biodiversity of current Northern Hemisphere permafrost region. Thus, comprehensive understanding of the current distribution of studied landforms is needed.

Based on the recent period, the suitable environments for palsas and peat plateaus were predicted to occur around the Northern Hemisphere permafrost region, with hotspots at the most studied regions (i.e., Northern Fennoscandia, Western Siberia, and subarctic Canada). Our results from the Northern Fennoscandia and Western Siberia coincide well with the results of Fewster et al. (2022). Especially, suitable environments of the Northern Finland, Norway, and Sweden agreed well with the previous mappings and modellings (Fronzek et al., 2006; Backe, 2014; Metsähallitus 2019; Fewster et al., 2022). In contrast, our models predicted more extensive palsa and peat plateau occurrences in European Russia (e.g., Kola Peninsula and Komi Republic) than expected, and RF did not predict landforms to occur as far north in Yamal-Nenets than Fewster et al. (2022).

For previously unmapped regions of Central and Eastern Siberia our models predicted suitable environments in the east coast of Russia and inside a zone stretching southeast from the Western Siberia. Our RF models did not predict palsas or peat plateaus in the central parts of Siberia. This might indicate too dry and continental climate or otherwise unsuitable environmental conditions or might have been caused by insufficient number of presence observations to characterize the possibly suitable environmental conditions for palsas and peat plateaus in the region (Fig. 1).

For North America our results aligned well with Fewster et al. (2020) around the Hudson Bay, Quebec, the Northwest Territories, and Yukon. However, our results indicated more variability in landform occurrence especially in the Northwest Territories and Yukon, showing e.g., a gap in suitable environments east of the Great Slave Lake, and clear differences in suitable environments of Alaska. For Alaska, our models predicted occurrence of landforms in the coastal regions whereas Fewster et al. (2020) predicted them in more central parts. The contrasting results may be partly explained by the inclusion of non-climatic variables, and the finer resolution of our study, which both can facilitate the differentiation of environmental suitability at an improved accuracy.

The optimal climatological conditions coincide quite well with the climate envelopes determined by previous studies for Fennoscandia (e.g., Luoto et al., 2004b; Aalto and Luoto, 2014) and Northern America (Fewster et al., 2020). For the Central and Eastern Siberia no optimal climatic ranges for palsas and peat plateaus have been determined before. TDD was the most important variable while FDD had only a minor importance in our models, indicating that the summer conditions during the thawing season have greater effect on the distribution of palsas and peat plateaus. Recent studies have similarly highlighted the importance of thawing season conditions for the occurrence of permafrost (Mekonnen et al., 2021), other periglacial landforms (Karjalainen et al., 2020), and active layer (Peng et al., 2018; Karjalainen et al., 2019).

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The negative effect of higher air temperatures on the distribution of palsas and peat plateaus can be observed from the response curve for TDD (Fig. 3a). Moreover, increasing rainfall can cause permafrost to thaw even faster than it would only because of the temperature rise (Magnússon et al., 2022). In addition, thicker snowpack can also lead to the permafrost thaw in the discontinuous permafrost region (Biskaborn et al., 2019) as the thick snowpack acts as an insulator preventing the frost from penetrating deep into the soil (Seppälä, 1990, 1994; Ge and Gong, 2010; Sannel, 2020). Increasing snowpack also leads to moister conditions during late spring due to abundant meltwaters (Sannel, 2020), and thus alters the thermal properties of peat (Kujala et al., 2008). Indeed, the thin snow cover has been tested in the field to be a key factor in the formation of palsas (Seppälä, 1982), and the negative effect of increasing snowfall (Johansson et al., 2013) can be recognized from our results (Fig. 3a). However, there might be a delay before the increasing snow depth will affect to the thaw depth (Sannel et al., 2016).

Other environmental conditions beside the climate affect also the distribution of peat dominated permafrost mounds and other periglacial landforms (Seppälä, 2011; Karjalainen et al., 2020). Our models indicate that palsas and peat plateaus require sufficient SOC content, which is logical, as the sufficient peat cover is considered crucial for the formation and occurrence of these landforms at the marginal permafrost regions (Kujala et al., 2008; Seppälä, 2011). Most of the previous modelling studies of palsas and peat plateaus (e.g., Fronzek et al., 2006; Parviainen and Luoto, 2007; Fewster et al., 2020, 2022) have used only climate envelope models. Our results show that incorporating other environmental variables may enhance the predictive performance of the models as SOC and TWI had the highest VI values after TDD (Fig. 3). In addition, compared to previous broad-scale studies (Fewster et al., 2022, 2020) the used high spatial resolution allows for identifying unsuitable areas within the climatically suitable envelopes and thereby reduces the risk of overestimating palsa and peat plateau distribution.

Even though our models predicted major losses in the suitable environments, the peat cover of the landforms may cause time delay in the degradation process, as dry peat acts as an effective insulator for permafrost cores of the mounds (Kujala et al., 2008). Thus, the actual degradation of palsas and peat plateaus might happen later than our statistical models predict. The documented areal degradation rates varying from 0.5–1 % a^{-1} (e.g., Borge et al., 2017; Mamet et al., 2017), however, support the rapid degradation of the landforms. Although the timing of the degradation might be delayed, our predictions can be used to estimate the forthcoming spatial changes in the distribution of the suitable environments.

Previous studies have suggested that the development of thermokarst can be used as an indicator of the former distribution of palsas (Matthews et al., 1997; Luoto and Seppälä, 2003). Thermokarst ponds are relatively common in Fennoscandian palsa mires (e.g., Luoto and Seppälä, 2003), although Olefeldt et al. (2016) classified this region to have a low thermokarst coverage. This mismatch was noticed also here, as we predicted extensive degradation of the landforms in the region. Overall, our results showed that regions with higher thermokarst coverage are in a higher risk to become unsuitable environments for palsas and peat plateaus, compared to the regions with lower thermokarst coverage. This indicated clear spatial relationship with our results and the thermokarst coverage. Recognition of the regions with a high degradation risk is useful in the estimation of future greenhouse gas fluxes from permafrost wetlands (Swindles et al., 2015; Miner et al., 2022) and establishing conservation actions for these endangered ecosystems and habitats (Janssen et al., 2016).

To further develop the statistical models for the prediction of palsa and peat plateau distribution we would need more spatially resolved datasets describing the thickness of the snowpack and peat layer instead of the indirect snowfall and SOC variables. Although our study gave new insights to the distribution of palsas and peat plateaus in Central and Eastern Siberia, future research should focus on acquiring better knowledge of the current distribution of palsas and peat plateaus in these regions.

5 Conclusions

From the results of this study, we conclude that:

- Based on a recent period, suitable environments for palsas and peat plateaus can be found across the Northern Hemisphere, with occurrence hotspots in Northern Europe, Western Siberia and around the Hudson Bay, Quebec, and the Northwest Territories of Canada.
- A dramatic loss of the suitable environments for palsas and peat plateaus is predicted to occur already by 2041–2060 and almost complete loss by 2061–2080.
- Under a moderate emissions scenario (RCP4.5), landforms can persist in the coldest parts of the recent distribution area, but if the climate change mitigation fails (RCP8.5), suitable environments are predicted to be lost from almost the entire Northern Hemisphere.
- The pronounced importance of thawing-season climate conditions for circumpolar palsa and peat plateau occurrence suggests that the projected increases in summer temperatures and rainfall may strongly affect the stability of permafrost peatland landforms.
- In addition to the climatic variables, soil organic carbon, and moisture accumulation potential of the soil affect the landform occurrence at circumpolar scale, and they need to be considered in order to draw a detailed picture of the landforms' distribution.
- Projected loss of the suitable palsa and peat plateau environments overlapped with the regions having a high thermokarst coverage. In the future, it is likely to find increasing amount of thermokarst from recent palsa and peat plateau environments.

The degradation of permafrost peatlands will potentially have an influence on the diversity of subarctic nature and the carbon balance of Earth. Thus, the predicted changes should be taken into consideration when the estimating the pace and impacts of the climate change over northern regions.

Data availability

Used climate data were obtained from WorldClim – Global Climatic Data, available at https://worldclim.org/ (Hijmans et al., 2005). Variables describing the soil properties were calculated from data in SoilGrids – global gridded soil information database https://files.isric.org/soilgrids (Poggio et al., 2021). Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010; Danielson and Gesch, 2011) https://doi.org/10.5066/F7J38R2N were used to calculate TWI. Thermokarst dataset (Olefeldt et al., 2016) can be obtained from https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1332. Landform observations compiled in this study are available from the corresponding author upon reasonable request. List of references used in the compilation is provided in appendices.

Author contribution

OHK, OK and JH conceptualized the research idea. OHK collected the observational data and complied it with the environmental data. OK led the compilation of the environmental datasets and their geospatial processing with OHK and JA. OHK performed the statistical analysis with contribution from OK and JH. OHK wrote the paper with contributions from all the authors.

Disclaimer

The authors declare that they have no conflict of interests.

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Appendix A

List of references used in the compilation of palsa and peat plateau data.

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