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

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

1 Introduction

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

30   a greater extent, even over one square kilometer, but are elevated from their surroundings by only about one meter (Kershaw and Gill, 1979; Zoltai, 1972).

Permafrost peatlands, such as palsa mires and peat plateaus, are widespread, and according to Hugelius et al. (2020) nearly half of the peatlands of the Northern Hemisphere contain permafrost. Previous studies have shown that most palsas were formed in much colder climate than present (Vorren, 2017; Fewster et al., 2020). Palsas and peat plateaus are highly
35   sensitive to further changes in climate, and many studies have reported rapid degradation of palsas (e.g., Borge et al., 2017; Mamet et al., 2017; Olvmo et al., 2020). As the permafrost thaws from peatlands, changes in the greenhouse gas fluxes are expected (Turetsky et al., 2020; Miner et al., 2022). Increasing CO_2, CH_4 and N_2O -emissions further accelerate the climate change (Marushchak et al., 2011; Schuur et al., 2015; Hugelius et al., 2020).

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

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

In this study, we provide the first predictions of suitable environmental spaces for palsas over the entire Northern
60   circumpolar region. As the explored landforms are not found from the Southern Hemisphere (Seppälä, 2011), this study

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

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

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

2 Materials and methods

2.1 Palsa and peat plateau observations

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

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

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

95   same person (Könönen) collected and validated both presence and absence datasets.

Compiled data were further split into model calibration (N = 2057), and evaluation (N = 400) sets. These sample sizes are expected to be large enough to give robust predictions in geomorphological distribution modelling (see Hjort and Marmion, 2008). The separate evaluation dataset was formed by taking a random sample from the whole data. The random sample was taken separately from presence and absence observations, to retain the same relative portion (i.e., prevalence) with the

100 original dataset (ca. 40 % presence, and 60 % absence observations) (Hjort and Luoto, 2013). Observations in the evaluation were selected so that they located at least 50 km from each other. Because of this criteria, two absence observations had to be removed from the evaluation data, as they located too close (< 50 km) to presence observations (final N = 398).
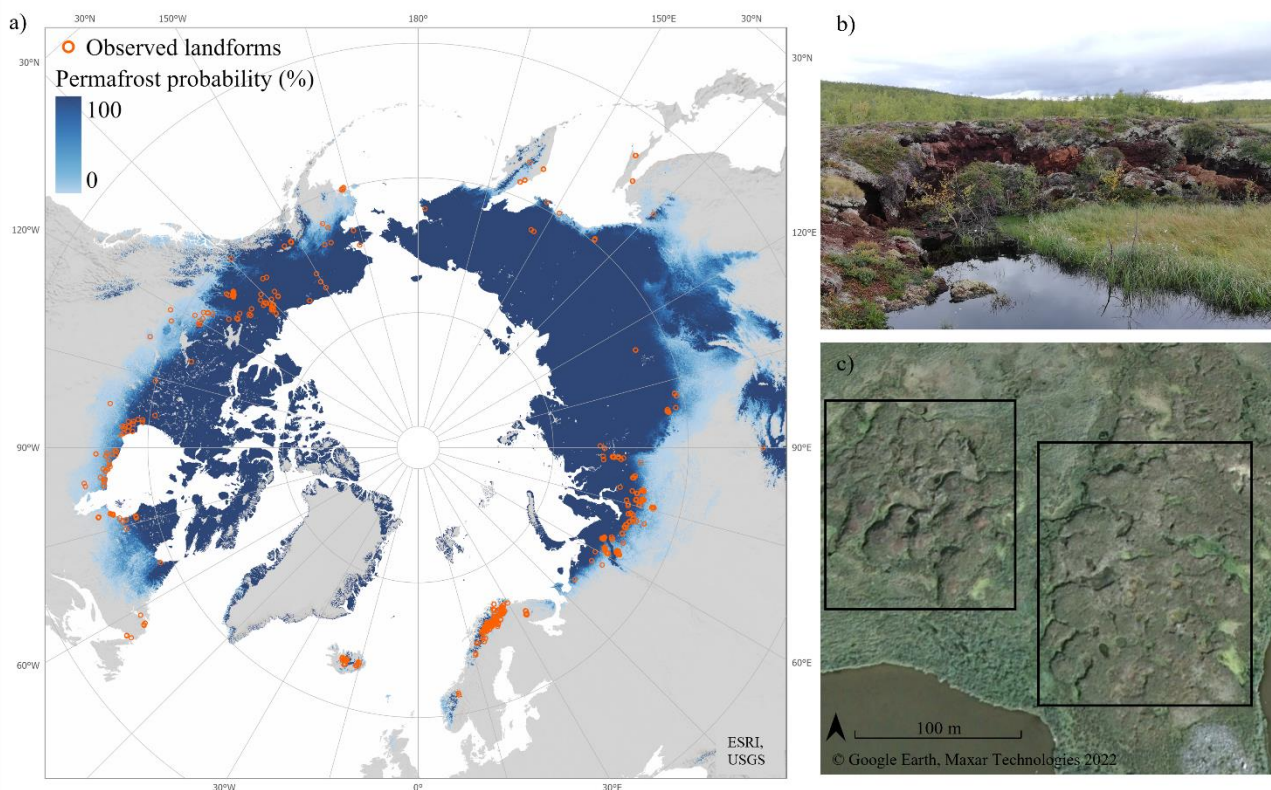
Figure 1: Distribution of the observed palsas and peat plateaus (N = 961) across the Northern Hemisphere and the probability of
105 **the permafrost occurrence (%, Ran et al., 2022) (a). A thawing palsa in Kilpisjärvi, Finland (b), and satellite image of a palsa mire in Kiruna, Sweden (68°28'N, 20°55'E), groups of palsas have been framed with black lines (c).**

2.2 Environmental data

In this study, we used various geospatial datasets at a 30 arc-second (ca. 1 km) spatial resolution to describe the climatological conditions, soil properties, and topographical variation relevant to palsa mires and peat plateaus. Freezing and
110 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
115 sum of precipitation for months with average air temperature below 0 °C and rainfall for months with average air temperature over 0 °C (Aalto et al., 2018).

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

Variables to describe the surficial soil conditions (≤ 2 m depth) were obtained from SoilGrids250m 2.0 database (Poggio et al., 2021). Owing to the lack of high-resolution peat data we used soil organic carbon content (SOC, g kg^{-1}) to estimate it. In
125 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
130 environmental variable was available at presence or absence location (109 cases), the value was extracted from the neighboring grid cell. If none of the neighboring grid cells had the missing value, the observation was removed from the dataset.

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

2.3 Statistical modelling

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

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

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

The predicted probability surfaces for suitable environments were finally classified to binary distribution maps. The
classification was performed by the true skill statistic (TSS) cut-off values that were estimated during each model run. From
165 these cut-off values (100 model runs per method) the average cut-off value was computed and used for classification. Used
cut-off values are presented in the supplements (Table S1). Binary maps were utilized when we calculated the areas of
suitable environments. Average variable importance (VI) values (Breiman, 2001; Fisher et al., 2019) were calculated from
the results of 100 modeling runs. In VI computation, the values of one variable in its turn are shuffled (i.e., a random sample

is drawn from the values recorded at the modelling data grid cells) while the other variables are fixed to their mean values.
170   Then, model predictions are produced by using these variables. Finally, VI is derived from the Pearson correlation between the predictions from the initial models (all variables having their recorded values) and from the models including the shuffled variable with the following Eq. (1) (Thuiller et al, 2009):

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

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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
180   and the remaining 30 % (N = 617) was used to validate them. Secondly, independent evaluation was conducted by using the separate evaluation data (N = 398), which was set aside before model calibration (as described in the section 2.1). Performance of the models was evaluated with two prevalence-independent statistical measures of classification accuracy, area under the receiving operating characteristic curve (AUC) and TSS (Allouche et al., 2006). Model reliability was also evaluated spatially by exploring the modelling agreement between four independent modelling methods (Luoto et al., 2010).
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3 Results

3.1 Suitable environments in recent conditions

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

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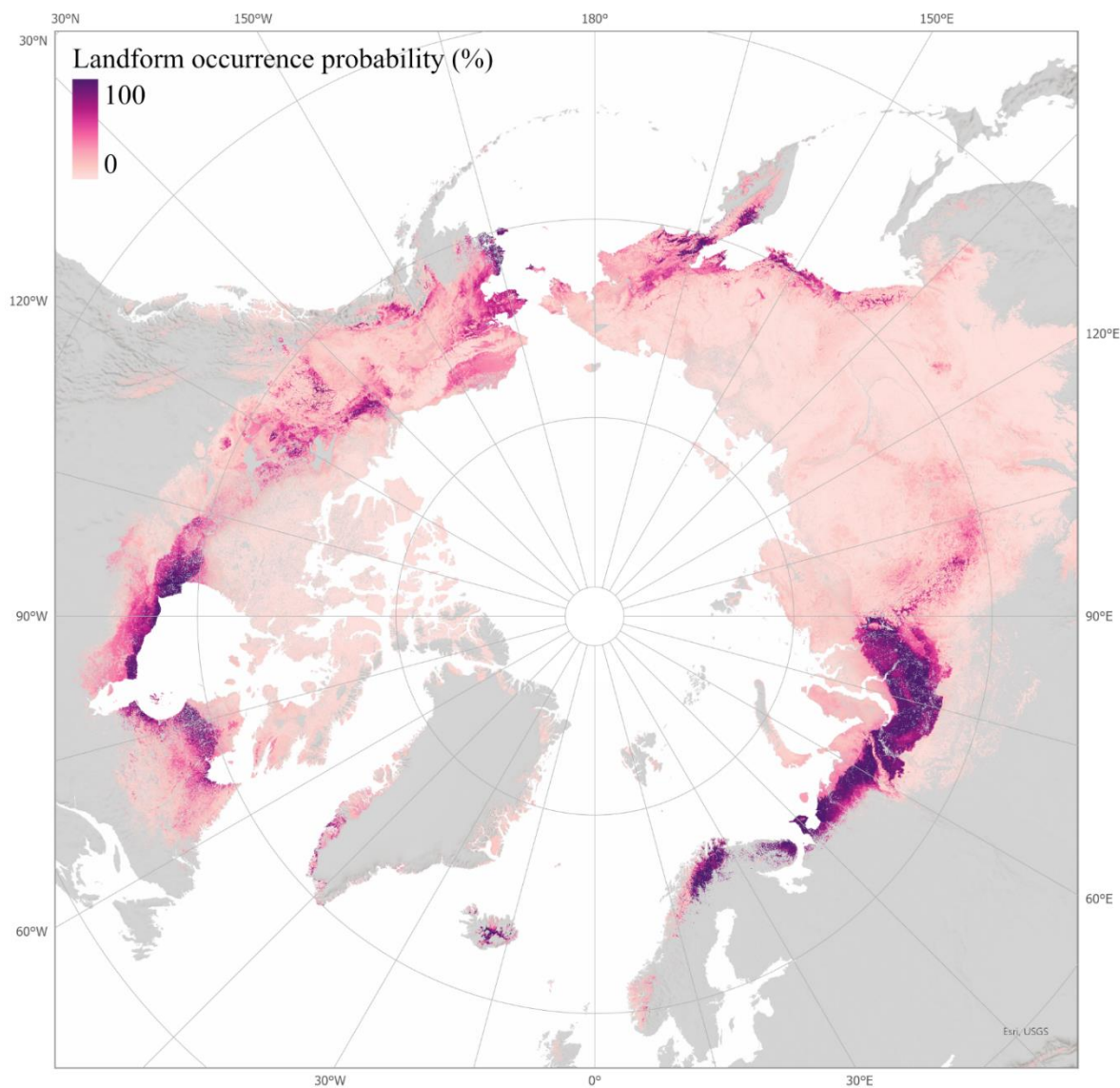
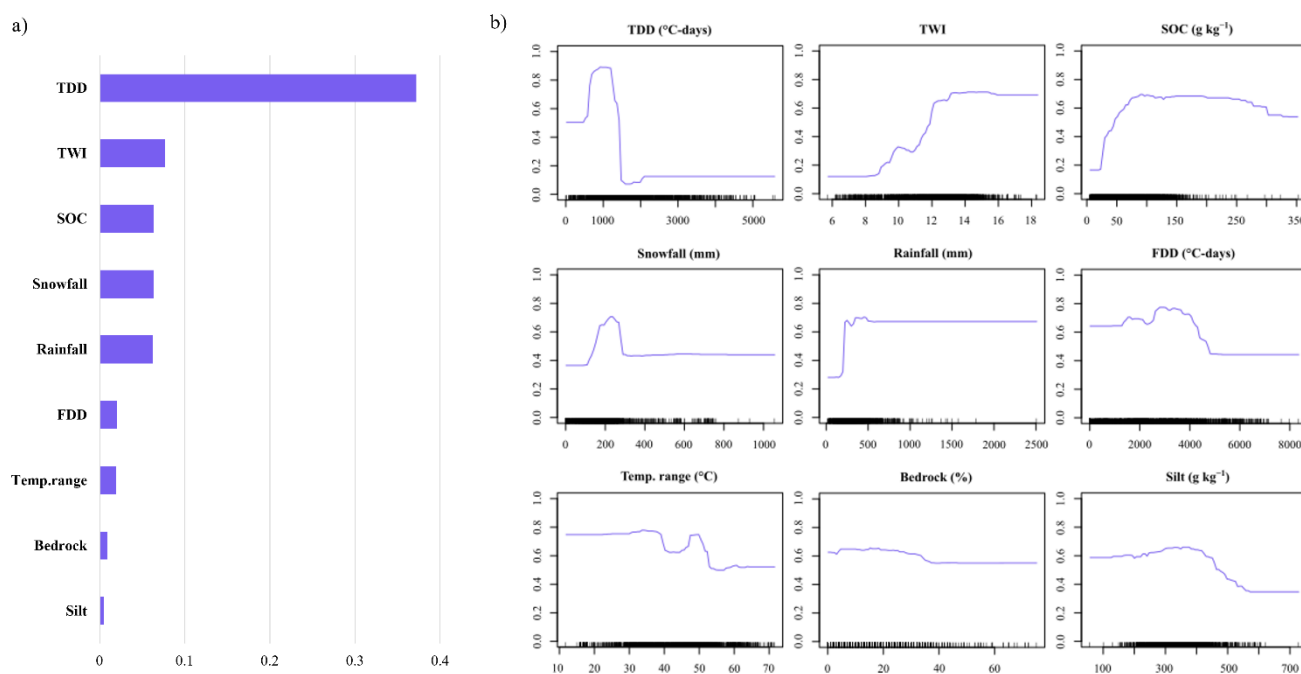


Figure 2: The probability (%) for palsa and peat plateau occurrence illustrated with a color gradient from light pink to dark purple, grey color illustrates areas outside the permafrost region and glaciers. Results of the random forest model are provided for the permafrost region (Ran et al., 2022).

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

The response curve of TDD shows the optimal summer air temperatures to be around 1000 °C-days, with a steep drop in the probability of occurrence beyond ~1250 °C-days (Fig. 3b). The response of TWI shows a higher occurrence probability with higher values, indicating that palsas and peat plateaus are most likely found from flat or gently sloping basin environments with abundant soil moisture. RF model shows the highest probabilities for regions with a SOC content of over 70 g kg^{-1}. The

210 snowfall variable shows also a clear optimum environmental space for the landforms around 200 mm, whereas the pattern is not equally clear for the rainfall (Fig. 3b). Response curves for all used modelling methods are provided in the supplementary material (Fig. S4).

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

3.2 Future changes in the circumpolar suitable environments

Our results suggest a dramatic loss of suitable environments for palsas and peat plateaus already by the mid of the 21st

220 century (Table 1.; Table S2 in supplements). The high-emission scenario RCP8.5 predicted even larger losses by the period 2041–2060, than the moderate-emissions scenario RCP4.5 predicted by the second period 2061–2080. RCP8.5 scenario for 2061–2080 showed almost complete loss (-98,2 %) of recently suitable environments (Table 1e).

225 **Table 1: Suitable environmental spaces (in km²) for palsas and peat plateaus at different time periods and RCP climate change scenarios in Nordic countries (a), Western Siberia (b), Central and Eastern Siberia (c), North America (d), and entire circumpolar permafrost region (e). Areal percentage changes are given in relation to the modelled area for the period 1950–2000. Results are based on random forest modelling.**

	Suitable area (km²)	Percentage change (%)
a) Nordic countries		
1950–2000	77 540	
RCP4.5 2041–2060	17 120	–77.9
RCP4.5 2061–2080	12 140	–84.3
RCP8.5 2041–2060	11 890	–84.7
RCP8.5 2061–2080	5 600	–92.8
b) Western Siberia		
1950–2000	562 750	
RCP4.5 2041–2060	48 270	–91.4
RCP4.5 2061–2080	14 930	–97.3
RCP8.5 2041–2060	10 110	–98.2
RCP8.5 2061–2080	10	–99.9
c) Central and Eastern Siberia		
1950–2000	305 580	
RCP4.5 2041–2060	62 550	–79.5
RCP4.5 2061–2080	30 350	–90.1
RCP8.5 2041–2060	25 140	–91.8
RCP8.5 2061–2080	1 070	–99.6
d) North America		
1950–2000	640 070	
RCP4.5 2041–2060	167 430	–73.8
RCP4.5 2061–2080	111 450	–82.6
RCP8.5 2041–2060	104 310	–83.7
RCP8.5 2061–2080	21 570	–96.6
e) Permafrost region		
1950–2000	1 587 360	
RCP4.5 2041–2060	296 110	–81.4
RCP4.5 2061–2080	169 460	–89.3
RCP8.5 2041–2060	151 990	–90.4
RCP8.5 2061–2080	28 590	–98.2

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According to our results, the suitable environments for palsas and peat plateaus will disappear almost all around the Northern Hemisphere even under the moderate climate change scenarios (Table 1; Fig. 4a). The suitable environments would disappear almost completely from Northern Fennoscandia, West Siberia, coasts of Hudson Bay, western Alaska, and eastern
235 Siberia already by the period 2041–2060. Only in Iceland and Greenland, the modelled palsa and peat plateau environments seemed to persist without major distributional changes. In addition to these regions, the suitable environments could remain in North America in the Northwest Territories, northern Quebec, and Alaska during the period 2061–2080. In Russia, palsas and peat plateaus could be found mainly from the Yamal Nenets Autonomous Okrug and Turukhansky district (Table 1b–c; Fig. 4a). The predictions based on the RCP8.5 scenario for period 2041–2060 present similar distribution of suitable
240 environmental spaces, compared with the RCP4.5 scenario for 2061–2080 (Fig. 4a–b). Only 1.8 % of the recently suitable environments would persist under RCP8.5 scenario in the period 2061–2080 (Table 1).
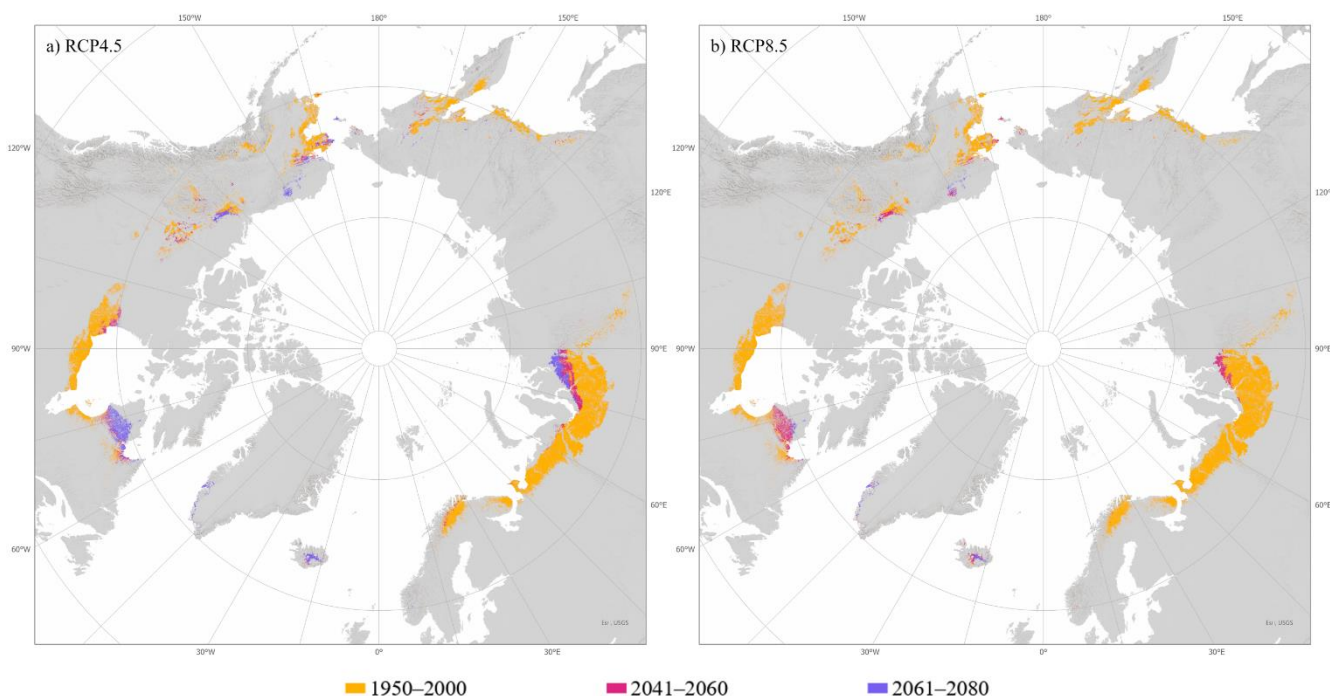
Figure 4: Predicted distributions of suitable environmental spaces for palsas and peat plateaus for different time periods under
245 **moderate (a) and high emissions (b) Representative Concentration Pathway climate change scenarios (RCP4.5 and RCP8.5).**
Modelling results are presented for periods 1950–2000, 2041–2060 and 2061–2080. RF model results are provided for the
permafrost region (Ran et al., 2022) and for the future periods for the extent of the period 1950–2000.

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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
255 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).

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

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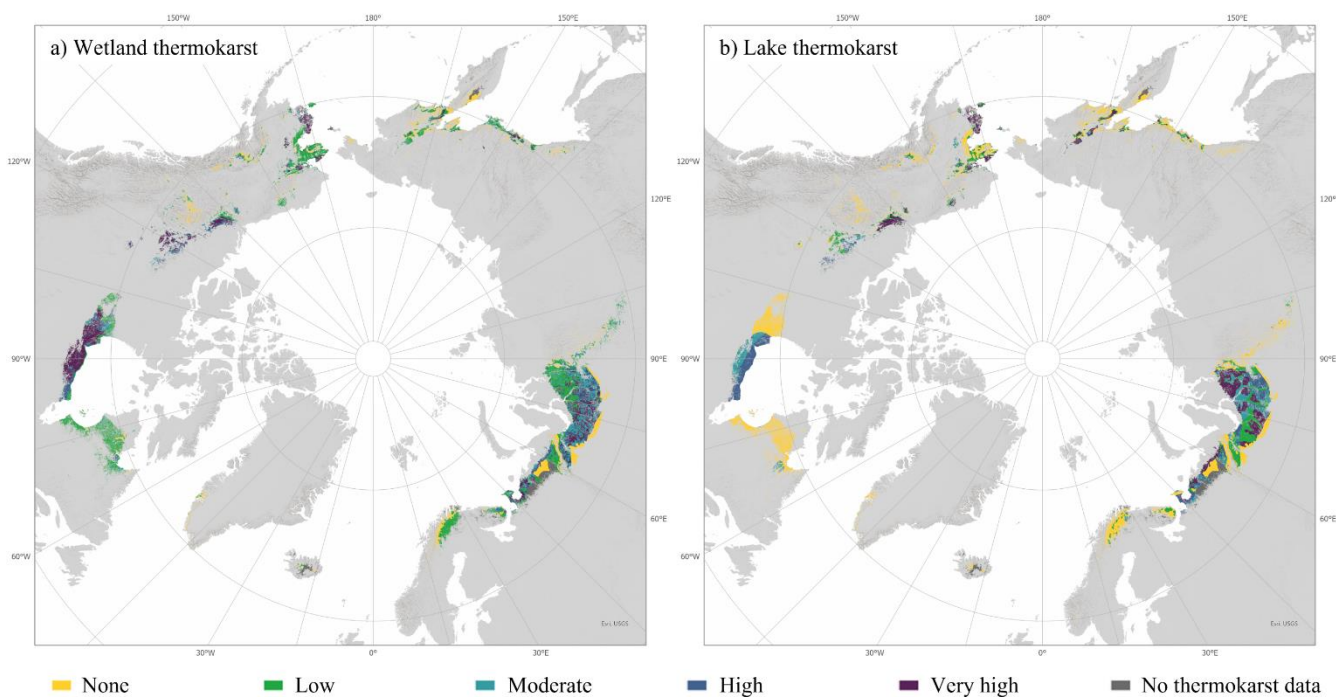
Figure 5: Suitable environmental spaces for palsas and peat plateaus (for period 1950–2000) against thermokarst classification by Olefeldt et al. (2016). Wetland (a) and lake (b) thermokarst coverages range from none (yellow) to very high (dark violet). Dark grey illustrates regions for which the thermokarst 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
270 **region (Ran et al., 2022).**

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

3.4 Statistical and spatial evaluation of the models

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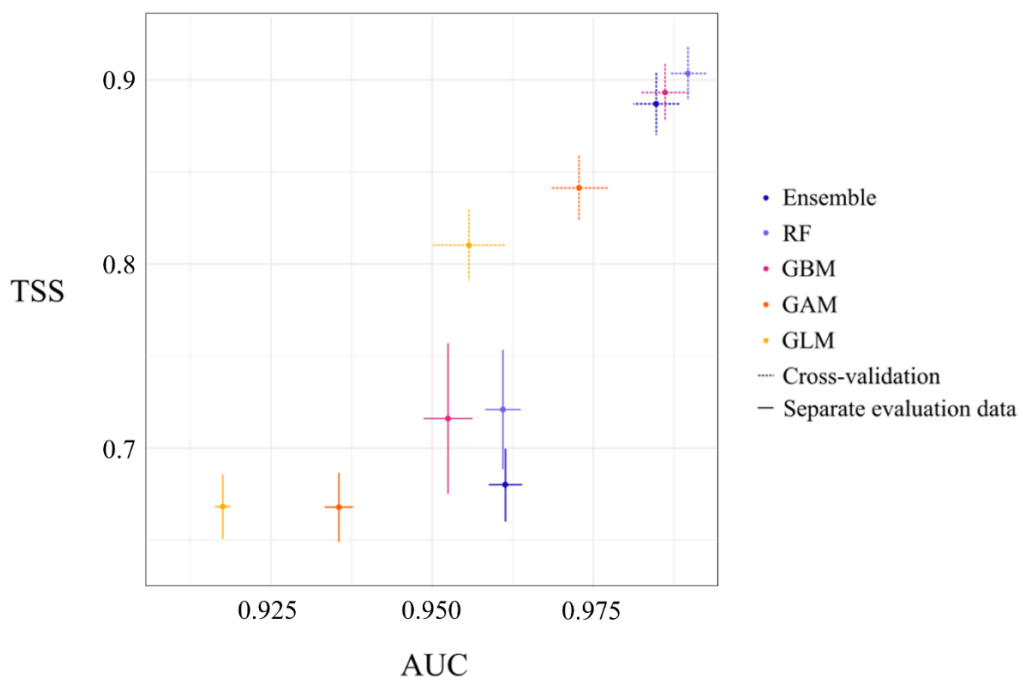
Figure 6: Statistical evaluation metrics for different modelling techniques. The averages of AUC and TSS values with one standard deviation (whiskers) are based on 100 runs of the models. Evaluation results for the 100-fold cross validation with the calibration data are presented with dashed line and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

The total area for which all four models predicted occurrence of palsas, and peat plateaus was 0.8 million km². This represents approximately 28 % of the area for which at least one model predicted occurrence of the landforms (3.1 million km²), indicating relatively low model agreement. The highest model agreement (Fig. S7) was found in Northern Fennoscandia, Western Siberia and Northern Canada around the Hudson Bay and Quebec. Also, west coast of Alaska, regions around Kamchatka Peninsula and Iceland had a high model agreement.

4 Discussion

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

310 the climate change (Turetsky et al., 2020; Miner et al., 2022). Moreover, the predicted permafrost degradation may have a major impact on both geodiversity and biodiversity of current Northern Hemisphere permafrost region. Thus, comprehensive understanding of the current distribution of studied landforms is needed.

Based on the recent period, the suitable environments for palsas and peat plateaus were predicted to occur around the Northern Hemisphere permafrost region, with hotspots at the most studied regions (i.e., Northern Fennoscandia, Western

315 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

320 al. (2022).

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

325 possibly suitable environmental conditions for palsas and peat plateaus in the region (Fig. 1).

For North America our results aligned well with Fewster et al. (2020) around the Hudson Bay, Quebec, the Northwest Territories, and Yukon. However, our results indicated more variability in landform occurrence especially in the Northwest Territories and Yukon, showing e.g., a gap in suitable environments east of the Great Slave Lake, and clear differences in suitable environments of Alaska. For Alaska, our models predicted occurrence of landforms in the coastal regions whereas

330 Fewster et al. (2020) predicted them in more central parts. The contrasting results may be partly explained by the inclusion of non-climatic variables, and the finer resolution of our study, which both can facilitate the differentiation of environmental suitability at an improved accuracy.

The optimal climatological conditions coincide quite well with the climate envelopes determined by previous studies for Fennoscandia (e.g., Luoto et al., 2004b; Aalto and Luoto, 2014) and Northern America (Fewster et al., 2020). For the Central

335 and Eastern Siberia no optimal climatic ranges for palsas and peat plateaus have been determined before. TDD was the most important variable while FDD had only a minor importance in our models, indicating that the summer conditions during the thawing season have greater effect on the distribution of palsas and peat plateaus. Recent studies have similarly highlighted the importance of thawing season conditions for the occurrence of permafrost (Mekonnen et al., 2021), other periglacial landforms (Karjalainen et al., 2020), and active layer (Peng et al., 2018; Karjalainen et al., 2019).

340 The negative effect of higher air temperatures on the distribution of palsas and peat plateaus can be observed from the response curve for TDD (Fig. 3a). Moreover, increasing rainfall can cause permafrost to thaw even faster than it would only because of the temperature rise (Magnússon et al., 2022). In addition, thicker snowpack can also lead to the permafrost thaw in the discontinuous permafrost region (Biskaborn et al., 2019) as the thick snowpack acts as an insulator preventing the frost from penetrating deep into the soil (Seppälä, 1990, 1994; Ge and Gong, 2010; Sannel, 2020). Increasing snowpack also leads

345 to moister conditions during late spring due to abundant meltwaters (Sannel, 2020), and thus alters the thermal properties of peat (Kujala et al., 2008). Indeed, the thin snow cover has been tested in the field to be a key factor in the formation of palsas (Seppälä, 1982), and the negative effect of increasing snowfall (Johansson et al., 2013) can be recognized from our results (Fig. 3a). However, there might be a delay before the increasing snow depth will affect to the thaw depth (Sannel et al., 2016).

350 Other environmental conditions beside the climate affect also the distribution of peat dominated permafrost mounds and other periglacial landforms (Seppälä, 2011; Karjalainen et al., 2020). Our models indicate that palsas and peat plateaus require sufficient SOC content, which is logical, as the sufficient peat cover is considered crucial for the formation and occurrence of these landforms at the marginal permafrost regions (Kujala et al., 2008; Seppälä, 2011). Most of the previous modelling studies of palsas and peat plateaus (e.g., Fronzek et al., 2006; Parviainen and Luoto, 2007; Fewster et al., 2020,

355 2022) have used only climate envelope models. Our results show that incorporating other environmental variables may enhance the predictive performance of the models as SOC and TWI had the highest VI values after TDD (Fig. 3). In addition, compared to previous broad-scale studies (Fewster et al., 2022, 2020) the used high spatial resolution allows for identifying unsuitable areas within the climatically suitable envelopes and thereby reduces the risk of overestimating palsa and peat plateau distribution.

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

365 to estimate the forthcoming spatial changes in the distribution of the suitable environments.

Previous studies have suggested that the development of thermokarst can be used as an indicator of the former distribution of palsas (Matthews et al., 1997; Luoto and Seppälä, 2003). Thermokarst ponds are relatively common in Fennoscandian palsa mires (e.g., Luoto and Seppälä, 2003), although Olefeldt et al. (2016) classified this region to have a low thermokarst coverage. This mismatch was noticed also here, as we predicted extensive degradation of the landforms in the region.

370 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).

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

5 Conclusions

From the results of this study, we conclude that:

- Based on a recent period, suitable environments for palsas and peat plateaus can be found across the Northern Hemisphere, with occurrence hotspots in Northern Europe, Western Siberia and around the Hudson Bay, Quebec, and the Northwest Territories of Canada.

385 - A dramatic loss of the suitable environments for palsas and peat plateaus is predicted to occur already by 2041–2060 and almost complete loss by 2061–2080.

- Under a moderate emissions scenario (RCP4.5), landforms can persist in the coldest parts of the recent distribution area, but if the climate change mitigation fails (RCP8.5), suitable environments are predicted to be lost from almost the entire Northern Hemisphere.

390 - 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

395 landforms' distribution.

- Projected loss of the suitable palsa and peat plateau environments overlapped with the regions having a high thermokarst coverage. In the future, it is likely to find increasing amount of thermokarst from recent palsa and peat plateau environments.

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

400 of the climate change over northern regions.

Data availability

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

Author contribution

410 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

415 The authors declare that they have no conflict of interests.

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References

Aalto, J., and Luoto, M.: Integrating climate and local factors for geomorphological distribution models, Earth Surf. Proc.
420 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 Northern Europe by 2100, Nat. Commun., 8, 1–8. https://doi.org/10.1038/s41467-017-00669-3, 2017.

425 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.

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

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

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,
435 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., 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.,
440 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 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.,
445 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
450 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.

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

455 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.

460 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.

465 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.

470 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.

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, 475 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.

480

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.

485

Hao, T., Elith, J., Guillera-Arroita, G., and Lahoz-Monfort, J. J.: A review of evidence about use and performance of species distribution modelling ensembles like BIOMOD, Divers. Distrib., 25, 839–852, https://doi.org/10.1111/DDI.12892, 2019.

Hao, T., Elith, J., Lahoz-Monfort, J. J., and Guillera-Arroita, G.: Testing whether ensemble modelling is advantageous for maximising predictive performance of species distribution models, Ecography, 43, 549–558, https://doi.org/10.1111/ECOG.04890, 2020.

490

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

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.

495

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.

500

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

505 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.,

510 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., Dimopoulus, 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

515 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.

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,

520 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– 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

525 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 for loss of permafrost landforms in a changing climate, Environ. Res. Lett., 15, 104065. https://doi.org/10.1088/1748-9326/abafd5, 2020.

530 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., 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.

Kit, J. L. O. W., Asirvadam, V. S., and Hassan, M. F.: Enhanced Ensemble Models for Predictive Modeling: A Conceptual Framework, in: Proceedings of IEEE 17th International Colloquium on Signal Processing and Its Applications, Online, 5–6 March 2021, 24–28, https://doi.org/10.1109/CSPA52141.2021.9377299, 2021

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.

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, 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.

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 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.

Magnússon, R., Hamm, A., Karsanaev, S. v., Limpens, J., Kleijn, D., Frampton, A., Maximov, C. T., and Heijmans, M. M. P. D.: Extremely wet summer events enhance permafrost thaw for multiple years in Siberian tundra, Nat. Commun., 13, 1–10, https://doi.org/10.1038/s41467-022-29248-x, 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.

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.

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, 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, 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. J., Schuur, E. A. G., Matamala, R., Siewert, M., Nave, L. E., Koven, C. D., Fuchs, M., Palmtag, J., Kuhry, P., Treat, C. C.,

585 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 Engineering Study, 62, 136 pp., 1943.

590 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, 41–49, https://doi.org/10.2136/sssaj2016.05.0148, 2017.

595 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.

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,
600 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,
605 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,
610 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.

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.

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.

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.: 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.

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.

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., 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.

665   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.

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.

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

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.: Ensemble Platform for Species Distribution Modelling.
675   CRAN, https://cran.r-project.org/web/packages/biomod2/biomod2.pdf, 2021.

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., 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,
680   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 permafrost zone, Eng. Geol., 1, 40–64, 2014.

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

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,
690 https://doi.org/10.1016/J.EARSCIREV.2022.104042, 2022.

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.

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.,
695 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.

700 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. (1975). Perennially Frozen Peatlands in the Western Arctic and Subarctic of Canada, Can. J.
705 Earth Sci., 12, 28–43, https://doi.org/10.1139/e75-004, 1975.

Appendix A

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

710   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.

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
715   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.

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,
720   subarctic Québec, Canada, Ecoscience, 13, 56–65, http://dx.doi.org/10.2980/1195-6860(2006)13[56:ROCIVA]2.0.CO;2, 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.

Calmels, F., and Allard M.: Segregated Ice Structures in Various Heaved Permafrost Landforms Through CT scan, Earth
725   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 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,
730   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 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.

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-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 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.

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.

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
760   James Bay Lowland and adjacent regions, Arct. Antarct. Alp. Res., 46, 19–39, https://doi.org/10.1657/1938-4246-46.1.19,
2014.

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,
765   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
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
770   permafrost   pvolution   in   the   lacustrine   lowlands   of   West-Central   Alaska.   Permafrost   Periglac.,   25,   14–34,
https://doi.org/10.1002/ppp.1800, 2014.

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.

775   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,
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.,
780   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,
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-
785   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, CO2, 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
815   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.

820   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
825   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:
830   NáttúrufræðistofnunΊslands (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.

835   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 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.

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.

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 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.

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 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.