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

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Abstract. 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 suitable environments for 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 suitable environments for the landforms were assessed by using low, moderate, and high emissions scenarios (Representative Concentration Pathways; RCP2.6, RCP4.5 and RCP8.5, respectively) for two periods (2041–2060 and 2061–2080). Hotspots for palsa and peat plateau environments occurred in Northern Europe, Western Siberia, and subarctic Canada. Climate change was predicted to cause an almost complete loss (decrease of 98.2 %) of suitable environmental spaces under the high emissions scenario by 2061–2080, while under low and moderate emissions scenarios the predicted loss was 76.3 and 89.3 % respectively. Our modelling results are in-line with previously published thermokarst data pointing out areas of recent degradation of palsa and peat plateau environments. Our results provide new insights into the distribution of the permafrost landforms in less studied areas such as Central and Eastern Siberia. In addition, the predictions provide new understanding of the changing geoecological conditions of the circumpolar region with important implications for greenhouse gas emissions.

1 Introduction

Northern environments are heavily affected by climate change (IPCC, 2021). Because of Arctic amplification these environments are warming two to three times as fast as the global average (You et al., 2021). As 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., 2022a), 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 primarily found in regions of sporadic and discontinuous permafrost (Seppälä, 1988). They mainly differ in 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 usually elevated from their surroundings by about one meter (Kershaw and Gill, 1979; Zoltai, 1972). Palsas and peat plateaus are not clearly distinguishable from each other and many transitional types between these landforms are found. Peat plateaus can be considered as a morphological class of palsas, so-called palsa plateaus (e.g., Åhman, 1977; Seppälä, 1988).

35   According to Hugelius et al. (2020) nearly half of the peatlands of the Northern Hemisphere, including palsa mires and peat plateaus, contain permafrost. Previous studies have shown that most palsas were formed in considerably colder climate than present (Halsey et al., 1995; Treat et al., 2016a; Vorren, 2017; Fewster et al., 2020). Thus, these landforms are highly sensitive to further changes in climate, and many studies have reported rapid degradation of them (e.g., Borge et al., 2017; Mamet et al., 2017; Olvmo et al., 2020). As permafrost thaws from peatlands, changes in greenhouse gas fluxes are expected

40   (Turetsky et al., 2020; Miner et al., 2022). Increasing CO_2, CH_4 and N_2O -emissions further accelerate climate change (Marushchak et al., 2011; Schuur et al., 2015; Hugelius et al., 2020).

    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

45   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 (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 as critically endangered habitats in 2016, mainly because of the degradation of permafrost (Janssen et

50   al., 2016).

    Palsas and peat plateaus in 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., Zoltai et al., 2000; 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 and peat plateaus are available for Central and Eastern Siberia (Vasil'chuk

55   et al., 2013a, 2013b, 2014). The distribution of these landforms 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 and peat plateaus require specific climatic conditions (e.g., Luoto et al., 2004b; Parviainen and Luoto, 2007; Aalto et al., 2017; Fewster et al., 2020, 2022). Besides air temperature and precipitation, wind patterns, vegetation,

60   snow depth, topography and soil properties also affect their distribution (Seppälä, 2011). Especially, the role of sufficient peat cover is crucial in marginal permafrost regions, as the thermal properties of peat protect frozen cores against thawing (Kujala et al., 2008).

In this study, we provide the first predictions of suitable environmental spaces for palsas and peat plateaus over the entire Northern circumpolar region. As the explored landforms are not found in 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 these landforms in a recent (1950–2000) and in two future periods (2041–2060 and 2061–2080), using three Representative Concentration Pathway climate-scenarios (RCP2.6, RCP4.5 and RCP8.5). Moreover, we compare our predictions with thermokarst data produced by Olefeldt et al. (2016). The purpose of the comparison is to assess the consistency of our future predictions as palsas and peat plateaus form thermokarst ponds when ice-rich permafrost thaws (e.g., Seppälä, 2011). Consequently, regions with high thermokarst coverage can be assumed to indicate degradation of palsas and peat plateaus. 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 these questions, we used extensive observational data on landform occurrences and high-resolution geospatial data on environmental conditions to predict the suitable environmental spaces with four different statistical modelling methods and their ensemble. Because of the uneven distribution of the landform observations, our results for the Central and Eastern Siberia are extrapolations of models fitted to other parts of the Northern Hemisphere. By extrapolating the models to the Central and Eastern Siberia our results offer new insights into the circumpolar distribution of suitable environments for palsas and peat plateaus, especially in these poorly mapped regions. Moreover, changes in the studied landforms 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 mainly collected 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') (see Fewster et al., 2022). 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).

95 Palsa observations were limited to 'true palsas' (Fig. 1b) based on the description of the landform provided in the used literature (see Appendix A) or a comprehensive interpretation of the satellite images (based on the size, form, and location of the landform and its surroundings for example). 'Palsa-like' formations and 'lithalsas' (so-called mineral palsas) were excluded, because of the lack of substantial peat cover on these landforms (Pissart, 2002). In this study, peat plateaus were considered as palsa plateaus, instead of distinguishing these two landforms from each other, (Zoltai and Tarnocai, 1975;
100 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 palsas or peat plateaus.

Statistical distribution modelling often requires absence observations (i.e., presence-absence data) (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
105 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 occurring 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
110 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 drawing 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). In order to reduce the effect of spatial autocorrelation on model evaluation, observations in the evaluation dataset were selected so that they were located at
115 least 50 km from each other (Roberts et al., 2016). Because of this criterion, two absence observations had to be removed from the evaluation data, as they were located too close (< 50 km) to presence observations (final N = 398).
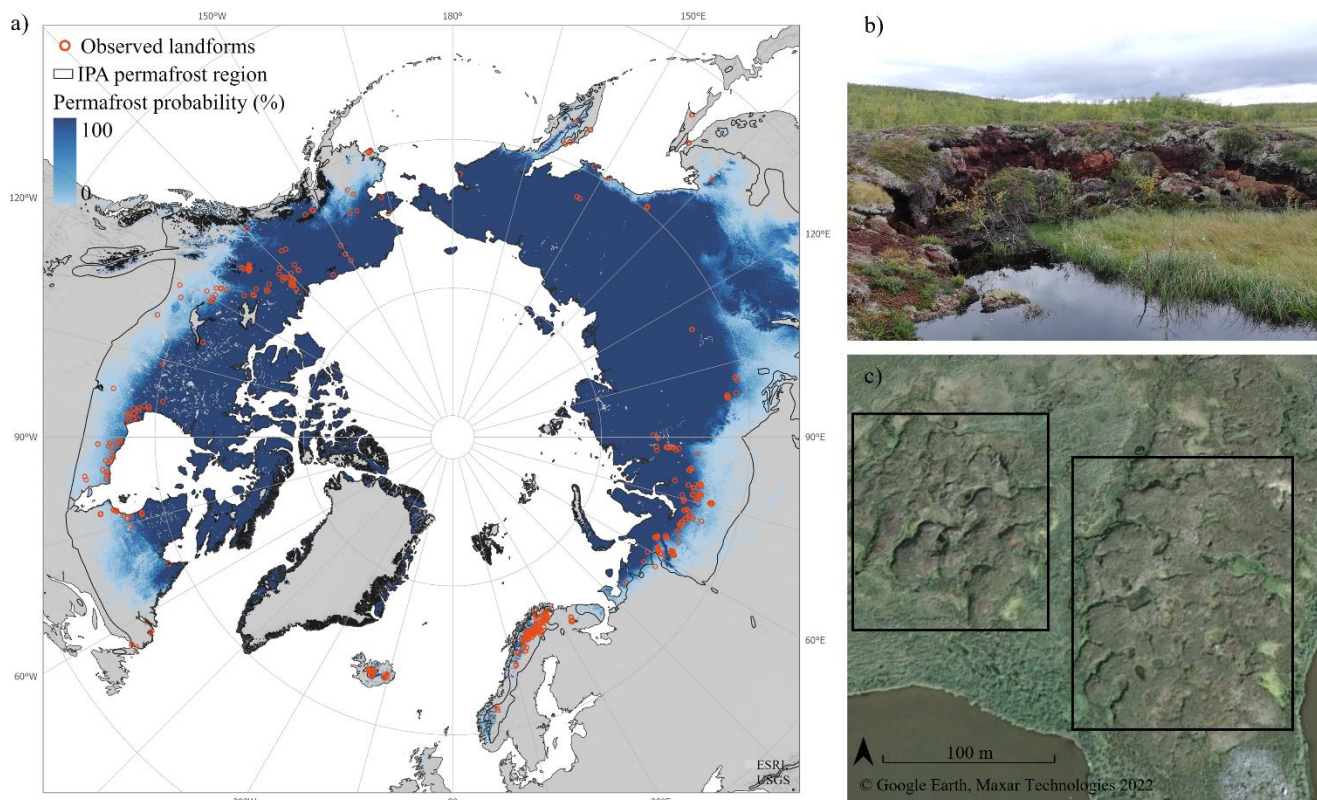
Figure 1: Distribution of the observed palsas and peat plateaus (N = 961) across the Northern Hemisphere,the probability of the permafrost occurrence (%, Ran et al., 2022) and International Permafrost Association (IPA) permafrost region (Brown et al., 1997) (a). A thawing palsa in Kilpisjärvi, Finland (b), and satellite image of a palsa mire in Kiruna, Sweden (68°28'36.0''N, 20°55'06.0''E), groups of palsas are delimited by black rectangles (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 climate, 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 computed separately 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. The use of recent climate period instead of the current one better acknowledges the possibility that the compiled landform observations are representing the conditions of past climate. For the climate change scenarios, we used the low emissions scenario RCP2.6, 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). Noteworthy, the SoilGrids data layers have been produced using a relatively small amount of data from some permafrost regions, especially Central Siberia and High-Arctic Canada, which may affect the accuracy of data in these regions, especially at finer resolution. SoilGrids were used as alternative soil data were not available in the used (30 arc sec) resolution, and we considered it necessary to account for soil properties, especially soil organic carbon (SOC), which are essential to palsa and peat plateau formation. Here, the SoilGrid variables at the spatial resolution of 7.5 arc-second (~250 meters) were aggregated to the 30 arc-second resolution using bilinear interpolation in ArcGIS Pro. Owing to the lack of high-resolution peat thickness data we used SOC, (g kg^{-1}) as a proxy for the of peat layer. 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). Their prediction of thermokarst coverage is based on six environmental variables including the permafrost zonation, ground ice content, thickness of the sedimentary overburden, ecoregion, and ruggedness of the topography. These variables were not utilized in our study, and thus our analyses can be considered as independent. The dataset includes different types of thermokarst landscapes, and their areal coverages classified into five classes, ranging from none (0–1 %) to very high (60–100 %). 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). Regions predicted to become unsuitable for palsas and peat plateaus in future scenarios should have higher thermokarst coverage than persisting suitable environments.

165 In addition, we spatially compared our predictions to four peatland datasets (Treat et al., 2016b; Xu et al., 2018, Hugelius et al., 2020; Olefeldt et al., 2021) and two suitable climate spaces to further assess our results. Comparison with the peatland datasets was conducted to examine how well our predictions coincide with the distribution of peatlands, whereas the suitable climate spaces were estimated to recognize the suitable peatlands (i.e., in less studied parts of Siberia). The suitable climate spaces, based on FDD and TDD values, were estimated by a literature review (see e.g., Seppälä and Hassinen, 1997; Luoto

170 et al., 2004b; Aalto and Luoto, 2014; Fewster et al., 2020) and by interpreting results from regional palsa analyses (results not shown). The first classification (FDD: 1500–4500, and TDD: 500–1500) is stricter interpretation of the suitable climate space, and the second (FDD<5000, and TDD<2000) is a more liberal one.

2.3 Statistical modelling

175 Statistical modelling was conducted using the biomod2 (version 3.5.1; Thuiller et al., 2021) package in R (version 4.1.3; R Core Team, 2022). 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). The used methods were generalized linear model (GLM, Nelder and Wedderburn, 1972), generalized additive model (GAM, Hastie and Tibshirani, 1986),

180 generalized boosted model (GBM, Elith et al., 2008) and random forest (RF, Elith et al., 2005). Multiple modelling techniques were utilized in order to acknowledge the uncertainties associated with individual modelling methods (see Thuiller et al., 2009) and to select the one with the highest model performance. In addition, we built an ensemble based on the former methods to find out whether it outperforms the individual modelling techniques in the distribution modelling of suitable environments for palsas and peat plateaus. Ensemble approach has been utilized previously for example to predict

185 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.

190 Variables for the final GLM were selected in a stepwise fashion using the Bayesian information criteria (BIC, Schwarz, 1978) to find the balance between model complexity and performance. In GAMs we used the generalized cross-validation to optimize limit the degrees of freedom with initial values set to three to avoid overfitting. 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

195 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.

200 We performed 100 iterations with random sampling of calibration data for each modelling method and built an ensemble of the produces models at each round by averaging the four modelling algorithms. Moreover, the performed 100-fold random sampling of modelling data allowed us to provide uncertainty measures (standard deviation) for the predicted probability values. Because of the uneven distribution of the landform observations, our results for Central and Eastern Siberia should be interpreted as an extrapolation of model fitted for other parts of the Northern Hemisphere.

205 Future predictions were performed by using the BIOMOD_Projection -function in biomod2 (Thuiller et al., 2021; see Karjalainen et al., 2020). Here, the models calibrated for the recent period (1950–2000) were used to predict future suitable conditions by substituting the climate variables with future climatologies (Hijmans et al., 2005). Predictions were performed for each RCP-scenario (2.6, 4.5 and 8.5) and future period (2041–2060 and 2061–2080). Predictions were extracted to the current extent of the suitable environments because we did not consider it temporally plausible for new palsas and peat

210 plateaus to develop in the region of continuous permafrost during the 21st century.

Finally, the predicted probability surfaces for suitable environments were classified to binary distribution maps, which were then used to calculate the areas of the suitable environmental spaces. 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

215 supplements (Table S1). Average variable importance (VI) values (Breiman, 2001; Fisher et al., 2019) were calculated from the results of 100 modeling runs in order to analyze the contribution of each variable to the models. 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.,

220 2009):

$$VI = 1 - \text{cor}(\text{initial model predictions}, \text{shuffled model prediction}). \qquad (1)$$

225 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, semi-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).

230 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), and by the comparison of our predictions and the four peatland datasets (Treat et al., 2016b; Xu et al., 2018, Hugelius et al., 2020; Olefeldt et al., 2021).

3 Results

3.1 Suitable environments in recent conditions

The presented results are based on the random forest (RF) models, which yielded the highest evaluation statistics among the used methods (see section 3.4 and supplementary material). 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

240 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 in the Northwest Territories of Canada, west coast of Alaska and the Russian Far East. The probability of palsa and peat plateau occurrence decreased relatively sharply outside the most suitable environments (Fig. 2).

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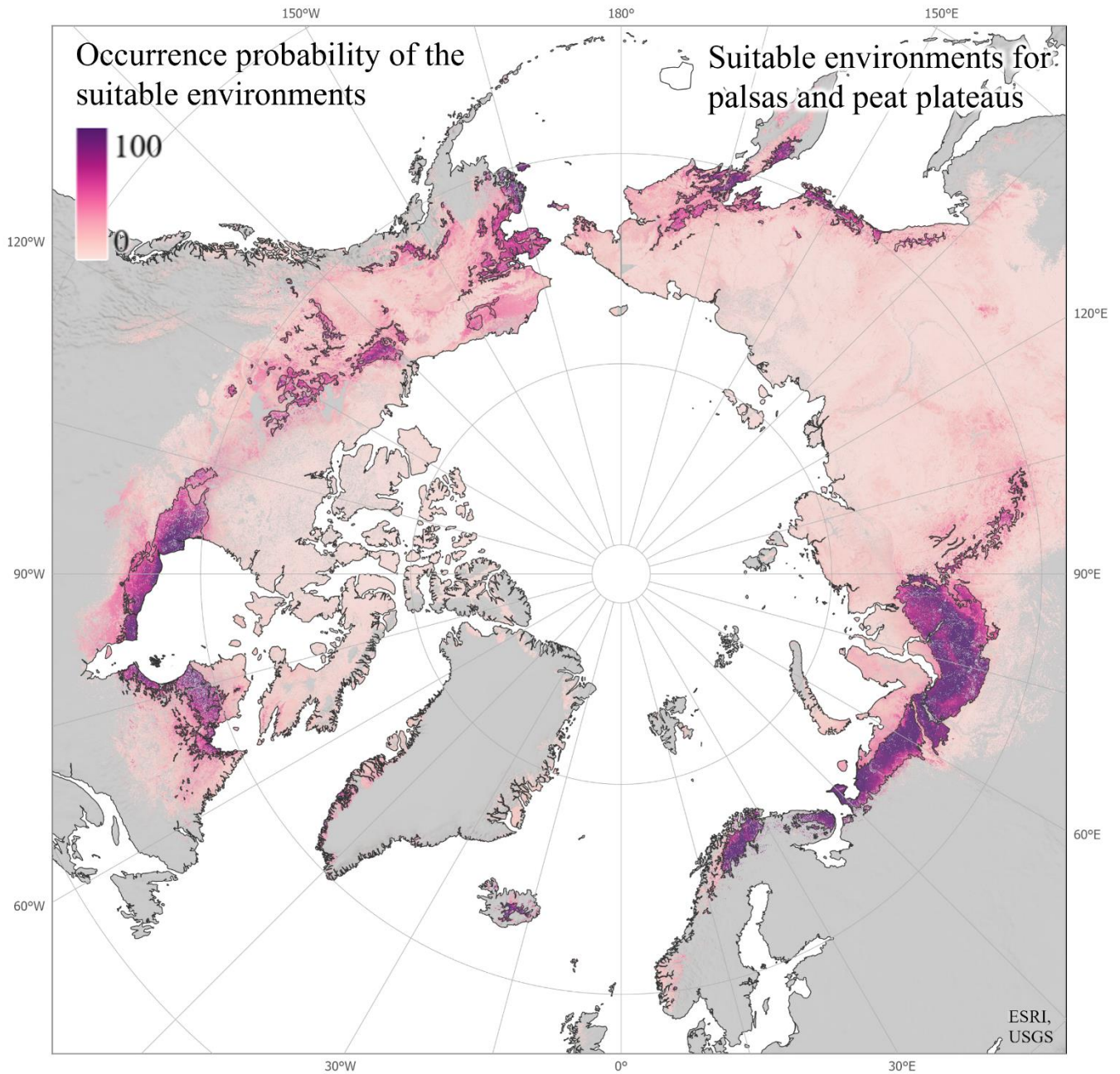
Figure 2: The probability (%) of the suitable environments for palsas and peat plateaus illustrated with a color gradient from light pink to dark purple. Black outlines delineate the palsa and peat plateau domain, and grey color illustrates areas outside the permafrost region and glaciers. Results of 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 occurrence probability increases with higher TWI 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 optimal 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).
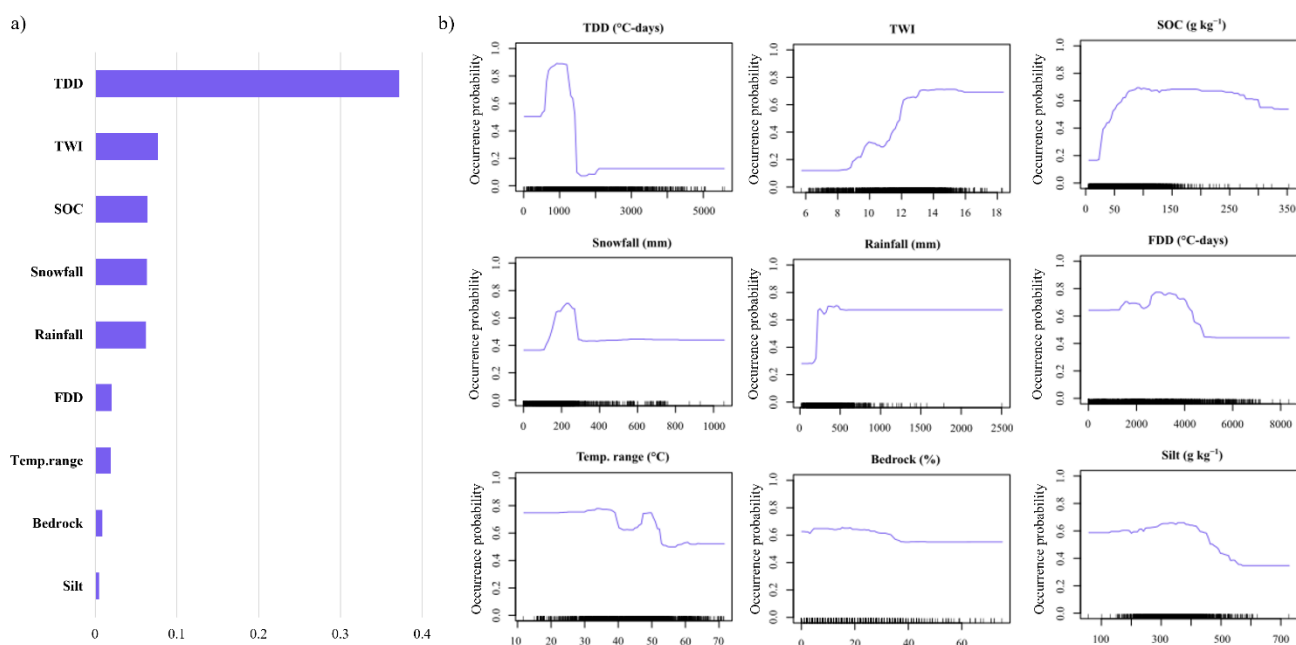
Figure 3: Variable importance values (a) and response curves (b) for the environmental variables based on the random forest model. Abbreviated variables are thawing- and freezing degree-days (TDD and FDD, °C-days), annual air temperature range (Temp.range, °C), topographic wetness index (TWI), soil organic carbon content (SOC, g kg^{-1}), silt content (Silt, g kg^{-1}) and bedrock probability within two meters (Bedrock, %).

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
275 century (Table 1.; Table S2 in supplements). The high-emissions scenario RCP8.5 predicted even larger losses by the period
2041–2060, than low and moderate emissions scenarios (RCP2.6 and 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).

Table 1: Predicted suitable environmental spaces (in km^2) for palsas and peat plateaus at different time periods and RCP climate
280 **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. Three True Skill Statistic cut-off values of occurrence probability were used (an
average cut-off based on 100 model iterations and average cut-off±1 standard deviation) to classify continuous occurrence
probabilities into binary maps.

	Suitable area (km^2)			Percentage change (%)		
	Average	+1 s.d.	-1 s.d.	Average	+ 1 s.d.	- 1 s.d.
a) Nordic countries						
1950–2000	77 540	72 900	84 060			
RCP2.6 2041–2060	20 100	16 380	25 750	-74.1	-77.5	-69.4
RCP2.6 2061–2080	20 750	16 862	26 410	-73.2	-76.9	-68.6
RCP4.5 2041–2060	17 120	14 020	21 280	-77.9	-80.8	-74.7
RCP4.5 2061–2080	12 140	7 520	14 220	-84.3	-89.7	-83.1
RCP8.5 2041–2060	11 890	10 040	14 030	-84.7	-86.2	-83.3
RCP8.5 2061–2080	5 600	4470	6630	-92.8	-93.9	-92.1
b) Western Siberia						
1950–2000	562 750	537 930	598 390			
RCP2.6 2041–2060	78 930	58 790	89 150	-86.0	-89.1	-85.1
RCP2.6 2061–2080	67 190	54 740	72 450	-88.1	-89.8	-87.9
RCP4.5 2041–2060	48 270	36 600	53 100	-91.4	-93.2	-91.1
RCP4.5 2061–2080	14 930	7 280	18 860	-97.3	-98.6	-96.8
RCP8.5 2041–2060	10 110	1 940	15 252	-98.2	-99.6	-97.5
RCP8.5 2061–2080	10	8	33	-99.9	-99.9	-99.9
c) Central and Eastern Siberia						
1950–2000	305 580	226 520	415 610			
RCP2.6 2041–2060	91 360	72 360	109 880	-70.1	-68.1	-73.6
RCP2.6 2061–2080	80 290	65 940	97 410	-73.7	-70.9	-76.6
RCP4.5 2041–2060	62 550	50 260	78 110	-79.5	-77.8	-81.2
RCP4.5 2061–2080	30 350	25 330	39 050	-90.1	-88.8	-90.6
RCP8.5 2041–2060	25 140	19 710	34 270	-91.8	-91.3	-91.8
RCP8.5 2061–2080	1 070	420	3 270	-99.6	-99.8	-99.2

(Table 1 continues)

d) North America

1950–2000	640 070	459 730	913 453			
RCP2.6 2041–2060	225 830	164 440	311 950	-64.7	-64.2	-65.8
RCP2.6 2061–2080	207 690	146 350	291 890	-67.6	-68.2	-68.1
RCP4.5 2041–2060	167 430	115 180	255 590	-73.8	-74.9	-72.0
RCP4.5 2061–2080	111 450	81 070	173 390	-82.6	-82.4	-81.0
RCP8.5 2041–2060	104 310	74 210	165 190	-83.7	-83.9	-81.9
RCP8.5 2061–2080	21 570	13 740	43 480	-96.6	-97.0	-95.2

e) Permafrost region

1950–2000	1 587 360	1 298 230	2 013 390			
RCP2.6 2041–2060	416 910	312 610	537 560	-73.7	-75.9	-73.3
RCP2.6 2061–2080	376 650	284 540	488 980	-76.3	-78.1	-75.7
RCP4.5 2041–2060	296 110	216 610	408 830	-81.4	-83.3	-79.7
RCP4.5 2061–2080	169 460	124 440	246 150	-89.3	-90.4	-87.8
RCP8.5 2041–2060	151 990	106 300	229 190	-90.4	-91.8	-88.6
RCP8.5 2061–2080	28 590	18 860	53 790	-98.2	-95.9	-97.3

285

Remarkable reductions in suitable environments were predicted even under the low emissions scenario (RCP2.6) (Table 1; Fig. 4a). Reductions in suitable areas between the future periods in this scenario were minimal; difference in the average changes was 2.6 % for the whole permafrost region and varied from 0.9 to 3.6 % between regions. The predictions based on

290   RCP2.6 scenario for 2061–2080 were more extensive than the RCP4.5 -predictions for the period 2041–2060. The suitable environments for palsas and peat plateaus will disappear almost all around the Northern Hemisphere under the moderate emissions climate change scenario (Table 1; Fig. 4b). 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

295   major distributional changes. In addition to these regions, the suitable environments could persist in North America in the Northwest Territories, northern Quebec, and Alaska during the period 2061–2080. In Russia, palsas and peat plateaus could persist mainly in the Yamal Nenets Autonomous Okrug and Turukhansky district (Table 1b–c; Fig. 4b). 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. 4b–c). Only 1.8 % of the recently suitable environments would persist under

300   RCP8.5 scenario in the period 2061–2080 (Table 1). However, predicted areas for the suitable environments are sensitive to the used occurrence probability cut-off values (Table 1).
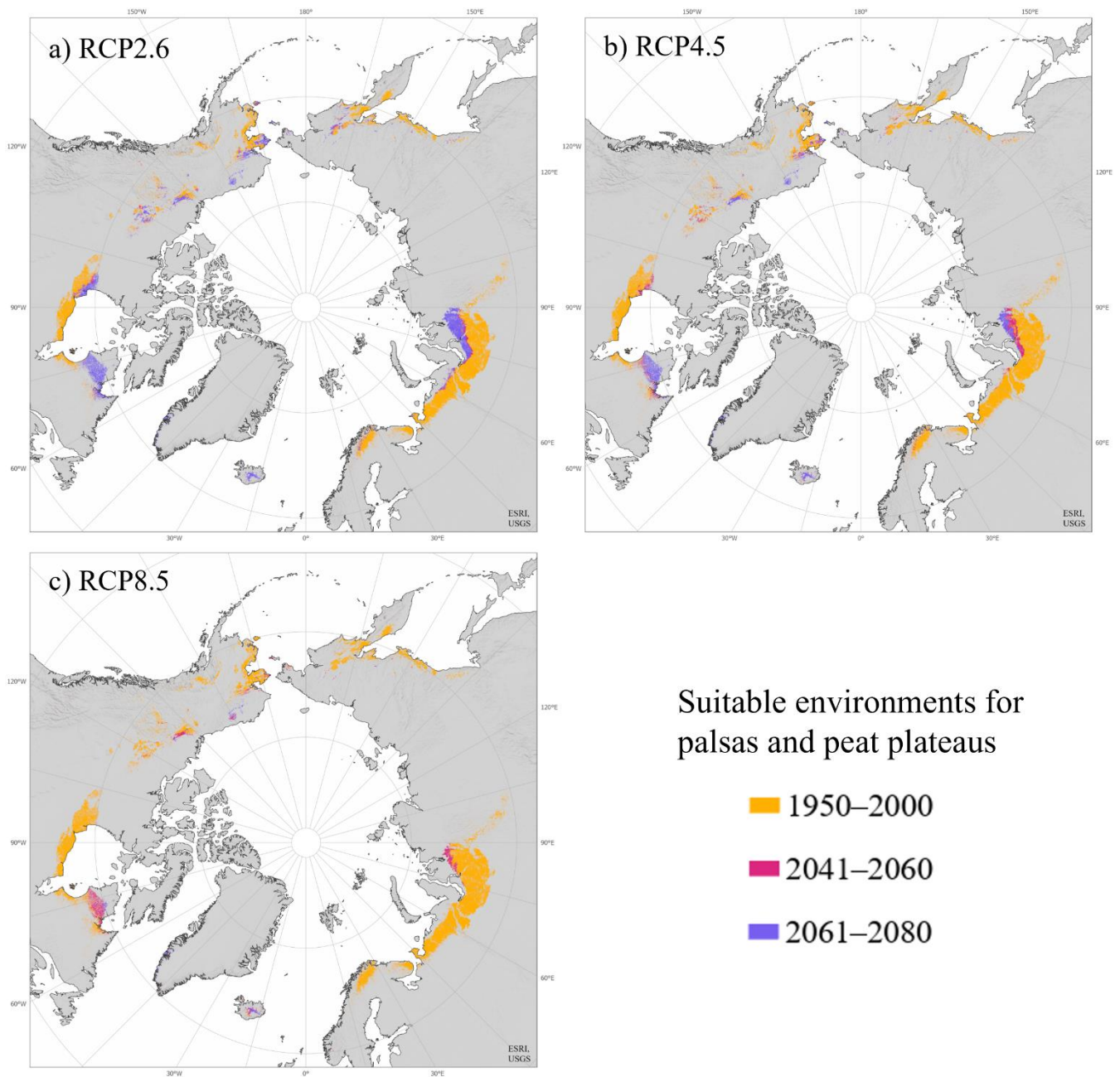
Figure 4: Predicted distributions of suitable environmental spaces for palsas and peat plateaus for different time periods under low (a), moderate (b), and high emissions (c) Representative Concentration Pathway climate change scenarios (RCP2.6, RCP4.5 and RCP8.5). Modelling results are presented for periods 1950–2000, 2041–2060 and 2061–2080. Random forest 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 northern Fennoscandia, consistency between the predicted suitable environments and the thermokarst data was not so clear in the eastern parts of the Siberia.
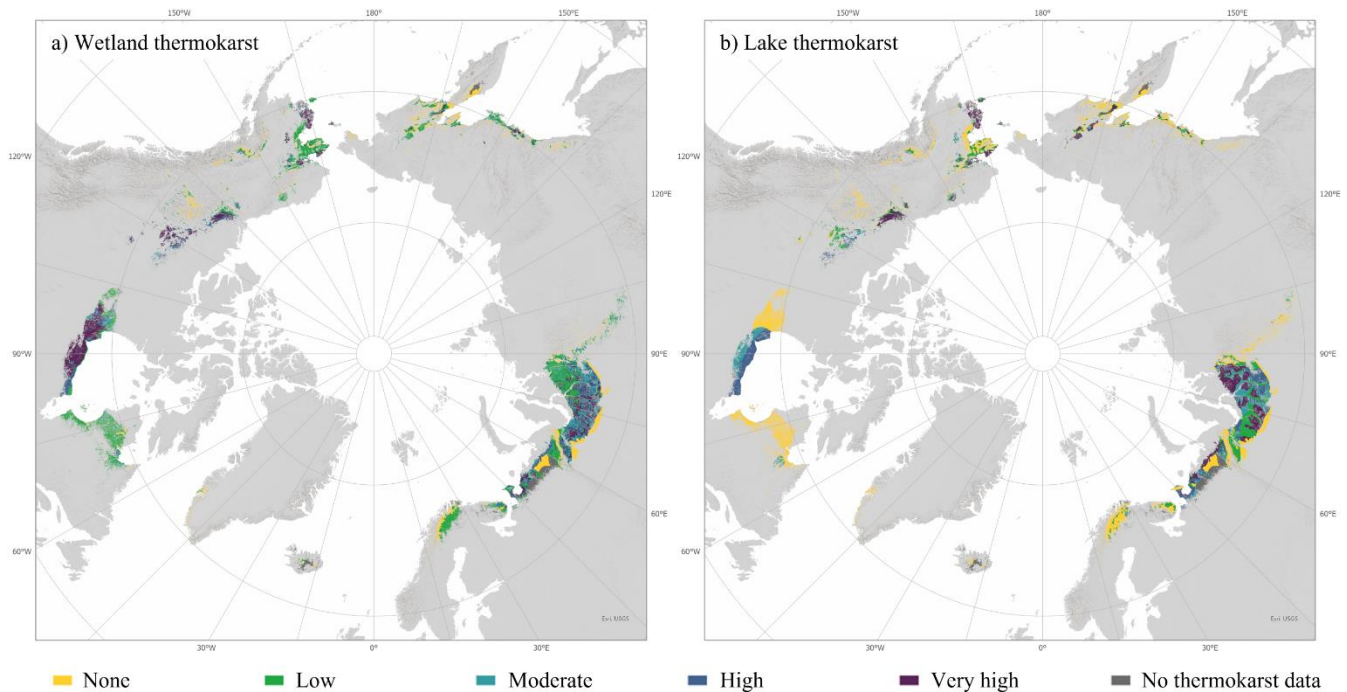
Figure 5: Suitable environmental spaces for palsas and peat plateaus (for period 1950–2000) against thermokarst classification by Olefeldt et al. (2016). Wetland (a) and lake (b) thermokarst coverages range from none (yellow) to very high (dark violet). Dark grey illustrates regions for which the thermokarst 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

335 become unsuitable for the landforms first (by 2040–2061 in RCP2.6 scenario), 40.7 % presented high or very high wetland thermokarst coverage, whereas 43.1 % had none or low coverage. This indicated slightly conflicting spatial relationship. However, when compared to the regions that were predicted to remain suitable during the period 2040–2061 in RCP2.6, 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).

340

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

345 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. With the separate evaluation data, RF and GBM had the highest TSS values, whereas the ensemble

350 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.

355 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.
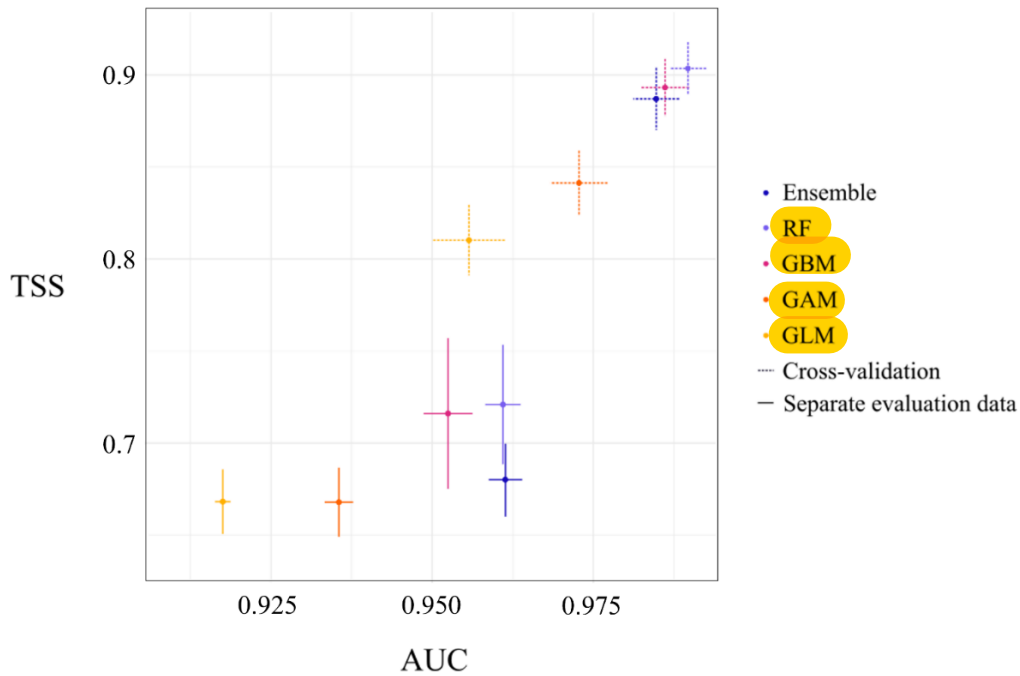
Figure 6: Statistical evaluation metrics for different modelling techniques. The averages of AUC and TSS values with one standard deviation (whiskers) are based on 100 runs of the models. Evaluation results for the 100-fold cross validation with the calibration data are presented with dashed line and for the separate evaluation data, results are presented with solid line.

The comparison between our predictions and different peatland datasets show that the predicted suitable environments are more extensive than previously assessed permafrost peatland extent in Northern Fennoscandia, Iceland, Labrador Peninsula and Seward Peninsula (Fig. 7). Comparison with the PEATMAP also indicate overestimations in Western Siberia and in Eastern Siberia (Fig. 7c). Possible underestimations are found across the Canadian Shield also, where, however, the underestimations mostly occurred beyond the strict climate space (Fig. 7). According to the suitable climate spaces and used peatland datasets the suitable peatlands for palsas and peat plateaus are limited in Central Siberia (Fig. 7). Most of the region's permafrost peatlands locate north of the suitable climate space.
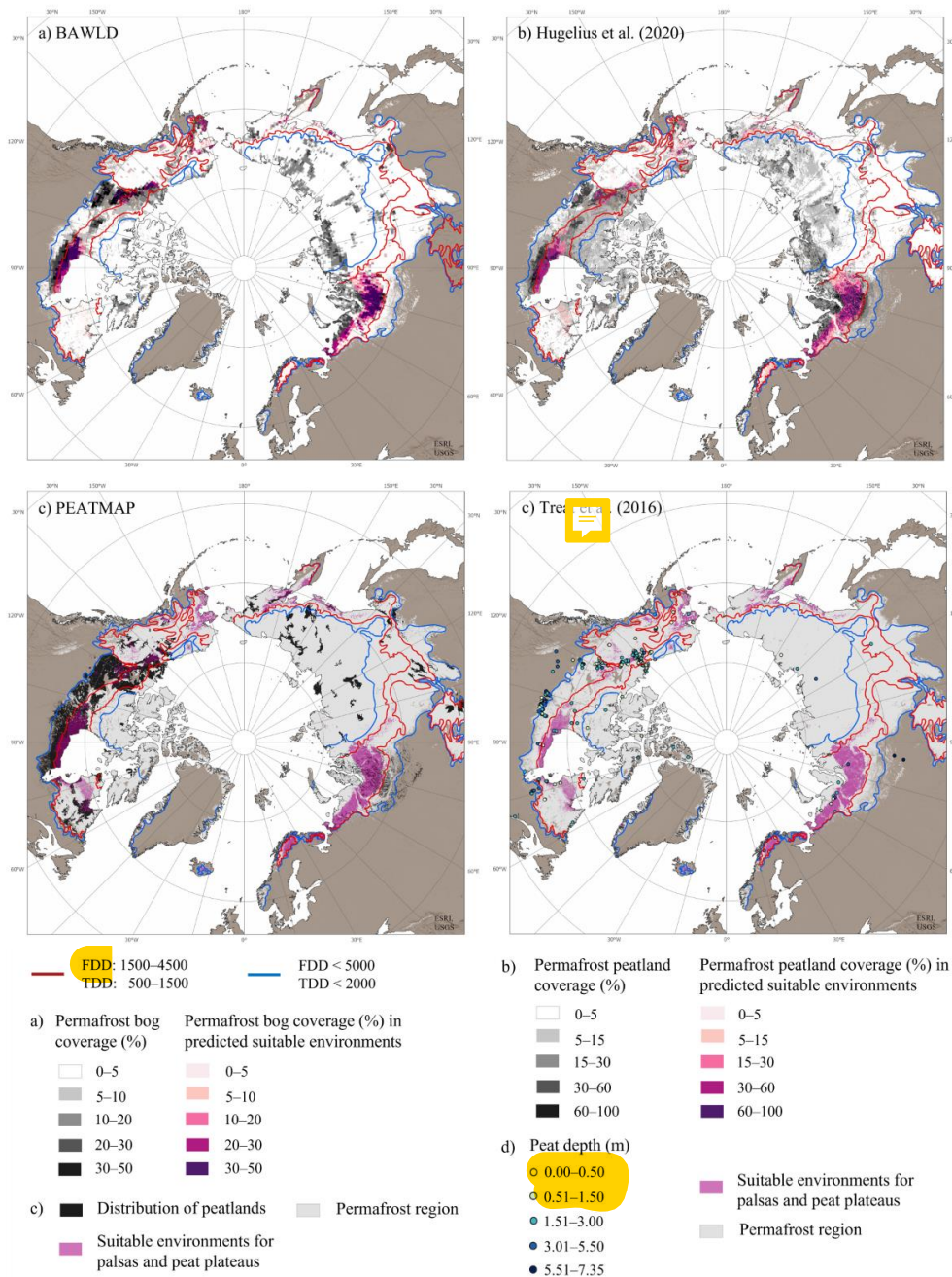
Figure 7: Comparison between the predicted suitable environmental spaces (for period 1950–2000), suitable climate spaces, and peatland datasets; (a) Permafrost bog coverage percent (0–50 %), in each grid cell according to the Boreal–Arctic Wetland and Lake Dataset (BAWLD; Olefeldt et al., 2021), (b) permafrost peatland coverage percent (0–100 %) (Hugelius et al., 2020), (c) distribution of peatlands according to PEATMAP (Xu et al., 2018), and (d) peat depth according to Treat et al. (2016b) in point symbols (yellow to blue scale). Permafrost regions are illustrated in light gray (Ran et al., 2022) and regions outside permafrost region with brown. The suitable environmental spaces are illustrated with pinkish colors, whereas areas outside our binary predictions are illustrated with grey scale. Two classification of suitable climate spaces are illustrated with red (a strict interpretation) and blue (a liberal interpretation) lines.

4 Discussion

Our models predicted drastic loss of suitable environments for palsas and peat plateaus, indicating almost complete loss of the landforms by 2080 according to the moderate and high emissions scenarios (RCP4.5 and RCP 8.5). 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 predicted the disappearance of suitable environments for the whole northern circumpolar permafrost region for the first time. The shrinkage of suitable environments continued in all used emissions scenarios (Table 1). This might indicate that even the strong climate change mitigation is not enough to slow the degradation of suitable palsa and peat plateau environments down. 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 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). The comparison with the peatland datasets (Fig. 7) indicated more extensive suitable environments especially in the Northern Fennoscandia, but this might have been caused by the coarse resolution of some of the peatland datasets (Fig. 7a–b), which did not allow for reproducing small-scale variation in sporadic permafrost in the region.

Our model extrapolations 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 (Fig. 2). This might indicate too dry and continental climate, conditions favoring other periglacial landforms, such as pingos and polygon mires (French, 2017), or too thin peat layers (Seppälä, 1988; Hugelius et al., 2020). Indeed, the comparison between peatland datasets and suitable climate spaces, showed that most of the peatlands of Central and Eastern Siberia are located north of the estimated suitable climate spaces (Fig. 7). Whatsoever, our models likely failed to recognize suitability of some of the relatively few peatlands inside the suitable climate space. It is possible that the limited distribution of suitable environments is caused by insufficient number of presence observations to characterize the possibly suitable environmental conditions for palsas and peat plateaus in the region (Fig. 1). However, based on the stricter suitable climate space the region for these

landforms is narrow, indicating that our extrapolations likely did not underestimate the distribution of suitable environmental spaces as much as one could expect based on the limited number of landform observations in the region.

415 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 spatially resolved 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 suitable environments in the coastal regions whereas Fewster et al. (2020) predicted them in more central parts. The contrasting results may be partly explained

420 by the inclusion of non-climatic variables to our models, and the substantially finer spatial resolution of our study, which both can facilitate the differentiation of environmental suitability at an improved accuracy. Comparison with peatland datasets show possible overprediction of suitable environments in North Slope and Seward Peninsula, for example. In Canada the most striking overprediction occurred in the Labrador Peninsula. However, a recent study from the region showed that previous studies have underestimated distribution of peatland permafrost along the coast of the peninsula (Wang

425 et al., 2022b).

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 thawing season conditions have a greater effect on the distribution of suitable environments for palsas and peat plateaus. Recent studies have similarly

430 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). According to these results, warmer and wetter summers might be most influential in accelerating the degradation of palsas and peat plateaus and decreasing the extent of the suitable environments in our future scenarios. In addition, thicker snowpack can

435 also lead to 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

440 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 also affect 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 suitable environments.

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. Moreover, not all palsas and peat plateaus are equal when comparing the rate of degradation. Landforms which are already imbalanced with the current climate (e.g., Olvmo et al., 2020) will degrade faster than landforms in equilibrium with climate (e.g., Tam et al., 2014). For these reasons we preferred to discuss about the distribution of suitable environments rather than claiming that our results would represent the actual distribution and degradation of the studied landforms. Despite the possible delayed or varying degradation rate between regions, our predictions can be used to estimate the forthcoming spatial changes in the distribution of the suitable environments.

It is important to note that most of palsas and peat plateaus were formed during the Little Ice Age (the 16th to mid-19th century period), in colder climates than we are currently facing (Halsey et al., 1995; Treat et al., 2016a; Vorren, 2017; Fewster et al., 2020). Because of this not all palsas and peat plateaus are in equilibrium with the current climate anymore. We did not model the historical distribution of suitable environments by using climate data from the landform initiation period, because it would have required historical data describing the other environmental factors also. Especially, the peat initiation data would have been necessary, and the compilation of the data for the whole pan-Arctic region was beyond the scope of this study. However, we acknowledged the role of past climates by choosing the 1950–2000 to be our baseline period as it was considered to better resemble the conditions of the period of palsa and peat plateau formation than the current climatology (e.g., 1991–2020; Seppälä, 2003; Saemundsson et al., 2012).

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).

Owing to the extensive study area with heterogeneous environmental conditions our aim was to compile as representative landform observation dataset as possible for model calibration. Due to this, no fully independent landform datasets were available for the evaluation of our models. This was however compensated in multiple ways. First, we divided the compiled landform observations into semi-independent calibration and evaluation datasets and performed evaluation both by the 100-fold cross-validation (with calibration dataset) and with the separate evaluation dataset (Fig. 6). Second, our predictions were compared with four peatland datasets (Treat et al., 2016b; Xu et al., 2018; Hugelius et al., 2020; Olefeldt et al., 2021) and suitable climate spaces to assess our predictions for the recent period (1950–2000) (Fig. 7). Third, our future predictions were compared to the independent thermokarst data (Olefeldt et al., 2016), to examine whether the degrading regions coincide with high thermokarst coverage. All these evaluations supported our predictions even in the regions with low number of landform observations. We recognize that our results for Central and Eastern Siberia are extrapolations of models fitted elsewhere as the landform observations from the region are scarce and this must be considered when interpreting the results. In addition, it is important to acknowledge the uncertainties related to statistical modelling itself (see e.g., Heikkinen et al., 2006; Hjort and Luoto, 2013). To overcome these methodological caveats, we used multiple modelling methods and quantified the prediction uncertainty.

To further develop the statistical models for the prediction of suitable environmental spaces for palsas and peat plateaus we would need more spatially resolved datasets describing the thickness of the snowpack and peat layer instead of the indirect snowfall and SOC variables. Incorporating variables describing, e.g., average wind conditions and vegetation structure could improve the performance of the models, but their applicability is hampered by the lack of suitable high-resolution data depicting future conditions. Although our study gave new insights into the distribution of suitable environments for palsas and peat plateaus in Central and Eastern Siberia, future research should focus on acquiring better knowledge of the current distribution of the landforms in these regions.

5 Conclusions

From the results of this study, we conclude that:

- 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 low and moderate emissions scenarios (RCP2.6 and 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.

- Further research on the distribution of the landforms is needed especially in Central and Eastern Siberia, for more reliably assessing their current state and potential future development.

- 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 in the suitable environmental spaces for palsas and peat plateaus should be taken into consideration when the estimating the pace and impacts of the climate change over northern regions.

525 **Appendix A**

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

Allards, M., and Seguin, M. K.: The Holocene evolution of permafrost near the tree line, on the eastern coast of Hudson Bay (northern Québec), Can. J. Earth Sci., 24, 2206–2222, https://doi.org/10.1139/e87-209, 1987.

530 An, W., and Allard, M.: A mathematical approach to modelling palsa formation: Insights on processes and growth conditions, Cold Reg. Sci. Tech., 23, 231–244, https://doi.org/10.1016/0165-232X(94)00015-P, 1995.

Arlen-Pouliot, Y., and Bhiry, N.: Palaeoecology of a palsa and a filled thermokarst pond in a permafrost peatland, subarctic Québec, Canada, Holocene 15:3, 408–419, https://doi.org/10.1191%2F0959683605hl818rp, 2005.

Backe, S.: Kartering av Sveriges palsmyrar, Länsstyrelsen, Luleå, 72 pp., urn:nbn:se:naturvardsverket:diva-2318, 2014.

535 Beilman, D. W., and Robinson, S. D.: Peatland permafrost thaw and landform type along a climatic gradient, in: Permafrost, edited by Philips, M., Springman S. M., and Arenson L. U., Swets & Zeitlinger, Lisse, 61–65, ISBN 90 5809 582 7, 2003.

Bhiry, N., and Robert, É.: Reconstruction of changes in vegetation and trofic conditions of a palsa in a permafrost peatland, subarctic Québec, Canada, Ecoscience, 13, 56–65, http://dx.doi.org/10.2980/1195-6860(2006)13[56:ROCIVA]2.0.CO;2, 2006.

540 Borge, A. F., Westermann, S., Solheim, I., and Etzelmüller, B.: Strong degradation of palsas and peat plateaus in northern Norway during the last 60 years, The Cryosphere, 11, 1–16, https://doi.org/10.5194/tc-11-1-2017, 2017.

Calmels, F., and Allard M.: Segregated Ice Structures in Various Heaved Permafrost Landforms Through CT scan, Earth Surf. Proc. Land., 33, 209–225, https://doi.org/10.1002/esp.1538, 2008.

Camill, P., Barry, A., Williams, E., Andreassi, C., Limmer J., and Solick, D.: Climate-vegetation-fire interactions and their 545 impact on long-term carbon dynamics in a boreal peatland landscape in northern Manitoba, Canada, J. Geophy. Res., 114, G04017, https://doi.org/10.1029/2009JG001071, 2009.

Christiansen, H. H., Etzelmüller, B., Isaksen, K., Juliussen, H., Farbrot, H., Humlum, O., Johansson, M., Ingeman-Nielsen, T., Kristensen, L., Hjort, J., Holmlund, P., Sannel, A. B. K., Sigsgaard, C., Foged, N., Blikra, L. H., Pernosky, M. A., Ødegård, R. S., and Åkerman, H. J.: The Thermal State of Permafrost in the Nordic Area during the International Polar Year 550 2007–2009, Permafrost Periglac., 21, 156–181, https://doi.org/10.1002/ppp.687, 2010.

Cyr, S., and Payette S.: The origin and structure of wooded permafrost mounds at the treeline in eastern Canada, Plant Ecol. Div., 3, 35–46, https://doi.org/10.1080/17550871003777176, 2010.

Dionne, J. C.: Formes et phénomènes périglaciaires en Jamésie, Québec subarctique, Géogr. Phys. Quartr., 32, 187–247, https://doi.org/10.7202/1000303ar, 1978.

555 Dionne, J. C., and Richard, P. J. H.: Origine, Age et taux d'accrétion verticale de la tourbiere palses de Blanc-Sablon, basse Cote-Nord, Golfe du Saint-Laurent, Québec, Géogr. Phys. Quartr., 60, 199–205, https://doi.org/10.7202/016829ar, 2006.

Dredge, L., and Mott J.: Holocone Pollen Records and Peatland Development, Northeastern Manitoba, Géogr. Phys. Quartr., 57, 7–19, https://doi.org/10.7202/010328ar, 2003.

Eisner, W. R., Hinkel, K. M., Nelson, F. E., and Bockheim, J. G.: Late-Quaternary paleoenvironmental record from a palsa-560 scale frost mound in northern Alaska, in: Permafrost, edited by Philips, M., Springman S. M., and Arenson L. U., Swets & Zeitlinger, Lisse, 299–234, ISBN 90 5809 582 7, 2003.

Ferbar, M.: Palsa development in Dovrefjell, southern Norwegian Mountains Breakdown in a warming climate, Master's Thesis, Department of Geosciences, University of Oslo, Norway, 2009.

Fewster, R. E., Morris, P. J., Swindles, G. T., Gregoire, L. J., Ivanovic, R. F., Valdes, P. J., and Mullan, D.: Drivers of 565 Holocene palsa distribution in North America, Quaternary Sci. Rev., 240, 106337, https://doi.org/10.1016/j.quascirev.2020.106337, 2020.

Fillion, M. E., Bihry, N., and Touazi, M.: Differential Development of Two Palsa Fields in a Peatland Located near Whapmagoostui-Kuujjuarapik, Northern Québec, Canada, Arct. Antarct. Alp. Res., 46, 40–5, https://doi.org/10.1657/1938-4246-46.1.40, 2014.

570 Glagolev, M., Kleptsova, I., Filippov, I., Maksyutov, S., and Machida, T.: Regional methane emission from West Siberia mire landscape. Environ. Res. Lett., 6, 045214, http://dx.doi.org/10.1088/1748-9326/6/4/045214, 2011.

Goncharova, O. Y., Matyshak Y. V., Bobrik, A. A., Moskalenko, N. G., and Ponomareva, O. E.: Temperature Regimes of Northern Taiga Soils in the Isolated Permafrost Zone of Western Siberia, Eurasian Soil Sci., 48, 1329–1340, https://doi.org/10.1134/S1064229315100038, 2015.

575 Göttlich, K., Hornburg, P., Köning, D., Schwaar, J., and Vorren, K.-D.: An examination of a palsa with layers of diatomite at Kautokeino, North Norway. Norsk. Geogr. Tidsskr., 37, 1–31, https://doi.org/10.1080/00291958308552086, 1983.

Holmquist, J. R., MacDonald, G. M., and Gallego-Sala, A.: Peatland initiation, carbon accumulation, and 2 ka depth in the James Bay Lowland and adjacent regions, Arct. Antarct. Alp. Res., 46, 19–39, https://doi.org/10.1657/1938-4246-46.1.19, 2014.

580   Hunt, S., Yu, Z., and Jones, M.: Lateglacial and Holocene climate, disturbance, and permafrost peatland dynamics on the Seward Peninsula, western Alaska, Quatr. Sci. Rev., 63, 42–58, https://doi.org/10.1016/j.quascirev.2012.11.019, 2013.

Jean, M., and Payette, S.: Effect of Vegetation Cover on the Ground Thermal Regime of Wooded and Non-Wooded Palsas, Permafrost Periglac., 25, 281–294, https://doi.org/10.1002/ppp.1817, 2014.

Jones, M. C., Harden, J., O'donnel, J., Manies, K., Jorgenson, T., Treat, C., and Ewing, S.: Rapid carbon loss and slow
585   recovery   following   permafrost   thaw   in   boreal   peatlands,   Glob.   Change   Biol.,   23,   1109–1127, https://doi.org/10.1111/gcb.13403, 2017.

Kanevskiy, M., Jorgenson, T., Shur, Y., O'Donnell, J. A., Harden, J. W., Zhuang, Q., and Fortier, D.: Cryostarigraphy and permafrost pvolution in the lacustrine lowlands of West-Central Alaska. Permafrost Periglac., 25, 14–34, https://doi.org/10.1002/ppp.1800, 2014.

590   Kaverin, D. A., Pastukhov, A. V., and Novakovsky, A. B.: Specifity of the present-day soil temperature regime in a peat plateau (southern part of Bolshezemelskaya tundra) at locations crossed by regional highway, Earth`s Cryosphere 24, 20–28, 2020.

Kirpotin, S., Polishchuk, Y., Bryksina, N., Sugaipova, A., Kouraev, A., Zakharova, E., Pokrovsky, O. S., Shirokova, L., Kolmakova, M., Manassypov, R., and Dupre, B.: West Siberian palsa peatlands: distribution, typology, cyclic development,
595   present day climate-driven changes, seasonal hydrology, and impact on CO2 cycle, Int. J. Environ. Stud., 68, 603–623, https://doi.org/10.1080/00207233.2011.593901, 2011

Kirpotin, S. N., Kvasnikova, Z. N., Potapova, S. A., Volkova, I. I., Volkov, I. V., Pyak, A. I., Byzaakay, A. A., Kolesnichenko, L. G., Lushchaeva, I. V., Khovalyg, A. O., Kuzhevskaia I. V. Chursin, V. V., and Peregon, A. M.: Pilot studies of the unique highland palsa mire in Western Sayan (Tuva Republic, Russian Federation), Atmosphere, 13,
600   https://doi.org/10.3390/atmos13010032, 2022.

Koronatova, N. G., Mironycheva-Tokareva, N. P., & Solomin, Y. R.: Thermal Regime of Peat Deposits of Palsas and Hollows of Peat Plateaus in Western Siberia, Earth's Cryosphere 24, 15–23, https://doi.org/10.21782/EC2541-9994-2018-6(15-23), 2018.

Kosykh, N., Koronatova, N. G., Naumova, N. B., and Titlyanova, A. A.: Above- and below-ground phytomass and net primary production in boreal mire ecosystems of Western Siberia, Wetlands Ecological Management, 16, 139–153, https://doi.org/10.1007/s11273-007-9061-7, 2008.

Kultti, S., Oksanen, P., and Väliranta, M.: Holocene tree line, permafrost, and climate dynamics in the Nenets Region, East European Arctic, Can. J. Earth Sci., 41, 1141–1158, https://doi.org/10.1139/e04-058, 2004.

Kettles, I. M., Robinson, S. D., Bastien, D.-F., Garneau, M., and Hall, G. E. M.: Physical, geochemical, macrofossil and ground penetrating radar information on fourteen permafrost-affected peatlands in the Mackenzie Valley, Northwest Territories, Natural Resources Canada, Geological Survey of Canada, Ottawa, https://doi.org/10.4095/214221, 2003.

Kuhry, P.: Palsa and peat plateau development in the Hudson Bay Lowlands, Canada: timing, pathways and causes, Boreas, 37, 316–327, https://doi.org/10.1111/j.1502-3885.2007.00022.x, 2008.

Lamarre, A., Garneau, M., and Asnong, H.: Holocene paleohydrological reconstruction and carbon accumulation of a permafrost peatland using testate amoeba and macrofossil analyses, Kuujjuarapik, subarctic Quebec, Canada, Rev. Palaeobot. Palyno., 186, 131–141, https://doi.org/10.1016/j.revpalbo.2012.04.009, 2012.

Langlais, K.: Dynamique holocéne d'une tourbiére á palses de la region du lac á l'Eau-Claire (Nunavik), Master's thesis, University of Laval, Quebec, Canasa, 68 p, 2016.

Lavoie, C., and Payette, S.: Analyse macrofossile d'une palse subarctique (Québec nordique), Can. J. Bot., 73, 527–537, https://doi.org/10.1139/b95-054, 1995.

Lewkowicz, A. G., and Coultish, T. L.: Beaver Damming and Palsa Dynamics in a Subarctic Mountainous Environment, Wolf Creek, Yukon Territory, Canada, Arct. Antarct. Alp. Res., 36, 208–218, http://dx.doi.org/10.1657/1523-0430(2004)036[0208:BDAPDI]2.0.CO;2, 2004.

Loiko, S. V., Pokrovsky, O. S., Raudina, T. V., Lim, A., Kolesnichenko, L. G., Shirokova, L. S., Vorobyev S. N., and Kirpotin, S. N.: Abrupt permafrost collapse enhances organic carbon, CO_2, nutrient, and metal release into surface waters, Chem. Geol., 47, 153–165, https://doi.org/10.1016/j.chemgeo.2017.10.002, 2017.

Lundqvist, G.: En palsmyr sydost om Kebnekaise. Geol. Forenings. Stock. For., 73, 209–225, https://doi.org/10.1080/11035895109453338, 1951.

Mamet, S. D., Chun, K. P., Kershaw, G. G. L., Loranty, M. M., and Peter Kershaw, G.: Recent Increases in Permafrost Thaw Rates and Areal Loss of Palsas in the Western Northwest Territories, Canada, Permafrost Periglac., 28, 619–633, https://doi.org/10.1002/ppp.1951, 2017.

Martin, L. C. P., Nitzbon, J., Aas, K. S., Etzelmüller, B., Kristiansen, H., and Westermann, S.: Stability Conditions of Peat Plateaus and Palsas in Northern Norway, J. Geophy. Res. Earth Sur., 124, 705–719, https://doi.org/10.1029/2018JF004945, 2019.

Matthews, J. A., Dahl, S.-O. O., Berrisford, M. S., and Nesje, A.: Cyclic development and thermokarstic degradation of palsas in the mid-alpine zone at Leirpullan, Dovrefjell, Southern Norway, Permafrost Periglac., 8, 107–122, https://doi.org/10.1002/(sici)1099-1530(199701)8:1<107::aid-ppp237>3.0.co;2-z, 1997.

Metsähallitus: Valtion suojelualueiden biotooppikuviot (Finnish dataset of biotopes), Metsähallitus, luontopalvelut, e3aa7b2a-e6e2-45dc-a29a-b64bcf2aba9f, 2019.

Nelson, F., Outcalt, S., Goodwin, C., and Hinkel, K.: Diurnal Thermal Regime in a Peat-Covered Palsa, Toolik Lake, Alaska, Arctic, 38, 310–315, 1985.

Oksanen, P. O., Kuhry, P., and Alekseeva, R. N.: Quaternaire Holocene Development and Permafrost History of the Usinsk Mire, Geogr. Phys. Quatr., 57, 169–187, https://doi.org/10.7202/011312ar, 2003.

Olvmo, M., Holmer, B., Thorsson, S., Reese, H., and Lindberg, F.: Sub-arctic palsa degradation and the role of climatic drivers in the largest coherent palsa mire complex in Sweden (Vissátvuopmi), 1955–2016, Sci. Rep.–UK., 10, 8937, https://doi.org/10.1038/s41598-020-65719-1, 2020.

Ottósson, J. G., Sveinsdóttir, A., and Harðardóttir, M.: Vistgerðirá Íslandi, Fjölrit Náttúrufræðistofnunar 54. Garðabær: NáttúrufræðistofnunÍslands (Habitat types in Iceland, Icelandic Institute of Natural History), ISBN 978-9979-9335-8-8, 2016.

Ou, C., Leblon, B., Zhang, Y., LaRocque, A., Webster, K., and McLaughlin, J.: Modelling and mapping permafrost at high spatial resolution using Landsat and Radarsat images in northern Ontario, Canada: part 1 – model calibration. Int. J. Remote Sens., 37, 2727–2750, https://doi.org/10.1080/01431161.2016.1157642, 2016.

Outcalt, S., and Nelson, F.: Computer simulations of buoyancy and snow-cover effects in palsa dynamics, Arct. Alp. Res., 16, 259–263, https://doi.org/10.1080/00040851.1984.12004413, 1984.

Patzner, M. S., Mueller, C. W., Malusova, M., Baur, M., Nikeleit, V., Scholten, T., Hoeschen, C., Byrne, J. M., Borch, T., Kappler, A., and Bryce, C.: Iron mineral dissolution releases iron and associated organic carbon during permafrost thaw, Nat. Commun., 11, 6329, https://doi.org/10.1038/s41467-020-20102-6, 2020.

Payette, S., Delwaide, A., Caccianiga, M., and Beauchemin, M.: Accelerated thawing of subarctic peatland permafrost over the last 50 years, Geophys. Res. Lett., 31, L18208, https://doi.org/10.1029/2004GL020358, 2004.

Pironkova, Z.: Mapping Palsa and Peat Plateau Changes in the Hudson Bay Lowlands, Canada, Using Historical Aerial Photography and High-Resolution Satellite Imagery, Can. J. Remote Sens., 43, 455–467, https://doi.org/10.1080/07038992.2017.1370366, 2017.

Plug, L. (2003). Ground-ice features and depth of peat across a mire chronosequence, NW Alaska, in: Permafrost, edited by Philips, M., Springman S. M., and Arenson L. U., Swets & Zeitlinger, Lisse, 901–906, ISBN 90 5809 582 7, 2003.

Points of Interest – Palsa MP 41, Alaska.org, https://www.alaska.org/detail/palsa-mp-41, last access: 08 May 2021.

Prater, J. L., Chanton, J. P., and Whiting, G. J.: Variation in methane production pathways associated with permafrost decomposition in collapse scar bogs of Alberta, Canada. Global Biogeo. Cyc., 21, GB4004, https://doi.org/10.1029/2006GB002866, 2007.

Railton, J. B., and Sparling, J. H.: Preliminary studies on the ecology of palsa mounds in northern Ontario, Can. J. Bot., 51, 1037–1044, https://doi.org/10.1139/b73-128, 1973.

Reger, R., Bundtzen, T., and Smith, T.: Geology of the Healy A-3 quadrangle, Alaska, Alaska Division of Geological & Geophysical Surveys Public-Data File 90-1, Fairbanks, Alaska, 13 p, 1990.

Robinson, S. D., and Moore, T. R.: The influence of permafrost and fire upon carbon accumulation in high boreal peatlands, Northwest Territories, Canada, Arct. Antarct. Alp. Res., 32, 155–166, https://doi.org/10.1080/15230430.2000.12003351, 2000.

Saemundsson, T., Arnalds, O., Kneisel, C., Jonsson, H. P., and Decaulne, A.: The Orravatnsrustir palsa site in Central Iceland-Palsas in an aeolian sedimentation environment, Geomorphology, 167–168, 13–20, https://doi.org/10.1016/j.geomorph.2012.03.014, 2012.

Sannel, B. K., and Kuhry, P.: Long-term stability of permafrost in subarctic peat plateaus, west-central Canada, The Holocene, 18, 589–601, https://doi.org/10.1177/0959683608089658, 2008.

Sannel, B. K., and Brown, I. A.: High-resolution remote sensing identification of thermokarst lake dynamics in a subarctic peat plateau complex, Can. J. Remote Sens., 36, S26–S40, https://doi.org/10.5589/m10-010, 2010.

Tam, A.: Permafrost in Canada's Subarctic Region of Northern Ontario, Master's thesis, Department of Geography, University of Toronto, Scarborough, Ontario, Canada, 2009.

Tam, A., Gough, W. A., Kowal, S., and Xie, C. (2014). The Fate of Hudson Bay Lowlands Palsas in a Changing Climate, Arct., Antarct. Alp. Res., 46, 114–120, https://doi.org/10.1657/1938-4246-46.1.114, 2014.

Tarnocai, C., and Bockheim, J. G.: Cryosolic soils of Canada: Genesis, distribution, and classification, Can. J. Soil Sci., 91, 749–762, https://doi.org/10.4141/cjss10020, 2011.

Terentieva, I. E., Glagolev, M. V., Lapshina, E. D., Faritovich Sabrekov, A., and Maksyutov, S.: Mapping of West Siberian taiga wetland complexes using Landsat imagery: implications for methane emissions, Biogeosciences, 13, 4615–462, https://doi.org/10.5194/bg-13-4615-2016, 2016.

Thibault, S., and Payette, S.: Recent Permafrost Degradation in Bogs of the James Bay Area Northern Quebec, Canada, Permafrost Periglac., 20, 383–389, https://doi.org/10.1002/ppp.660, 2009.

Throop, J., Lewkowicz, A. G., and Smith, S. L.: Climate and ground temperature relations at sites across the continuous and discontinuous permafrost zones, northern Canada, Can. J. Earth Sci., 49, 865–876, https://doi.org/10.1139/e11-075, 2012.

Treat, C. C., Wollheim, W. M., Varner, R. K., Grandy, A. S., Talbot, J., and Frolking, S.: Temperature and peat type control CO_2 and CH_4 production in Alaskan permafrost peats, Global Change Biol., 20, 2674–2686, https://doi.org/10.1111/gcb.12572, 2014.

Tsuyuzaki, S., Sawada, Y., Kushida, K., and Fukuda, M.: A preliminary report on the vegetation zonation of palsas in the Arctic National Wildlife Refuge, northern Alaska, USA, Ecol. Res., 23, 787–793, https://doi.org/10.1007/s11284-007-0437-1, 2008.

Vallée, S., and Payette, S.: Collapse of permafrost mounds along a subarctic river over the last 100 years (Northern Québec), Geomorphology, 90, 162–170, https://doi.org/10.1016/j.geomorph.2007.01.019, 2007.

Vasil'chuk Y. K., Vasil'chuk, A. C., Budantseva, N. A., Volkova, Y. M., Sulerzhitsky, L. D., Chizhova, J. N., and Jungner, H.: Radiocarbon age and Holocene dynamics of palsa in the Usa River valley, Doclady Earth Sciences, 384, 442–447, 2002.

Vasil'chuk, Y., Vasil'chuk, A. C., Sulerzhitskiim L. D., Budantseva N. A., Volkova, E. M., and Chizhova, J. N.: Radiocarbon chronology of palsen in the Bol'shaya Zemlya Tundra, Doklady Earth Sciences, 396, 1160–1164, 2003.

710 Vasil'chuk Y. K., Vasil'chuk, A. C., Budantseva, N. A., and Chizhova, J. N.: Palsas in the north of Western Siberia: the southern and northern limits of the areal and the modern dynamics, Eng. Geol., 3, 62–78, 2012.

Vasil'chuk, Y., Vasil'chuk, A. C., Jungner, H., Budantseva, N. A., Chizhova, J. N.: Radiocarbon chronology of Holocene palsa of Bol'shemel'skaya tundra in Russian North, Geography, Environment, Sustainability, 6, 38–59, https://doi.org/10.24057/2071-9388-2013-6-3-38-59, 2013.

715 Vasil'chuk, Y. K., Vasil'chuk, A. C., and Repkina, T. Y.: Palsas in the polar part of the Middle Siberia permafrost zone, Eng. Geol. 2, 28–45, 2013a.

Vasil'chuk, Y. K., Vasil'chuk, A. C., Budantseva, N. A., Yoshikawa, K., Chizhova, J. N., and Stanilovskaya, J. V.: Palsas in the southern part of the Middle Siberia permafrost zone, Eng. Geol. 3, 13–34, 2013b

Vasil'chuk, Y. K., Budantseva, N. A., Vasil'chuk, A. C., and Chizhova, J. N.: Palsas in the Eastern Siberia and Far East
720 permafrost zone, Eng. Geol., 1, 40–64, 2014.

Wang, Z., and Roulet, N.: Comparison of plant litter and peat decomposition changes with permafrost thaw in a subarctic peatland, Plant Soil 417, 197–216, https://doi.org/10.1007/s11104-017-3252-7, 2017.

Way, R. G., and Lewkowicz, A. G.: Environmental controls on ground temperature and permafrost in Labrador, northeast Canada, Permafrost Periglac., 29, 73–85, https://doi.org/10.1002/ppp.1972, 2018.

725 Way, R. G., Lewkowicz, A. G., and Zhang, Y.: Characteristics and fate of isolated permafrost patches in coastal Labrador, Canada, The Cryosphere 12, 2667–2688, https://doi.org/10.5194/tc-12-2667-2018, 2018.

White, S., Clark, G., and Rapp, A.: Palsa Localities in Padjelanta National Park, Swedish Lapland, Geogr. Ann., 51, 97–103, https://doi.org/10.1080/04353676.1969.11879793, 1969.

Yukon Geological Survey, Yukon Landform Atlas: https://open.yukon.ca/data/datasets/yukon-landform atlas, last access: 28
730 May 2021

Zhang, H., Amesbury, M. J., Ronkainen, T., Charman, D. J., Gallego-Sala, A. V., and Väliranta, M.: Testate amoeba as palaeohydrological indicators in the permafrost peatlands of north-east European Russia and Finnish Lapland, J. Quatr. Sci., 32, 976–988, https://doi.org/10.1002/jqs.2970, 2017.

Zoltai, S. C., R. M. Siltanen & J. D. Johnson: A wetland environmental data base, NOR-X Report, Northern Forestry Centre, Canadian Forest Service, Edmonton, Alberta, Canda, ISSN 0704-7673, 2000.

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. BAWLD - database (Olefeldt et al., 2021) is available at https://arcticdata.io/catalog/view/doi:10.18739/A2C824F9X, Hugelius et al. (2020) data at Bolin Centre for Climate (https://doi.org/10.17043/hugelius-2020-peatland-2), PEATMAP (Xu et al., 2018) at https://doi.org/10.5518/252, and Treat et al. (2016b) data at https://doi.org/10.1594/PANGAEA.863689. The coordinates of the landform observations compiled in this study are available in the supplementary materials. List of references used in the compilation is provided in Appendix A.

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

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References

760   Aalto, J., and Luoto, M.: Integrating climate and local factors for geomorphological distribution models, Earth Surf. Proc. Land., 39, 1729–1740, https://doi.org/10.1002/esp.3554, 2014.

Aalto, J., Venäläinen, A., Heikkinen, R. K., and Luoto, M.: Potential for extreme loss in high-latitude Earth surface processes due to climate change, Geophys. Res. Lett., 41, 3914–3924, https://doi.org/10.1002/2014GL060095, 2014.

Aalto, J., Harrison, S., and Luoto, M.: Statistical modelling predicts almost complete loss of major periglacial processes in
765   Northern Europe by 2100, Nat. Commun., 8, 1–8. https://doi.org/10.1038/s41467-017-00669-3, 2017.

Aalto, J., Karjalainen, O., Hjort, J., and Luoto, M.: Statistical forecasting of current and future circum-Arctic ground temperatures and active layer thickness, Geophys. Res. Lett., 45, 4889–4898, https://doi.org/10.1029/2018GL078007, 2018.

Allouche, O., Tsoar, A., Kadmon, R.: Assessing the accuracy of species distribution models: prevalence, kappa and true skill statistic (TSS), J. Appl. Ecol., 43, 1223–1232, https://doi.org/10.1111/j.1365-2664.2006.01214.x, 2006.

770   Araújo, M. B., Pearson, R. G., Thuiller, W., and Erhard, M.: Validation of species–climate impact models under climate change, Glob. Change Biol., 11, 1504–1513, https://doi.org/10.1111/J.1365-2486.2005.01000.X, 2005.

Åhman, R.: Palsar i Nordnorge: En studie av palsars morfologi, utbredning och klimatiska förutsättningar i Finnmarks och Troms fylke, Royal University of Lund, Department of Geography, 165 pp, 1977.

Backe, S.: Kartering av Sveriges palsmyrar, Länsstyrelsen, Luleå, 72 pp., urn:nbn:se:naturvardsverket:diva-2318, 2014.

775   Barcan, V.: Stability of palsa at the southern margin of its distribution on the Kola Peninsula, Polar Sci., 4, 489–495, https://doi.org/10.1016/j.polar.2010.07.002, 2010.

Beilman, D. W.: Plant community and diversity change due to localized permafrost dynamics in bogs of western Canada, Can. J. Bot., 79, 983–993, https://doi.org/10.1139/cjb-79-8-983, 2001.

Biskaborn, B. K., Smith, S. L., Noetzli, J., Matthes, H., Vieira, G., Streletskiy, D. A., Schoeneich, P., Romanovsky, V. E.,
780   Lewkowicz A. G., Abramov, A. Allard, M., Boike, J., Cable, W. L., Christiansen, H. H., Delaloye, R., Diekmann, B., Drozdov, D., Etzelmüller, B., Grosse, G., Guglielmin, M., Ingeman-Nielsen, T., Isaksen, K., Ishikawa, M., Johansson, M., Johansson, H., Joo, A., Kaverin, D., Kholodov, A., Konstantinov, P., Kröger, T., Lambiel, C., Lanckman, J. -P., Luo, D., Malkova, G., Meiklejohn, I., Moskalenko, N., Oliva, M., Phillips, M., Ramos, M., Sannel, B. A. K., Sergeev, D., Seybold, C., Skryabin, P., Vasiliev, A., Wu, Q., Yoshikawa, K., Zhelenznyak, M., and Lantuit, H.: Permafrost is warming at a global
785   scale, Nat. Commun., 10, 264, https://doi.org/10.1038/s41467-018-08240-4, 2019.

Böhner, J., and Selige, T.: Spatial prediction of soil attributes using terrain analysis and climate regionalization, SAGA - Analyses and Modelling Applications, Göttinger Geographische Abhandlungen 115, edited by: McCloy K., and Strobl, J., Goltze, 13–28, ISSN 0341-3780, 2006.

Borge, A. F., Westermann, S., Solheim, I., and Etzelmüller, B.: Strong degradation of palsas and peat plateaus in northern Norway during the last 60 years, The Cryosphere, 11, 1–16, https://doi.org/10.5194/tc-11-1-2017, 2017.

Breiman, L.: Random forests, Mach. Learn., 45, 5–32, https://doi.org/10.1023/A:1010933404324, 2001.

Brotons, L., Thuiller, W., Araújo, M. B., Brotons, A. H. H., Jo, A., Hirzel, M. B., and Thuiller, W.: Presence-absence versus presence-only modelling methods for predicting bird habitat suitability, Ecography, 27, 437–448. https://doi.org/10.1111/J.0906-7590.2004.03764.X, 2004.

Brown, J., O. J. Ferrians, Jr., J. A. Heginbottom, and E. S. Melnikov, eds.: Circum-Arctic map of permafrost and ground-ice conditions. Washington, DC: U.S. Geological Survey in Cooperation with the Circum-Pacific Council for Energy and Mineral Resources. Circum-Pacific Map Series CP-45, scale 1:10,000,000, 1 sheet, 1997.

CAFF: Arctic Flora and Fauna: Status and Conservation, Edita, Helsinki, Finland, 266 pp. ISBN 9979-9476-5-9, 2001.

Cisty, M., Celar, L., and Minaric, P. (2014). Ensemble modelling in soil hydrology, Proceedings of the International Multidisciplinary Scientific GeoConference SGEM, Albena, Bulgaria, 17–26 June 2014, 239–245, 2014

Danielson, J. J., and Gesch, D. B.: Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010), U.S. Geological Survey Open-File Report 2011–1073, 26 pp., 2011.

Elith, Jane, Ferrier, S., Huettmann, F., and Leathwick, J.: The evaluation strip: A new and robust method for plotting predicted responses from species distribution models, Ecol. Model., 186, 280–289. https://doi.org/10.1016/J.ECOLMODEL.2004.12.007, 2005.

Elith, Jane, H. Graham, C., P. Anderson, R., Dudík, M., Ferrier, S., Guisan, A., Hijimans, R. J., Huettmann, F., Leathwick, J. R., Lehmann, A., li, J., Lohmann, L. G., Loiselle, B. A., Manion, G., Moritz, C., Nakamura, M., Nakazawa, Y., Overton, J., McC., M., Peterson., T. A., Phillips, S. J., Richardson, K., Scachetti-Pereira, R., Schapire, R. E., Soberón, J., Eilliams, S., Misz, M. S., and E. Zimmermann, N.: Novel methods improve prediction of species' distributions from occurrence data, Ecography, 29, 129–151. https://doi.org/10.1111/J.2006.0906-7590.04596.X, 2006.

Elith, J., Leathwick, J. R., and Hastie, T.: A working guide to boosted regression trees, J. Anim. Ecol., 77, 802–813, https://doi.org/10.1111/j.1365-2656.2008.01390.x, 2008.

Fewster, R. E., Morris, P. J., Swindles, G. T., Gregoire, L. J., Ivanovic, R. F., Valdes, P. J., and Mullan, D.: Drivers of Holocene palsa distribution in North America, Quaternary Sci. Rev., 240, 106337, https://doi.org/10.1016/j.quascirev.2020.106337, 2020.

Fewster, R. E., Morris, P. J., Ivanovic, R. F., Swindles, G. T., Peregon, A. M., and Smith, C. J.: Imminent loss of climate space for permafrost peatlands in Europe and Western Siberia, Nat. Clim. Change, 1–7. https://doi.org/10.1038/s41558-022-01296-7, 2022.French, H. M.: The periglacial Environment, 4th edition, Wiley-Blackwell, Hoboken, 515 pp. LCCN 2017027903, 2017.

Fisher, A., Rudin, C., Dominici, F.: All models are wrong, but many are useful: Learning a variable's importance by studying an entire class of prediction models simultaneously, J. Mach. Learn. Res., 20, https://doi.org/10.48550/arXiv.1801.01489, 2019.

Fronzek, S., Luoto, M., and Carter, T.: Potential effect of climate change on the distribution of palsa mires in subarctic Fennoscandia, Clim. Res., 32, 1–12, https://doi.org/10.3354/cr032001, 2006.

Fronzek, S., Carter, T. R., and Luoto, M.: Evaluating sources of uncertainty in modelling the impact of probabilistic climate change on sub-arctic palsa mires, Nat. Hazard. Earth Sys., 11, 2981–2995, https://doi.org/10.5194/nhess-11-2981-2011, 2011.

Ge, Y., and Gong, G.: Land surface insulation response to snow depth variability, J. Geophys. Res.–Atmos., 115, D8, https://doi.org/10.1029/2009JD012798, 2010.

Goetz, S. J., MacK, M. C., Gurney, K. R., Randerson, J. T., and Houghton, R. A.: Ecosystem responses to recent climate change and fire disturbance at northern high latitudes: observations and model results contrasting northern Eurasia and North America. Environ, Res. Lett., 2, 045031, https://doi.org/10.1088/1748-9326/2/4/045031, 2007.

Halsey, L. A., Vitt, D. H., and Zoltai, S. C.: Disequilibrium response of permafrost in boreal continental western Canada to climate-change, Clim. Change, 30, 57–73, https://doi.org/10.1007/BF01093225, 1995.

Hastie, T., and Tibshirani, R.: Generalized Additive Models, Stat. Sci., 1, 297–318, 1986.

Heikkinen, R. K., Luoto, M., Araújo, M. B., Virkkala, R., Thuiller, W., and Sykes, M. T.: Methods and uncertainties in bioclimatic envelope modelling under climate change, Proc. Phys. Geogr., 6, 751–777, https://doi.org/10.1177/0309133306071957, 2006.

Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G., and Jarvis, A.: Very high-resolution interpolated climate surfaces for global land areas, Int. J. Climatol., 25, 1965–1978, https://doi.org/10.1002/joc.1276, 2005.

Hjort, J. and Marmion, M.: Effects of sample size on the accuracy of geomorphological models, Geomorphology, 102, 341–350, https://doi.org/10.1016/J.GEOMORPH.2008.04.006, 2008.

Hjort, J., and Luoto, M.: Statistical Methods for Geomorphic Distribution Modeling, Treatise on Geomorphology Vol. 2, edited by: Shroder, J. F. and Baas A. C. W., Academic Press, 59–73, https://doi.org/10.1016/B978-0-12-374739-6.00028-2, 2013.

Hjort, J., Streletskiy, D., Doré, G., Wu, Q., Bjella, K., and Luoto, M.: Impacts of permafrost degradation on infrastructure. Nature Reviews Earth & Environment, 3, 24–38, https://doi.org/10.1038/s43017-021-00247-8, 2022.

Hugelius, G., Loisel, J., Chadburn, S., Jackson, R. B., Jones, M., MacDonald, G., Marushchak, M., Olefeldt, D., Packalen, M., Siewert, M. B., Treat, C., Turetsky, M., Voight, C. and Yu, Z.: Large stocks of peatland carbon and nitrogen are vulnerable to permafrost thaw, P. Natl. A. Sci. USA., 117, 20438–20446, https://doi.org/10.1073/pnas.1916387117, 2020.

IPCC: Climate Change 2021: The Physical Science Basis, the Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Cambridge Press, Cambridge, United Kingdom and New York, USA, https://doi.org/10.1017/9781009157896, 2021.

Janssen, J. A. M., Rodwell, J. S., García Criado, M., Gubbay, S., Haynes, T., Nieto, A., Sanders, N., Landucci, F., Loidi, J., Ssymank, A., Tahvanainen, T., Valderrabano, M., Acosta, A., Aronsson, M., Arts, G., Attorre, F., Bergmeier, E., Bijlsma, R.-J., Bioret, F., Bita-Nicolae, C., Biurrun, I., Calix, M., Capelo, J., Carni, A., Dengler, J., Dimopoulos, P., Essl, F., Gardfjell, H., Gigante, D., Giusso del Galdo, G., Hájek, M., Jansen, J., Kapfer, J., Mickolajczak, A., Molina, J. A., Molnár, Z., Paternoster, D., Piernik, A., Poulin, B., Renaux, B., Schaminée, J. H. J., Sumberová, K., Toivonen, H., Tonteri, T., Tsiripidis, I., Tzonev, R. and Valachovic, M.: European Red List of Habitats. Part 2. Terrestrial and freshwater habitats European Red List of Habitats Environment, Europen Union, 38 pp., https://doi.org/10.2779/091372, 2016.

Järvinen, O., and Sammalisto, L.: Regional trends in the avifauna of Finnish peatland bogs, Ann. Zool. Fenn., 13, 31–43, 1976.

865   Johansson, M., Callaghan, T. v., Bosiö, J., Åkerman, J. H., Jackowicz-Korczynski, M., and Christensen, T. R.: Rapid responses of permafrost and vegetation to experimentally increased snow cover in sub-arctic Sweden, Environ. Res. Lett., 8, 035025, https://doi.org/10.1088/1748-9326/8/3/035025, 2013.

Johansson, T., Malmer, N., Crill, P. M., Friborg, T., Åkerman, J. H., Mastepanov, M., and Christiansen, T. R.: Decadal vegetation changes in a northern peatland, greenhouse gas fluxes and net radiative forcing, Global Change Biol., 12, 2352–
870   2369. https://doi.org/10.1111/j.1365-2486.2006.01267.x, 2006.

Karjalainen, O., Luoto, M., Aalto, J., and Hjort, J.: New insights into the environmental factors controlling the ground thermal regime across the Northern Hemisphere: A comparison between permafrost and non-permafrost areas, The Cryosphere, 13, 693–707, https://doi.org/10.5194/TC-13-693-2019, 2019.

Karjalainen, O., Luoto, M., Aalto, J., Etzelmüller, B., Grosse, G., Jones, B. M., Lilleøren, K., S. and Hjort, J.: High potential
875   for loss of permafrost landforms in a changing climate, Environ. Res. Lett., 15, 104065. https://doi.org/10.1088/1748-9326/abafd5, 2020.

Kershaw, G. P., and Gill, D.: Growth and decay of palsas and peat plateaus in the Macmillan Pass - Tsichu River area, Northwest Territories, Canada, Can. J. Earth Sci., 16, 1362–1374, https://doi.org/10.1139/e79-122, 1979.

Kirpotin, S., Polishchuk, Y., Bryksina, N., Sugaipova, A., Kouraev, A., Zakharova, E., Pokrovsky, O. S., Shirokova, L.,
880   Kolmakova, M., Manassypov, R., and Dupre, B.: West Siberian palsa peatlands: distribution, typology, cyclic development, present day climate-driven changes, seasonal hydrology, and impact on CO2 cycle, Int. J. Environ. Stud., 68, 603–623, https://doi.org/10.1080/00207233.2011.593901, 2011.

Kujala, K., Seppälä, M., and Holappa, T.: Physical properties of peat and palsa formation, Cold Reg. Sci. Technol., 52, 408–414. https://doi.org/10.1016/j.coldregions.2007.08.002, 2008.

885   Lagarec, D.: Cryogenetic mounds as indicators of permafrost conditions, northern Québec, in: Proceedings in Fourth Canadian Permafrost Conference, 43–48, 1982.

Liljedahl, A. K., Boike, J., Daanen, R. P., Fedorov, A. N., Frost, G. v., Grosse, G., Hinzman, L. D., Iijma, Y., Jorgenson, J. C., Matveyeva, N., Necsoiu, M., Raynolds, M. K., Romanovsky, V. E., Schulla, J., Tape, K. D., Walker, D. A., Wilson, C. J., Yabuki, H., and Zona, D.: Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology,
890   Nat. Geosci., 9, 312–318, https://doi.org/10.1038/ngeo2674, 2016.

Luoto, M., and Seppälä, M.: Thermokarst ponds as indicators of the former distribution of palsas in Finnish Lapland, Permafrost Periglac., 14, 19–2, https://doi.org/10.1002/PPP.441, 2003.

Luoto, M., Heikkinen, R., and Carter, T. R.: Loss of palsa mires in Europe and biological consequences, Environ. Conserv., 31, 30–37, https://doi.org/10.1017/S0376892904001018, 2004a.

895 Luoto, M., Fronzek, S., and Zuidhoff, F. S.: Spatial modelling of palsa mires in relation to climate in Northern Europe, Earth Surf. Proc. Land., 29, 1373–1387, https://doi.org/10.1002/esp.1099, 2004b.

Luoto, M., Marmion, M., and Hjort, J.: Assessing spatial uncertainty in predictive geomorphological mapping: A multi-modelling approach, Comput. Geosci., 36, 355–361. https://doi.org/10.1016/J.CAGEO.2009.07.008, 2010.

Magnan, G., Sanderson, N. K., Piilo, S., Pratte, S., Väliranta, M., van Bellen, S., Zhang, H., and Garneau, M.: Widespread
900 recent ecosystem state shifts in high-latitude peatlands of northeastern Canada and implications for carbon sequestration, Glob. Change Biol., 28, 1919–1934, https://doi.org/10.1111/GCB.16032, 2022.

Malmer, N., Johansson, T., Olsrud, M., and Christensen, T. R.: Vegetation, climatic changes, and net carbon sequestration in a North-Scandinavian subarctic mire over 30 years, Glob. Change Biol., 11, 1895–1909, https://doi.org/10.1111/j.1365-2486.2005.01042.x, 2005.

905 Mamet, S. D., Chun, K. P., Kershaw, G. G. L., Loranty, M. M., and Peter Kershaw, G.: Recent Increases in Permafrost Thaw Rates and Areal Loss of Palsas in the Western Northwest Territories, Canada, Permafrost Periglac., 28, 619–633, https://doi.org/10.1002/ppp.1951, 2017.

Markkula, I.: Permafrost dynamics structure species compositions of oribatid mite (Acari: Oribatida) communities in sub-Arctic palsa mires, Polar Res., 33, 22926, https://doi.org/10.3402/polar.v33.22926, 2014.

910 Marushchak, M., Pitkämäki, A., Koponen, H., Biasi, C., Seppälä, M., and Martikainen P. J.: Hot spots for nitrous oxide emissions found in different types of permafrost peatlands, Global Change Biol., 17, 2601–12614, https://doi.org/10.1111/j.1365-2486.2011.02442.x, 2011.

Matthews, J. A., Dahl, S.-O. O., Berrisford, M. S., and Nesje, A.: Cyclic development and thermokarstic degradation of palsas in the mid-alpine zone at Leirpullan, Dovrefjell, Southern Norway, Permafrost Periglac., 8, 107–122,
915 https://doi.org/10.1002/(sici)1099-1530(199701)8:1<107::aid-ppp237>3.0.co;2-z, 1997.

Mekonnen, Z. A., Riley, W. J., Grant, R. F., and Romanovsky, V. E.: Changes in precipitation and air temperature contribute comparably to permafrost degradation in a warmer climate, Environ. Res. Lett., 16, 024008, https://doi.org/10.1088/1748-9326/ABC444, 2021.

Metsähallitus: Valtion suojelualueiden biotooppikuviot (Finnish dataset of biotopes), Metsähallitus, luontopalvelut, 920   e3aa7b2a-e6e2-45dc-a29a-b64bcf2aba9f, 2019.

Miner, K. R., Turetsky, M. R., Malina, E., Bartsch, A., Tamminen, J., McGuire, A. D., Fix, A., Sweeney, C., Elder, C. D., and Miller, C. E.: Permafrost carbon emissions in a changing Arctic, Nature Reviews Earth and Environment, 3, 55–67, https://doi.org/10.1038/S43017-021-00230-3, 2022.

Mishra, U., Hugelius, G., Shelef, E., Yang, Y., Strauss, J., Lupachev, A., Harden, J. W., Jastrow, J. D., Ping, C. L., Riley, W. 925   J., Schuur, E. A. G., Matamala, R., Siewert, M., Nave, L. E., Koven, C. D., Fuchs, M., Palmtag, J., Kuhry, P., Treat, C. C., Zubrzycki, S., Hoffman, F. M., Elberling, B., Camill, P., Veremeeva, A., and Orr, A.: Spatial heterogeneity and environmental predictors of permafrost region soil organic carbon stocks, Science Advances, 7, 5236–5260, https://doi.org/10.1126/sciadv.aaz5236, 2021.

Muller, S. W.: Permafrost or Permanently Frozen Ground and Related Engineering Problems, Special report, Strategic 930   Engineering Study, 62, 136 pp., 1943.

Nelder, J. A., and Wedderburn, R. W. M.: Generalized Linear Models, J. R. Stat. Soc. Ser. A–G., 135, 370–384, https://doi.org/10.2307/2344614, 1972.

Normand, A. E., Smith, A. N., Clark, M. W., Long, J. R., and Reddy, K. R. (2017). Chemical Composition of Soil Organic Matter in a Subarctic Peatland: Influence of Shifting Vegetation Communities Soil Chemistry, Soil Sci. Soc. Am. J., 81, 41– 935   49, https://doi.org/10.2136/sssaj2016.05.0148, 2017.

Olefeldt, D., Goswami, S., Grosse, G., Hayes, D., Hugelius, G., Kuhry, P., Mcguire, A. D., Romanovsky, V. E., Sannel, A. B. K., Schuur, E. A. G., and Turetsky, M. R.: Circumpolar distribution and carbon storage of thermokarst landscapes, Nat. Commun., 7, 1–11, https://doi.org/10.1038/ncomms13043, 2016.

940

Olefeldt, D., Hovemyr, M., McKenzie, A. K., Bastviken, D., Bohn, T. J., Connolly, J., Crill, P., Euskirchen, E. S., Finkelstein, S. A., Genet, H., Grosse, G., Harris, L. I., Heffernan, L., Helbig, M., Hugelius, G., Hutchins, R., Juutinen, S., Lara, M. J., Malhotra, A., Manies, K., McGuire., D. A., Natali, S. M., O'Donnell, J. A., Parmentier, F.-J. W., Räsänen, A., Schädel, C., Sonnentag, O., Strack, M., Tank, S. E, Treat, C., Varner, R. K., Virtanen, T., Warren, R. K., and Watts, J. D.: The Boreal-Arctic Wetland and Lake Dataset (BAWLD), Earth Syst. Sci. Data, 13, 5127–5149, https://doi.org/10.5194/essd-13-5127-2021, 2021.

Olvmo, M., Holmer, B., Thorsson, S., Reese, H., and Lindberg, F.: Sub-arctic palsa degradation and the role of climatic drivers in the largest coherent palsa mire complex in Sweden (Vissátvuopmi), 1955–2016, Sci. Rep.–UK., 10, 8937, https://doi.org/10.1038/s41598-020-65719-1, 2020.

Ottósson, J. G., Sveinsdóttir, A., and Harðardóttir, M.: Vistgerðirá Íslandi, Fjölrit Náttúrufræðistofnunar 54. Garðabær: NáttúrufræðistofnunÍslands (Habitat types in Iceland, Icelandic Institute of Natural History), ISBN 978-9979-9335-8-8, 2016.

Parviainen, M., and Luoto, M.: Climate envelopes of mire complex types in Fennoscandia, Geogr. Ann. A., 89, 137–151, https://doi.org/10.1111/J.1468-0459.2007.00314.X, 2007.

Payette, S., Delwaide, A., Caccianiga, M., and Beauchemin, M.: Accelerated thawing of subarctic peatland permafrost over the last 50 years, Geophys. Res. Lett., 31, L18208, https://doi.org/10.1029/2004GL020358, 2004.

Peng, X., Zhang, T., Frauenfeld, O. W., Wang, K., Luo, D., Cao, B., Su, H., Jin, H., and Wu, Q.: Spatiotemporal Changes in Active Layer Thickness under Contemporary and Projected Climate in the Northern Hemisphere, J. Climate, 31, 251–266, https://doi.org/10.1175/JCLI-D-16-0721.1, 2018.

Pissart, A.: Palsas, lithalsas and remnants of these periglacial mounds. A progress report, Prog. Phys. Geog., 26(4), 605–621, https://doi.org/10.1191/0309133302pp354ra, 2002.

Poggio, L., de Sousa, L. M., Batjes, N. H., Heuvelink, G. B. M., Kempen, B., Ribeiro, E., and Rossiter, D.: SoilGrids 2.0: Producing soil information for the globe with quantified spatial uncertainty, Soil, 7, 217–240, https://doi.org/10.5194/SOIL-7-217-2021, 2021.

R Core Team: R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/, 2022.

Ran, Y., Li, X., Cheng, G., Che, J., Aalto, J., Karjalainen, O., Hjort, J., Luoto, M., Jin, H., Obu, J., Hori, M., Yu, Q., and Chang, X.: New high-resolution estimates of the permafrost thermal state and hydrothermal conditions over the Northern Hemisphere, Earth Syst. Sci. Data, 14, 865–884, https://doi.org/10.5194/ESSD-14-865-2022, 2022.

Rissanen, T., Niittynen, P., Soininen, J., and Luoto, M.: Snow information is required in subcontinental scale predictions of mountain plant distributions, Global Ecol. and Biogeogr., 30, 1502–1513, https://doi.org/10.1111/GEB.13315, 2021.

Roberts, D. R., Bahn, V., Ciuti, S., Boyce, M. S., Elith, J., Guillera-Arroita, G., Hauenstein, S., Lahoz-Monfort, J. J., Schröder, B., & Thuiller, W.: Cross-validation strategies for data with temporal, spatial, hierarchical, or phylogenetic structure. Ecography, 40, 913–929, https://doi.org/10.1111/ecog.02881, 2016.

Rudy, A. C. A., Lamoureux, S. F., Treitz, P., and van Ewijk, K. Y.: Transferability of regional permafrost disturbance susceptibility modelling using generalized linear and generalized additive models, Geomorphology, 264, 95–108, https://doi.org/10.1016/J.GEOMORPH.2016.04.011, 2016.

Ruuhijärvi, R., Salminen, P., and Tuominen, S.: Distribution range, morphological types, and state of palsa mires in Finland in the 2010s, Suo, 73, 1–32, ISSN 0039-5471, 2022.

Saemundsson, T., Arnalds, O., Kneisel, C., Jonsson, H. P., and Decaulne, A.: The Orravatnsrustir palsa site in Central Iceland-Palsas in an aeolian sedimentation environment, Geomorphology, 167–168, 13–20, https://doi.org/10.1016/j.geomorph.2012.03.014, 2012.

Sannel, A. B. K. (2020). Ground temperature and snow depth variability within a subarctic peat plateau landscape, Permafrost Periglac., 31, 255–263, https://doi.org/10.1002/ppp.2045, 2020.

Sannel, A. B. K., Hugelius, G., Jansson, P., and Kuhry, P.: Permafrost Warming in a Subarctic Peatland – Which Meteorological Controls are Most Important? Permafrost Periglac., 27, 177–188, https://doi.org/10.1002/PPP.1862, 2016.

Schuur, E. A. G., McGuire, A. D., Schädel, C., Grosse, G., Harden, J. W., Hayes, D. J., Hugelius, G., Koven, C. D., Kuhry, P., Lawrence, D. M., Natali, S. M., Olefeldt, D., Romanovsky, V. E., Schaefer, K., Turetsky, M. R., Treat, C. C., and Vonk, J. E.: Climate change and the permafrost carbon feedback, Nature, 520, 171–179, https://doi.org/10.1038/nature14338, 2015.

Schwarz, G. (1978). Estimating the Dimension of a Model, Ann. Stat., 6, 461–464, https://doi.org/10.1214/aos/1176344136, 1978.

Seppälä, M.: An experimental study of the formation of palsas, in: Proceedings of the Fourth Canadian Permafrost Conference, Calgary, Canada, 2–6 March 1981, 36–42, 1982.

Seppälä, M.: Palsas and Related Forms, in: Advances in periglacial geomorphology, edited by: Clark, M. J., John Wiley & Sons, Ltd, Chichester, 247–278, IBSN 0 471 90981 5, 1988.

Seppälä, M.: Depth of Snow and Frost on a Palsa Mire, Finnish Lapland, Geogr. Ann. A., 72, 191–201, https://doi.org/10.2307/521114, 1990.

Seppälä, M.: Snow depth controls palsa growth, Permafrost Periglac., 5, 283–288. https://doi.org/10.1002/PPP.3430050407, 1994.

Seppälä, M.: Surface abrasion of palsas by wind action in Finnish Lapland, Geomorphology, 52, 141–148, https://doi.org/10.1016/S0169-555X(02)00254-4, 2003.

Seppälä, M.: Palsa mires in Finland, The Finnish Environment, 23, 155–162, 2006.

Seppälä, M.: Synthesis of studies of palsa formation underlining the importance of local environmental and physical characteristics, Quaternary Res., 75, 366–370, https://doi.org/10.1016/j.yqres.2010.09.007, 2011.

Seppälä, M. and Hassinen, S.: Freeze-thaw indices in northernmost Fennoscandia according to meteorological observations, 1980–1991. In: Knutsson, S. (ed.). Ground Freezing 97: Frost action in soils, 153–160. A. A. Balkema, Rotterdam, ISBN 9789054108726, 1997.

Shangguan, W., Hengl, T., Mendes de Jesus, J., Yuan, H., and Dai, Y. Mapping the global depth to bedrock for land surface modeling, J. Adv. Model. Earth Sy., 9, 65–88, https://doi.org/10.1002/2016MS000686, 2017.

Siewert, M. B.: High-resolution digital mapping of soil organic carbon in permafrost terrain using machine learning: A case study in a sub-Arctic peatland environment, Biogeosciences, 15, 1663–1682, https://doi.org/10.5194/BG-15-1663-2018, 2018.

Silva, A. G., Guimarães, F. R., Almeida, S. M., Salvador, G. N., Malacco, G. B., and de Melo, C.: Conservation of the Black-collared Swallow, Pygochelidon melanoleuca (Wied, 1820) (Aves: Hirundinidae) in Brazil: potential negative impacts of hydropower plants, Biota Neotrop., 22, e20211305, https://doi.org/10.1590/1676-0611-BN-2021-1305, 2022.

Sim, T. G., Swindles, G. T., Morris, P. J., Baird, A. J., Cooper, C. L., Gallego-Sala, A. v., Charman, D. J., Roland, T. P., Borken, W., Mullan, D. J., Aquino-López, M. A., and Gałka, M.: Divergent responses of permafrost peatlands to recent climate change, Environ. Res. Lett., 16, 034001, https://doi.org/10.1088/1748-9326/ABE00B, 2021.

1020 Sollid, J. L., and Sørbel, L.: Palsa bogs as a climate indicator - Examples from Dovrefjell, southern Norway, Ambio, 27, 287–291, https://doi.org/10.2307/4314737, 1998.

Swindles, G. T., Morris, P. J., Mullan, D., Watson, E. J., Turner, T. E., Roland, T. P., Amesbury, M. J., Kokfelt, U., Schoning, K., Pratte, S., Gallego-Sala, A., Charman, D. J., Sanderson, N., Garneau, M., Carrivick, J. L., Woulds, C., Holden, J., Parry, L., and Galloway, J. M.: The long-term fate of permafrost peatlands under rapid climate warming, Sci. Rep.-UK.,
1025 5, 17951, https://doi.org/10.1038/srep17951, 2016.

Tam, A., Gough, W. A., Kowal, S., and Xie, C. (2014). The Fate of Hudson Bay Lowlands Palsas in a Changing Climate, Arct., Antarct. Alp. Res., 46, 114–120, https://doi.org/10.1657/1938-4246-46.1.114, 2014.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An Overview of CMIP5 and the Experiment Design, B. Am. Meteorol. Soc., 93, 485–498, https://doi.org/10.1175/BAMS-D-11-00094.1, 2012.

1030 Terentieva, I. E., Glagolev, M. V., Lapshina, E. D., Faritovich Sabrekov, A., and Maksyutov, S.: Mapping of West Siberian taiga wetland complexes using Landsat imagery: implications for methane emissions, Biogeosciences, 13, 4615–462, https://doi.org/10.5194/bg-13-4615-2016, 2016.

Thuiller, W., Lafourcade, B., and Araujo, M.: Presentation Manual for BIOMOD. University of Joseph Fourier, Grenoble, 35 pp., 2010.

1035 Thuiller, W., Lafourcade, B., Engler, R., and Araújo, M. B.: BIOMOD - a platform for ensemble forecasting of species distributions, Ecography, 32, 369–373, https://doi.org/10.1111/j.1600-0587.2008.05742.x, 2009.

Thuiller, W., Georges, D., Gueguen,M., Engler, R., Breiner, F.: Biomod2: Ensemble Platform for Species Distribution Modelling. CRAN, https://cran.r-project.org/web/packages/biomod2/biomod2.pdf, 2021.

Treat, C. C., Jones, M. C., Camill, A., Gallego-Sala, A., Garneau, M., Harden, J. W., Hugelius, G., Klein, E. S., Kokfelt, U.,
1040 Kuhry, P., Loisel, J., Mathijissen, P. J. H., O'Donnell, J. A., Oksanen, P. O., Ronkainen, T. M., Sannel, A. B. K., Talbot, J., Tarnocai, C., and Väliranta, M.: Effects of permafrost aggradation on peat properties as determined from a pan-Arctic synthesis of plant macrofossils, J. Geophys. Res. Biogeo.sci 121, 78–94, https://doi.org/10.1002/2015JG003061, 2016a.

1045 Treat, C. C., Jones, M. C, Camill, P., Gallego-Sala, A. V, Garneau, M., Harden, J. W., Hugelius, G., Klein, E. S., Kokfelt, U., Kuhry, P., Loisel, J., Mathijssen, P. J. H., O'Donnell, J. A., Oksanen, P. O., Ronkainen, T. M., Sannel, A. B. K., Talbot, J., Tarnocai, C., Väliranta, M.: Synthesis dataset of physical and ecosystem properties from pan-arctic wetland sites using peat core analysis. PANGAEA, https://doi.org/10.1594/PANGAEA.863697, 2016b.Turetsky, M. R., Abbott, B. W., Jones, M. C., Anthony, K. W., Olefeldt, D., Schuur, E. A. G., Grosse, G., Kuhry, P., Hugelius, G., Koven, C., Lawrence, D. M.,
1050 Gibson, C., Sannel, A. B. K., and McGuire, A. D.: Carbon release through abrupt permafrost thaw, Nature Geosci., 13, 138–143, https://doi.org/10.1038/s41561-019-0526-0, 2020.

Vasil'chuk, Y. K., Vasil'chuk, A. C., and Repkina, T. Y.: Palsas in the polar part of the Middle Siberia permafrost zone, Eng. Geol. 2, 28–45, 2013a.

Vasil'chuk, Y. K., Vasil'chuk, A. C., Budantseva, N. A., Yoshikawa, K., Chizhova, J. N., and Stanilovskaya, J. V.: Palsas in
1055 the southern part of the Middle Siberia permafrost zone, Eng. Geol. 3, 13–34, 2013b.

Vasil'chuk, Y. K., Budantseva, N. A., Vasil'chuk, A. C., and Chizhova, J. N.: Palsas in the Eastern Siberia and Far East permafrost zone, Eng. Geol., 1, 40–64, 2014.

Vorren, K.-D.: The first permafrost cycle in Faerdesmyra, Norsk. Geogr. Tidsskr, 71, 114–121, https://doi.org/10.1080/00291951.2017.1316309, 2017.

1060 Wang, X., Ran, Y., Pang, G., Chen, D., Su, B., Chen, R., Li, X., Chen, H. W., Yang, M., Gou, X., Jorgenson, M. T., Aalto, J., Li, R., Peng, X., Wu, T., Clow, G. D., Wan, G., Wu, X., and Luo, D.: Contrasting characteristics, changes, and linkages of permafrost between the Arctic and the Third Pole, Earth-Sci. Rev., 230, 104042, https://doi.org/10.1016/J.EARSCIREV.2022.104042, 2022a.

Wang, Y., Way, R. G., Beer, J., Forget, A., Tutton, R., and Purcell, M. C.: Significant underestimation of peatland
1065 permafrost along the Labrador Sea coastline, The Cryosphere, https://doi.org/10.5194/tc-2022-38, 2022b (in review).

Washburn, A. L.: What is a palsa? in: Matematisch-Physikalische Klasse, Dritte folge, Mesoformen des reliefs im heutigen Periglazialraum, Berich über ein Symposium, 35, edited by: Poser, H. and Schunke, E., Vandenhoeck & Ruprecht, Göttingen, 34–47, 1983.

Xu, J., Morris, P. J., Liu, J., and Holden, J.: PEATMAP: Refining estimates of global peatland distribution based on meta-
1070 analysis, CATENA, 160,134–140, https://doi.org/10.1016/j.catena.2017.09.010, 2018.

You, Q., Cai, Z., Pepin, N., Chen, D., Ahrens, B., Jiang, Z., Wu, F., Kang, S., Zhang, R., Wu, T., Wang, P., Li, M., Zuo, Z., Gao, Y., Zhai, P., and Zhang, Y.: Warming amplification over the Arctic Pole and Third Pole: Trends, mechanisms, and consequences, Earth-Sci. Rev., 217, 103625, https://doi.org/10.1016/j.earscirev.2021.103625, 2021.

Zhao, D.-M., Jiao, Y.-M., Wang, J.-L., Liu, Z.-L., Qiu, Y.-M., and Zhang, J.: Comparative performance assessment of landslide susceptibility models with presence-only, presence-absence, and pseudo-absence data, J. Mi Sci., 17, 2961–2981, https://doi.org/10.1007/s11629-020-6277-y, 2020.

Zoltai, S. C.: Palsas and Peat Plateaus in Central Manitoba and Saskatchewan, Can. J. Forest Res., 2, 291–301, https://doi.org/10.1139/x72-046, 1972.

Zoltai, S. C., & Tarnocai, C.: Properties of A Wooded Palsa in Northern Manitoba, Arct. Alp. Res., 3, 115–129, https://doi.org/10.1080/00040851.1971.12003602, 1971.

Zoltai, S. C., & Tarnocai, C.: Perennially Frozen Peatlands in the Western Arctic and Subarctic of Canada, Can. J. Earth Sci., 12, 28–43, https://doi.org/10.1139/e75-004, 1975.

Zoltai, S. C., Siltanen, R. M., and Johnson, J. D.: A wetland data base for the western boreal, subarctic, and arctic regions of Canada, Northern Forestry Centre, Canadian Forest Service, Edmonton, 30 pp, ISBN: 0662285395, 2000.