Author`s response for the manuscript "Strong degradation of palsas and peat plateaus in northern Norway during the last 60 years" by Borge et al.

We have assembled a revised version of the manuscript in which the suggestions of two reviewers are incorporated. Most importantly, we have incorporated a better quantification of the potential uncertainties of our methodology, following reviewer 2. Furthermore, we have added a new figure with an aerial image to better illustrate some of the processes. In the following, we provide the replies to the reviewers and to Short Comment 1, followed by changes to the manuscript and the revised version of this manuscript in which changes are marked in bold.

Reply to Reviewer 1 (his/her text in bold):

Comments The subject of this paper is appropriate to the Cryosphere Journal. The paper contains original material on importance of studies on changes (decrease in area) of palsas and peat plateaus in northern Norway since 1950s in order closer understand of possible way of the evolution of palsas and peat plateaus. Most of this material is new for the investigated area, illustrates more precisely data and analysis of this material and the results discussed in the manuscript could bring the new knowledge to the existing concept of the sequence of palsa evolution. Using high-resolution aerial imagery, authors quantified the lateral changes of the extent of palsas and peat plateaus in northern Norway. Combining the change rates with the areal mapping authors report on widespread receding of palsas and peat plateaus area since the 1950s in northern Norway. The methodology is sound, the assumptions and objectives are clearly identified. It is a good paper and the publication of this kind of paper could be timely and beneficial for researchers working in the same field, as well as for many other researchers conducting a wide spectrum of environmental studies. From my point of view, the paper in review could be published as it is, but I have a few minor comments and questions to authors before the manuscript will be published in the Cryosphere Journal.

1. Page 7, block 30. Open the acronym LIA.

Done.

2. Conclusion. The first sentence. It is not clear to me what exact high-resolution aerial images are providing? 250 m? If so, how did you estimate that "newly formed palsas of diameter of more than 10 m were not observed"? (The last sentence at the page 10 and spatial scale at the Figure 2a).

In the revised version, we have added the spatial resolution of the aerial images to the first sentence in Sect 6, conclusion. We write: *Using high-resolution (0.2-0.5 m^2) aerial imagery, we systematically map the occurrence of palsas and peat plateaus on 250 m grids in the sporadic permafrost zone in northern Norway.* Thus, it should be clear that the high-resolution images features a spatial resolution of 0.2-0.5 m, while the mapping approach is based on 250 m grids. Using images with a spatial resolution of 0.2-0.5 m, it is relatively easy (if you know what to look for) to visually detect palsas with a diameter approximately larger than 10 m. The second last sentence at page 10, in Sect. 6, conclusion, is reformulated to clarify that this sentence only is valid for the four study areas. We write: *Newly formed palsas of diameter of more than 10 m were not observed in the study areas.*

Reply to Reviewer 2 (his/her text in bold):

I read through the manuscript several times with great interests. The authors have done a thorough job by documenting changes in palsas and peat plateau in northern Norway. The work will be very valuable for palsas and permafrost studies in the Arctic. I do have some concerns and suggestions about the current version of the manuscript.

Major concerns:

1). Potential error analysis: There are several places in the work which could produce substantial errors. First, the 10 m diameter threshold. By ignoring all palsas less than 10 m in diameter could produce potentially significant errors. The authors have four in-situ sites, they should their in-situ data to evaluate how much error it may bring out. Second, the authors just use one same person to delineate the boundaries of palsas for each study site. Yes, it will be very consistent but not necessarily the lowerest in errors. To digitize any data and information from paperwork into computer, it usually requires two persons to do the same work separately, then use a program to check each other. If both agree, pass, if not, go back and check the original paper version to reduce the human error to the minimum. If it did by the same one person as stated in this study, the potential error is unknown. The authors should seriously consider the issue.

The 10 m threshold was only used in the mapping of the palsa distribution at 250m scale, not in the delineation process for the four study areas, for which also palsas with diameter of less than 10m were mapped. We have clarified this in the revised verison of the manuscript.

In the revised version, we have also addressed the potential error of using the 10 m threshold in the distribution mapping process by using, as proposed by the referee, the data from our four study sites. This is now included in section 3. We find the difference (by comparison of using and not using a 10 m threshold) in number of grid-cells to be 8 % and the estimated difference in the total area of palsas for the four study sites to be 0.16 %, the latter of which is negligible in the context of our study. In the revised evrsion, we write:

"To determine the uncertainty induced by the 10 m threshold in the 250 m scale mapping (see above), we once again investigate the four main study areas and their surroundings (c. 140 km2). By mapping at best possible resolution, palsas with smaller diameter can be detected which facilitates estimating the number of 250 m grid-cells excluded due to the mapping threshold. We find that the number of grid-cells with presence of palsas is 8.6 % higher when including palsas and palsa remnants with diameters less than 10 m. However, the total area covered by palsas/peat plateaus increases by only 0.16 % due to the limited area of these palsas. We therefore conclude that our mapping can provide a robust estimate for the total area covered by palsas/peat plateaus, although isolated small palsas occur regulary in grid cells flagged as free of palsas/peat plateaus."

To address the uncertainty by only using one person to delineate the boundaries of palsas and peat plateaus, one of the authors has re-mapped about 50 % of the area of palsas/peat plateaus at mire 1 in Karlebotn for the 2008 image. Comparison of the total area gives a difference in 8 % in the mapped total area between the two persons, which is substantial, but signifantly smaller than the changes in extent over time. The process is described in Sect. 3:

"To ensure a consistent interpretation of the extent of palsas on the aerial images, the same person delineated the palsas for each individual study area. To estimate the accuracy of the manual and thus to a certain extent subjective delineation process, parts of the Karlebotn study area (~ 0.24-0.26 km2) were independently mapped (using the images from 2005) by two persons. This comparison yielded a difference of 8 % in the total area which can be considered a rough estimate for the mapping accuracy."

In Sect. 4.2 (Results) we write:

"We note that the reduction in areal extent is significantly larger than the estimated accuracy of the manual delineation process (8 % of the total mapped area, Sect. 3)."

2). The authors should provide more in-situ information, such as at a specific site or a specific palsa, what is happened and/or happening? If palsas disappeared, peat materials are still there. And also geomorphologically, what it looks like when palsa is gone. I believe that not all of them become thermokarst ponds or lakes.

We have added a paragraph to Section 5.3 and a new figure showing an aerial image form a peat plateau near *Suossjavri* with block erosion and pond formation clearly visible. In the revised version, we write:

"Fig. 13 shows an aerial image of a peat plateau near Suossjavri highly affected by block erosion, as common for palsas and peat plateaus in this area. At the actively degrading margins, the mire vegetation is not yet established and a water-filled depression forms, indicating that the retreat of the margin occurs at higher velocity than the regrowing of the mire vegetation. However, the water bodies become overgrown and many of them eventually disappear which is evident from both the aerial images and field observations. The proximity between the standing water and the ice-rich core of the peat plateaus and palsas most likely contributes to thermal undercutting and eventually block erosion at the margins (Kurylyk et al., 2016), but a variety of factors, such as the height of the palsa and the ground ice content can be expected to play a role for this process.

On the other hand, the interior of palsas and peat plateaus can also experience thaw subsidence resulting in thermokarst depressions and suprapermafrost taliks, as seen for peat plateaus in northern Sweden (Åkerman and Johansson, 2008, Sjöberg et al., 2015). Based on calculated thaw rates and an instant increase in air temperature of 2 °C, Sjöberg et al. (2015) estimated that it will take 175-260 years for the permafrost at their investigated peat plateaus to completely thaw. However, much more rapid degradation has been observed in the same region (Zuidhoff, 2002), which could be an indication that lateral erosion considerably increases the degradation rates. A recent study in south-central Alaska found that 85 % of the degradation of forested permafrost plateaus was due to lateral degradation along the margins (Jones et al., 2016). "

3). The authors indeed provide information about MAAT, changes in air temperature and precipitation in the study sites and the region as a whole. The authors do not provide the specific vaules for the changes in air temperature and precipitation. I hope in the revised version, this imformation will be provided. The most importanty, the authors rarely mention about snowfall and snow cover data and information. In the Arctic and Subarctic discontinuous and sporadic permafrost zones, the combination of peat layer and snow cover is often more important than air temperature in terms of permafrost presence or obsence. Changes in peat layer in a short period of time (60 years as in this study) may be very unlikely, changes in snowfall and snow cover conditions may be possible. Indeed, the authors state in the text that precipitation increased, but how much is it snowfall? What is snow cover variations? etc.

In the revised version, we provide additional information about snow cover and snow depth for the study areas. We write in Sect. 2: *"(...)while the mean annual (hydrological year) maximum snow depth (MASD, 1971-2000) ranges from less than 50 cm on Finnmarksvidda to more than 200 cm at the outer coast (seNorge, 2016). On Finnmarksvidda, the mean annual number of days with dry snow (MADDS, 1961-1990) is generally between 150* *and 200 (seNorge, 2016), and the mean fraction of snow of the total precipitation (MSFr, 1961-1990) is usually less than 40 % (seNorge, 2016).”*

In Sect. 4., we write: *“MASD increased in all areas except Lakselv according to seNorge (2016) data, although it is unclear if this result is representative for palsas and peat plateaus, as snow depths on palsas/peat plateaus are generally much lower than in the surrounding wet mire due to wind redistribution, as e.g. observed in Suossjavri and Lakselv in March 2013.”*

In Table 2, we have added data about maximum snow depth, days of dry snow and the mean fraction of snow for our four study areas.
In Sect. 3, we have added a short description of the snow model used by seNorge.

4). Some concepts are confusing: degradation of palsas, lateral erosion of palsas, and disappearance of palsa: By "degradation of palsas", we may understand it refers to the processes on the way or at the end; by "disappearance of palsas", it definitely refers to the end of palsas, and by "the lateral erosion of palsas", it is not clear it refers to lateral shrinking in size or materials are transported away. This may need to be clarified.

In the revised version, we have added a definition of the terms “degradation” (when it refers to palsas) and “lateral erosion”, as it is used throughout the manuscript, in Sect. 1. We write: “*By “degradation”, we refer to the processes (or the result of these processes) that decrease the volume of palsas and peat plateaus. With “lateral erosion”, we mean the lateral decrease in size (as seen on 2D aerial imagery) of palsas and peat plateaus, where the margin of palsas or peat plateaus is transformed to wetland. Lateral erosion is often due to block erosion, but may also be a result of ground subsidence due to melting of excess ground ice at the edge, followed by submergence below the water table of the surrounding wet mire.”*

5). Use the results from four sites to expand to the entire Finnmark, it is kind of skeptical. What is the total area of these four sites? What is the percentage fraction of the total area of these four sites to the whole Finnmark?

The total area of these four sites for 2010s is mentioned in Section 4.1, but we have now revised the sentence for clarity. We have also added the estimated percentage fraction of 2 % for the area of these four sites compared to the whole of Finnmark, and we also make clear that expanding the results to entuire Finnmark must be rega4rded a forst-oder approximation. In Sect. 4, we write:

"High-resolution delineation of palsas and peat plateaus in the four study areas (for the 2010s) covered in total 260 grid cells, corresponding to about 2 % of the 250 m grid cells with palsas/peat plateaus in Finnmark. The sites cover a gradient of climatic and environmental conditions across Finnmark, so that we consider the results a plausible first-order estimate, although it is unclear if the four sites are a fully representative subsample. We find a total area of 2.13 km^2 within the 260 grid cells, yielding an average areal fraction of palsas/peat plateaus of about 13 % in grid cells with presence of these features. The present-day total area of palsas and peat plateaus in Finnmark can thus be estimated to about 110 km^2 or 0.2 % of the total land area of Finnmark, with an estimated uncertainty of 10 km^2 due to the manual delineation process (Sect. 3). "

Some minor comments:

1). p.1, line 29 to p.2, line 1: The authors state "The permafrost temperature in palsas is thus relatively warm", the description is not precise, temperature iself cannot be warm or cold, it can be high or low. Permafrost can be warm or cold. Just a reminder.

Changed - the word temperature is removed.

2). p. 2, lines 19-20: same comments above.

Changed – the word warmer is replaced with higher.

3). p.4., the authors mentioned about winter and summer, please be specific, which months are referring to in terms of winter and summer, this is important in the Arctic and Subarctic sine the cold season is so long. Also, when you discuss about precipitation, what is the fraction of snowfall? when you discuss about changes in precipitation, what is the fraction of changes in snowfall? This information is very important for the potential readers to understand what is going on.

We have added the summer and winter months in brackets, which these data is based on. We calculated the fraction of snowfall of the total precipitation by using precipitation and snow data from seNorge. For other changes in the manuscript regarding snow depth and snow cover, see our answer above to your comment at major concern 3.

Reply to SC1, Ylva Sjöberg (her text in bold):.

We thank Ylva Sjöberg for her comments to our study and the additional references provided. All mentioned studies are cited in the revised version of the manuscript:

Kurylyk, B. L., M. Hayashi, W. L. Quinton, J. M. McKenzie, and C. I. Voss (2016), Influence of vertical and lateral heat transfer on permafrost thaw, peatland landscape transition, and groundwater flow, Water Resour. Res., 52, doi:10.1002/2015WR018057.

This reference is now included in the new manuscript in Sect. 5.3 and 5.4.

Sjöberg, Y., P. Marklund, R. Pettersson, and S. W. Lyon (2015), Geophysical mapping of palsa peatland permafrost, The Cryosphere, 9(2), 465-478.

This reference is now included in the new manuscript in Sect. 3 and 5.3.

Åkerman, H. J., and Johansson, M.: Thawing permafrost and thicker active layers in sub-arctic Sweden, Permafrost Periglac., 19, 279-292, 10.1002/ppp.626, 2008.

This reference is now included in the new manuscript in Sect. 5.3.

Payette, S., A. Delwaide, M. Caccianiga, and M. Beauchemin (2004), Accelerated thawing of subarctic peatland permafrost over the last 50 years, Geophysical Research Letters, 31(18).

This reference is incorporated in Sect. 1 and 5.2.

Changes to the manuscript – an overview

Sect. 1, Introduction: As suggested by reviewer 2, we have added definitions for the terms “degradation” and “lateral erosion”, as they are used throughout the manuscript.

Sect. 2, Setting: Following reviewer 2, we have added more information on climate data concerning snow depth and coverage for the region and for the specific study sites, including the fraction of snow of total precipitation.

Sect. 3, Methodology and data: Following reviewer 2, we have addressed the potential uncertainties of our methodology: a) we have evaluated the uncertainty of the distribution mapping due to the 10 m threshold, and b) we have provided estimates for the potential error of manual delineation of palsas by only one person. For this reason, one of the authors has re-mapped part of the Karlebotn peat plateau complex, so that two independent evaluations are available from which the uncertainty can be estimated.

Furthermore, we have added some information about the seNorge snow-model in the methodology, following reviewer 2`s request of more information about snow cover.

Sect. 4.1, The distribution of palsas and peat plateaus in Finnmark: Following reviewer 2, we added the information about the percentage fraction of palsa area mapped from the four study sites compared to the estimated area for the whole of Finnmark, and we added a sentence concerning the representativeness of the study sites.

Sect. 4.2, Areal change through lateral erosion: In this section, we have added information about the snow depth and coverage for the study sites (reviewer 2). We also added the total area of palsas and peat plateaus mapped from the four study sites using the images from the 2010s.

Sect. 5.3, Degradation of palsas and peat plateaus through lateral erosion: Following reviewer 2, we have provided more information about specific processes occurring at our study sites. We have included a high-resolution aerial image illustrating the formation of water bodies following degradation of the peat plateau. We also added new relevant references in response to the Short Comment by Ylva Sjöberg (SC1, 10 mars 2016).

Sect. 5.4, Implications for permafrost modelling and mapping: We have added a reference in response to the Short Comment by Ylva Sjöberg (SC1, 10 mars 2016).

Sect. 6, Conclusion: Following reviewer 1, some parts of the conclusion have been reformulated.

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Strong degradation of palsas and peat plateaus in northern Norway during the last 60 years

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Abstract. Palsas and peat plateaus are permafrost landforms occurring in subarctic mires which constitute sensitive ecosystems with strong significance for vegetation, wildlife, hydrology and carbon cycle. We have systematically mapped the occurrence of palsas and peat plateaus in the northernmost county of Norway (Finnmark, ~50,000 km^2) by manual interpretation of aerial images from 2005-2014 at a spatial resolution of 250 m^2. At this resolution, mires and wetlands with palsas or peat plateaus occur in about 850 km^2 of Finnmark, with the actual palsas and peat plateaus underlain by permafrost covering a surface area of approximately 110 km^2. Secondly, we have quantified the lateral changes of the extent of palsas and peat plateaus for four study areas located along a NW-SE transect through Finnmark by utilizing repeat aerial imagery from the 1950s to the 2010s. The results of the lateral changes reveal a total decrease of 33-71 % in the areal extent of palsas and peat plateaus during the study period, with the largest lateral change rates observed in the last decade. However, the results indicate that degradation of palsas and peat plateaus in northern Norway has been a consistent process during the second half of the 20th century and possibly even earlier. Significant rates **of areal change** are observed in all investigated time periods since the 1950s, and thermokarst landforms observed on aerial images from the 1950s suggest that lateral degradation was already an ongoing process at this time. The results of this study show that lateral erosion of palsas and peat plateaus is an important pathway for permafrost degradation in the sporadic permafrost zone in northern Scandinavia. While the environmental factors governing the rate of erosion are not yet fully understood, we note a moderate increase in both air temperature, precipitation and **snow depth** during the last few decades in the region.

1 Introduction

Palsas and peat plateaus are the most common landforms indicating permafrost in Fennoscandia, with widespread abundance in the sporadic permafrost zone in the northern region of Norway, Finland and Sweden (Seppälä, 1986). Palsas and peat plateaus are subarctic permafrost landforms in mires defined as *"a peaty permafrost mound possessing a core of alternating layers of segregated ice and peat or mineral soil material"* and as *"a generally flat-topped expanse of peat, elevated above the general surface of a peatland, and containing segregated ice that may or may not extend downward into the underlying mineral soil"* (van Everdingen, 1998). Palsa mires demarcate the outer or lower limit for permafrost in a given area (Sollid and Sørbel, 1998) and are found in a narrow climatic envelope (Parviainen and Luoto, 2007). The permafrost in palsas is thus relatively warm, with a mean annual ground temperature (MAGT) often close to 0 °C in northern Fennoscandia (Christiansen et al., 2010; Johansson et al., 2011). Thus, palsas are vulnerable to climate change (e.g. Aalto et al., 2014).

Palsas in northern Fennoscandia have been extensively studied in terms of processes and controlling factors (e.g. Kujala et al., 2008; Seppälä, 2011; Seppälä and Kujala, 2009), distribution (e.g. Luoto et al., 2004a; Malmström, 1988; Meier, 1996; Sollid and Sørbel, 1998) and stratigraphy and dating (e.g. Oksanen, 2006; Seppälä, 2005; Vorren, 1972). In 2004, the Norwegian institute for nature research (NINA) started a surveillance program of palsa mires in Norway, monitoring six selected palsa mires in Norway (Hofgaard, 2004). However, a recent inventory of palsa mire and peat plateaus and their long-term changes is lacking, despite earlier mapping approaches (Meier, 1987; Sollid and Sørbel, 1998, 1974).

In the Nordic countries, warming of permafrost in mountain areas has been evident since the beginning of 2000 (Christiansen et al., 2010; Isaksen et al., 2011; Isaksen et al., 2007), and degradation of sporadic permafrost in palsa mires has been observed at sites in northern Sweden (Zuidhoff and Kolstrup, 2000), southern Norway (Matthews et al., 1997; Sollid and Sørbel, 1998, 1974) and northern Norway (Hofgaard and Myklebost, 2015, 2014; Meier and Thannheiser, 2015).

Palsa mires and peat plateaus occur in many areas of the subarctic, e.g. in northwestern and northeastern Canada (Lewkowicz et al., 2011; Payette et al., 2004), in European Russia (Kuhry and Turunen, 2006) and in western Siberia (Blyakharchuk and Sulerzhitsky, 1999). The palsa mires in Fennoscandia constitute the westernmost edge of the discontinuous and sporadic lowland permafrost zone in northwestern Russia, where peat plateaus and palsa mires are abundant features (e.g. Väliranta et al., 2003). Ground temperatures observed in peat plateaus in Fennoscandia are generally **higher** than in Russia (Mazhitova et al., 2004; Sannel et al., 2015), so that changes observed in Fennoscandia today may be a window to the future development of the much larger areas in Russia.

Palsa mires constitute a sensitive ecosystem, with a biologically distinct and heterogeneous environment (Luoto et al., 2004b). Moreover, studies from Russia show that palsas and peat plateaus can contain a significant fraction of soil organic carbon within a landscape (Hugelius et al., 2011). An increase in carbon fluxes (especially CH_4) to the atmosphere from the thawing organic-rich permafrost soils could turn the subarctic to a net carbon source (Koven et al., 2011; Schaefer et al., 2011). Furthermore, significant emissions of the greenhouse gas N_2O have been observed in peat plateaus in northwestern Russia and in palsa mires in Finland (Marushchak et al., 2011; Repo et al., 2009), highlighting the active role of palsas and peat plateaus in the coupled carbon and nitrogen cycles. In river hydrology, several studies suggest permafrost thawing as one contributing reason to a widely observed increase in river base flow (e.g. Bense et al., 2012; St Jacques and Sauchyn, 2009; Walvoord and Striegl, 2007), which has also been observed in areas of Fennoscandia where palsa mires are known to exist (Sjöberg et al., 2013; Wilson et al., 2010).

In this study, we provide a quantitative assessment of the current extent of palsas and peat plateaus in Finnmark, the northernmost county of Norway. Furthermore, we quantify the degradation of selected palsa mires and peat plateaus due to lateral erosion between the 1950s until today. **By "degradation", we refer to the processes (or the result of these processes) that decrease the volume of palsas and peat plateaus. With "lateral erosion", we mean the lateral decrease**

in size (as seen on 2D aerial imagery) of palsas and peat plateaus, where the margin of palsas or peat plateaus is transformed to wetland. Lateral erosion is often due to block erosion, but may also be a result of ground subsidence due to melting of excess ground ice at the edge, followed by submergence below the water table of the surrounding wet mire.

2 Setting

The county of Finnmark is situated in northern Norway between roughly 68° N and 71° N and features a land area of 48 618 km^2 (Fig. 1). The geomorphology of Finnmark is dominated by alpine mountains in the northwest, and the plateau-like landscape of Finnmarksvidda at an elevation of about 300-500 m a.s.l. in the interior and south. The area was covered by ice sheets several times during the Pleistocene, and the plateau is normally covered by thick cover of ground moraines and glacio-fluvial and glacio-lacustrine sediments (Sollid et al., 1973). Wetlands and mires fill the depressions between moraines and ridges.

The climate in Finnmark is influenced by the North Atlantic Current, and varies from a relatively wet and warm maritime climate at the coast in the northwest to a rather dry and cold environment in the more continental Finnmarksvidda (Vikhamar-Schuler et al., 2010). The average winter (**December-February**) and summer (**June-August**) temperature (1961-1990) for the plateau are around -15 °C and 10 °C, respectively, with mean annual air temperature (MAAT, 1961-1990) generally varying between -2 °C and -4 °C (Aune, 1993). In comparison, the coast has a MAAT (1961-1990) mostly above 0 °C (Aune, 1993). The mean annual precipitation (MAP, 1961-1990) ranges from more than 1000 mm at the coast to less than 400 mm on Finnmarksvidda, **while the mean annual (hydrological year) maximum snow depth (MASD, 1971-2000) ranges from less than 50 cm on Finnmarksvidda to more than 200 cm at the outer coast (seNorge, 2016). On Finnmarksvidda, the mean annual number of days with dry snow (MADDS, 1961-1990) is generally between 150 and 200 (seNorge, 2016), and the mean fraction of snow of the total precipitation (MSFr, 1961-1990) is usually less than 40 % (seNorge, 2016).**

According to regional modelling approaches at 1 km^2 spatial resolution, permafrost underlays about one fifth of the land surface in Finnmark (Farbrot et al., 2013; Gisnås et al., 2013). The altitude of the lower limit of discontinuous mountain permafrost is above c. 500 m a.s.l. in continental areas of Finnmark (Farbrot et al., 2013), whereas sporadic permafrost in palsa mires can exist almost down to sea level.

Four study areas roughly situated in a NE-SW transect through Finnmark are chosen: *Karlebotn*, *Lakselv*, *Suossjavri*, and *Goatheluoppal* (Fig. 1), **with climate data (seNorge, 2016) provided in Table 2.** Two of the study areas, *Karlebotn* (25-40 m a.s.l.) and *Lakselv* (15-70 m a.s.l.), are located in a maritime setting below the local marine limit. The mires in *Karlebotn* (70°23′ N, 28°25′ E) are located close to inner parts of Varangerfjorden, eastern Finnmark, consisting of extensive peat plateaus and disintegrated remains of these. The mires in *Lakselv* (70°4′ N, 25°3′ E) are located in the inner parts of Porsangerfjorden, near inhabited areas belonging to the small town of Lakselv. Here, the mires consist of some larger peat plateaus or disintegrated remains of peat plateaus, and some larger thermokarst lakes. *Suossjavri* (300-350 m a.s.l., 69°23′ N, 24°15′ E) is situated on the plateau of Finnmarksvidda, with mires featuring both peat plateaus and dome palsas. *Goatheluoppal* (440 m a.s.l., 68°54′ N, 22°21′ E) is located in a flat area at the southwestern edge of Finnmarksvidda, approximately 5 km from the border of Finland. The mires in this area consist of dome palsas, which are small in extent but easily visible on aerial images. Larger peat plateaus do not exist here. Fig. 2 shows two examples of degradation and disappearance of palsas from *Suossjavri* and *Karlebotn*.

3 Methodology and data

In a first step, we map the presence of palsas and peat plateaus using a grid-based approach with a spatial resolution of 250 m^2 for the entire county of Finnmark. The occurrence of palsas and peat plateaus is based on visual interpretation of orthorectified aerial images provided on Norgeibilder.no by the Norwegian Mapping Authority (Norgeibilder, 2015) **at 1:4000 to 1:6000 (which is less than the best possible resolution)**. **The occurrence of palsas/peat plateaus is assigned to grid-cells that include one or more palsas with a diameter of at least 10 m.** The threshold is defined for practical reasons, as a palsa with diameter of less than 10 m is difficult to detect and correctly interpret **at the scale employed for the mapping** due to the quality of the aerial images.

The resulting map of palsa/peat plateau distribution is evaluated against gridded datasets of MAAT (seNorge, 2016) for the normal period 1961-1990 and a Digital Elevation Model (DEM) (Kartverket, 2015b) at 10 m^2 resolution. The MAAT dataset originally features a spatial resolution of 1 km^2 and has been resampled to 250 m^2 resolution using bilinear resampling technique to compare with the palsa/peat plateau map. As mires generally are situated in topographic depressions, we use the minimum elevation in each 250 m^2 grid-cells to assess the altitudinal distribution of palsa mires and peat plateaus.

To estimate the total area of the actual palsas and peat plateaus in Finnmark, we multiply the surface area of 250 m^2 grid-cells with the presence of palsas by a mean areal fraction that is covered by palsas/peat plateaus in each grid cell. To obtain an estimate for the latter, we delineate the exact boundaries of palsas and peat plateaus from the most recent available images (2005-2012) at the four study areas, covering in total **260** grid-cells, which we assume to be a representative sample for Finnmark. **This mapping is performed at the best possible resolution (c. 1:1250), so that also palsas with diameter smaller than 10 m are included (for grid cells for which palsa/peat plateau occurrence is determined by the 250 m scale mapping).** All digital geodata handling is performed in ArcGIS (© ESRI, Redlands, CA, USA).

To ensure a consistent interpretation of the extent of palsas on the aerial images, the same person delineated the palsas for each individual study area. **To estimate the accuracy of the manual and thus to a certain extent subjective delineation process, parts of the Karlebotn study area (~ 0.24-0.26 km^2) were independently mapped (using the images from 2005) by two persons. This comparison yielded a difference of 8 % in the total area which can be considered a rough estimate for the mapping accuracy.**

To determine the uncertainty induced by the 10 m threshold in the 250 m scale mapping (see above), we once again investigate the four main study areas and their surroundings (*c*. 140 km^2). By mapping at best possible resolution, palsas with smaller diameter can be detected which facilitates estimating the number of 250 m grid-cells excluded due to the mapping threshold. We find that the number of grid-cells with presence of palsas is 8.6 % higher when including palsas and palsa remnants with diameters less than 10 m. However, the total area covered by palsas/peat plateaus increases by only 0.16 % due to the limited area of these palsas. We therefore conclude that our mapping can provide a robust estimate for the total area covered by palsas/peat plateaus, although isolated small palsas occur regulary in grid cells flagged as free of palsas/peat plateaus.

In a second step, changes of palsa and peat plateau extent from the 1950s to now are evaluated for the four study areas. Here, aerial images at 1:20 000 to 1:50 000 scale with a ground sample distance (GSD) ranging from 0.24-0.50 m (Table 1) are extracted by the following procedures: (1) Aerial images from 2003 and 2008-2012 are directly provided on Norgeibilder.no. (2) Analogue aerial images from 1956-1959 and 1980-1982 are scanned (© The Norwegian Mapping Authority, Norway) and georeferenced. Due to the nature of palsas being situated in flat mires, georeferencing is considered to give sufficient accuracy in this study. The georeferencing procedure for *Lakselv*, *Suossjavri* and *Goatheluoppal* is concentrated around the individual mires, yielding low RMSEs for the investigated areas, mainly around 0.5-2 m. The two images from 1957 of *Karlebotn* are georeferenced using control points within the whole scene, resulting in RMSEs of 5.7 and 8.7 m. For the study areas *Lakselv* and *Karlebotn*, only images from the 1950s and 2005/2008 are utilized.

Polygons that match the individual palsas are produced by visual interpretation from the different time slices (example in Fig. 3). Knowledge obtained from fieldwork in *Suossjavri* in summer 2014 was crucial in the process to recognize and separate palsas from the rest of the landscape. Palsas and peat plateaus situated at the edge of the mire in sloping terrain covered by moraine material are especially difficult to delineate, as there is often a diffuse transition between the moraines and the palsa area. To avoid an effect on the change detection, the same boundaries are chosen for all time slices in such areas. For simplicity, thermokarst features within palsas or peat plateaus smaller than c. 10 m, e.g. small drainages and depressions with or without ponds, are ignored in the delineation process, **as they are likely to be still underlain by permafrost (Sjöberg et al., 2015).**

Finally, the observed changes are evaluated against changes in climatic variables. We use gridded data at a spatial resolution of 1 km^2 of air temperature, precipitation **and maximum snow depth (during a hydrological year)** provided by the Norwegian Meteorological Institute (Mohr, 2008; Mohr and Tveito, 2008; Tveito and Førland, 1999) and the Norwegian Water Resources and Energy Directorate through **www.senorge.no (seNorge, 2016**). **With the seNorge (2016) dataset, we** calculate MAAT, MAP, **MASD, MADDS and MSFr** at the location of the four study areas. For each location, a trend analysis is performed using linear regression.

The seNorge (2016) data set **of air temperature and precipitation** is based on interpolation between measurements at meteorological stations using altitudinal scaling (Mohr and Tveito, 2008). **Maximum snow depth, days of dry snow and snow fraction of the total precipitation are based on a snow model using the gridded air temperature**

and precipitation as input forcing (Saloranta, 2016). While the seNorge (2016) dataset is a consistent, gap-free dataset available for all study areas, the sparsity of meteorological stations in Finnmark leads to higher uncertainties on Finnmarksvidda compared with densely populated areas in south of Norway (Tveito et al., 2000). In addition, the occurrence of strong winter inversions in mire areas in northern Fennoscandia (e.g. Nordli, 1990; Pike et al., 2013) hampers interpolating meteorological observations.

4 Results

4.1 The distribution of palsas and peat plateaus in Finnmark

Palsas or peat plateaus are identified in 13 752 grid cells of 250 m size which corresponds to a total area of about 850 km^2 (Fig. 4). The distribution map shows that palsas are scattered over most of the more continental parts of Finnmark, with the highest concentration in the inner parts of Finnmarksvidda towards the southern border to Finland (Fig. 4). In the southeastern corner of Finnmarksvidda, close to the Finnish border, the abundance of palsa mires and peat plateaus is significantly lower than in the more central parts. The coastal sites of *Lakselv* and *Karlebotn* represent areas with medium to high concentrations of palsas. The dominating elevation range of palsa occurrence is around 300-500 m a.s.l., corresponding to the common elevations in Finnmarksvidda (Fig. 5a). In addition, a significant number of palsas and peat plateaus occur at low elevations of 0-100 m a.s.l., mainly in coastal areas. Palsas and peat plateaus are most concentrated at MAATs between -3 °C and -4 °C (Fig. 5b), but at a few sites they occur at locations with MAAT as high as +1 °C.

High-resolution delineation of palsas and peat plateaus in the four study areas (for the 2010s) covered in total 260 grid cells, corresponding to about 2 % of the 250 m grid cells with palsas/peat plateaus in Finnmark. The sites cover a gradient of climatic and environmental conditions across Finnmark, so that we consider the results a plausible first-order estimate, although it is unclear if the four sites are a fully representative subsample. We find a total area of 2.13 km^2 within the 260 grid cells, yielding an average areal fraction of palsas/peat plateaus of about 13 % in grid cells with presence of these features. The present-day total area of palsas and peat plateaus in Finnmark can thus be estimated to about 110 km^2 or 0.2 % of the total land area of Finnmark, with an estimated uncertainty of 10 km^2 due to the manual delineation process (Sect. 3).

4.2 Areal change through lateral erosion

In the four study areas, a total area of 4.4 km^2 of palsas and peat plateaus were mapped by aerial images from the 1950s, **which was reduced to less than half (2.13 km^2) in the 2010s**. No new palsas with diameter of more than 10 m were found and no palsas increased visibly in extent between the end of 1950s and 2010s. **We note that the reduction in areal extent is significantly larger than the estimated accuracy of the manual delineation process (8 % of the total mapped area, Sect. 3).**

Data from seNorge (2016) indicate that all of the four study areas have experienced a notable increase in MAAT during the study period (Table 2), while MAP increased slightly at two sites and remained more or less constant at the others. **MASD increased in all areas except Lakselv according to seNorge (2016) data, although it is unclear if this result is representative for palsas and peat plateaus, as snow depths on palsas/peat plateaus are generally much lower than in the surrounding wet mire due to wind redistribution, as e.g. observed in Suossjavri and Lakselv in March 2013.**

Karlebotn – Two large peat plateau **complexes** bordered by palsa mires were mapped (Fig. 6a). The total area for all palsas and peat plateaus was 2.17 km^2 in 1957, while it was reduced to 1.0 km^2 in 2005/2008, corresponding to a 54 % decrease in areal extent during 50 years (Fig. 6b). The mean annual rate of reduction based on the original area from the 1950s (from now on referred to as the mean annual loss rate) was on the order of 1 % a^{-1}. The *Karlebotn* site features the highest increase in MAAT during the study period, with a MAAT close to 0 °C for the last decades (Table 2).

Lakselv – In total eight distinct palsa mires were investigated in the *Lakselv* area (Fig. 7a). On average, they featured a decrease of 48 % in the total area of palsas and peat plateaus from 1959 to 2008, corresponding to a decrease from 0.95 km^2 to 0.49 km^2 (Fig. 7b) and a mean annual loss rate of about 1.0 % a^{-1}. In the *Lakselv* area, some of the mires are surrounded by cropland, and the image analysis revealed that small parts of palsa mires 5-8, including a few palsas, have been transformed to cropland during the period 1959-2008. However, this anthropogenic effect is only responsible for around 1% of palsa area that was lost in the 50-year study period, so that its influence on the mean annual loss rates is negligible. At the *Lakselv* sites, the MAAT is above 0 °C (Table 2), thus placing these palsa mires at the extreme upper end of the temperature range within which palsa mires are found (Fig. 5b). The meteorological station at Banak (5 m a.s.l.), situated at the coast a few kilometres away from the palsa mires, has documented a high average wind speed of about 5 m/s (based on data from 1967-2014, MET, 2015) and frequent wintertime rain events are known to occur (e.g. Vikhamar-Schuler et al., 2010; Vikhamar-Schuler et al., 2013). Both factors could lead to a reduction of the insulating wintertime snow cover on the palsas and thus influence the ground thermal regime, possibly contributing to the thermal stability of permafrost in the palsas. This interpretation is corroborated by observations during a field visit in March 2013, where the palsas were either completely free of snow or covered by an ice layer, while a snow cover exceeding 0.5 m depth was observed in the surrounding birch forest.

Suossjavri – In total seven distinct mires with palsas and peat plateaus were mapped (Fig. 8a). Around a third of the original area of palsas and peat plateaus in 1956/1959 had degraded by 2011 (Fig. 8b and 9, Table 3). The mean annual loss rates were relatively stable in time, with a notable acceleration in the most recent time period (Fig. 9). The larger peat plateaus in the *Suossjavri* area featured a smaller annual loss rate compared to smaller palsas. From 1956/1959 and 2011, the area of the four largest peat plateaus was reduced by 15 %, compared to 48 % areal loss for palsas and smaller peat plateaus. Measurements at the meteorological station Cuovddatmohkki (286 m a.s.l.), located around 5-10 km from the *Suossjavri* palsa mires, suggest a slightly colder and dryer environment than the seNorge (2016) data set (Table 2), with a MAAT of -2.6 °C for the normal period 1961-1990 (Aune, 1993) and a MAP of 380 mm for the same period (Førland, 1993). With about 1.5 m/s, the average wind speed at Cuovddatmohkki (based on data from 1967-2014, MET, 2015) is significantly lower than in the *Lakselv* area.

Goatheluoppal – The area features a large number of smaller palsas distributed within a large wetland and mire complex (Fig. 10a). Although the MAAT is rather cold at the site (Table 2), it experienced the by far largest changes in areal extent (Fig. 10b and 11, Table 4): in 2012, 71 % of the original palsa area from 1958 had disappeared. The mean annual loss rates were remarkably stable at this study area (Fig. 11), with an average rate of 1.3 % a^{-1}. **According to seNorge (2016), *Goatheluoppal* featured the highest increase in both MAP and MASD of all study areas (Table 2).**

If one extrapolates the mean observed annual loss rate of around 1 % a^{-1} to the entire county of Finnmark, about half of the area covered by palsas and peat plateaus in the 1950s has disappeared until today, corresponding to a total area loss of 110 km^2. In the earliest available images from the 1950s, landforms indicative **of** palsa degradation are already visible at all study areas. Examples are thermokarst lakes and rim ridges visible in the aerial images from 1958 from *Goatheluoppal* which most likely mark the position and the extent of former palsas (Fig. 12). This interpretation is corroborated by their similarity to degradational landforms in the 2012 images which were still mature palsas in 1958. The analysis of the aerial images from the 1950s therefore indicates that palsa degradation was already an ongoing process at this time.

5 Discussion

5.1 Comparison to previous studies

The mapped distribution of palsas and peat plateaus (Fig. 4a) is largely in agreement with the less detailed palsa mire map by Sollid and Sørbel (1998) (Fig. 4b) which is mostly based on work from the 1960s-1970s (Sollid and Sørbel, 1974). A notable difference is the presence of palsa mires in the Pasvik valley in the southeastern corner of Finnmark in the earlier map. In our study (Fig. 4a), no palsas were detected in this area, but large mire areas with evidence of former palsas were observed. This suggests that palsas have disappeared entirely from some marginal areas of the present distribution in the past 50 years.

In northern Fennoscandia, degradation of palsas has been documented in eastern Finnmark (Hofgaard and Myklebost, 2014), Troms county (Hofgaard and Myklebost, 2015) and in the southernmost palsa mire in northern Sweden (Zuidhoff and Kolstrup, 2000). However, palsa mires at the southern margin of the palsa extent on the Kola Peninsula, Russia, displayed no change in both areal extent, thickness of the active layer and height and number of permafrost mounds over the past 80 years (Barcan, 2010). Furthermore, investigations in the wider *Goatheluoppal* area (southeast of the mires mapped in this study) revealed no overall change in the distribution and size of palsas from 2004 to 2011 (Hofgaard and Myklebost, 2012). These conflicting results suggest that local factors – and not only the regional climate – influence the thermal regime in the ground and thus the survival of palsas and peat plateaus. Such factors could be snow redistribution due to wind drift (Seppälä, 1982), the thickness of peat and its water content (Kujala et al., 2008), groundwater flow (e.g. Vallee and Payette, 2007; Thórhallsdóttir, 1994) and vegetation (Zuidhoff and Kolstrup, 2005).

5.2 Palsas and peat plateaus in northern Norway

Dating of peat layers in palsas in northern Europe and northwestern Russia reveals that some palsas and peat plateaus were formed during cold conditions in the **Little Ice Age** (LIA), while others are significantly older and survived the Medieval warm period (Oksanen, 2005). While similar dating studies are lacking for our study area, the few datings available for northern Finland and Sweden (overview in Sannel and Kuhry, 2011) suggest that at least a large part of the palsa mires and peat plateaus in Finnmark is of LIA origin. Thus, it is well possible that these features entered a stage of slow, but consistent degradation in conjunction with post-LIA warming which is still ongoing today. At the two sites with repeat aerial imagery (*Goatheluoppal* and *Suossjavri*), the mean annual loss rates were remarkably stable over the past 50 years and do not seem to be directly correlated to MAAT, although the accelerated degradation at *Suossjavri* in the past decades may partly be related to pronounced increases of air temperatures since the 1980s (Hanssen-Bauer, 2005). The mean annual loss rates found in this study are of similar order of magnitude as rates observed in other areas, for example in northern Sweden (Zuidhoff and Kolstrup, 2000) and in the discontinuous permafrost zone in northwest (Kershaw, 2003; **Quinton et al., 2011**) and eastern Canada (Payette et al., 2004; Vallee and Payette, 2007).

Temperature projections indicate that Finnmarksvidda could experience a significant temperature increase during this century: for the moderate future emission scenario RCP4.5 (IPCC, 2014), an increase in MAAT of 3.6 °C from the period 1971-2000 to the period 2071-2100 is estimated (Hanssen-Bauer et al., 2015). Thus, only about one third of the palsas and peat plateaus will be situated in areas with MAAT below 0 °C by the end of this century (see Fig. 5b) so that the degradation is likely to continue or even accelerate in the future. Even without future acceleration, palsas and peat plateaus at the investigated areas will have disappeared by 2030 (*Goatheluoppal*), 2060 (*Lakselv* and *Karlebotn*) and 2080 (*Suossjavri*), if the mean annual loss rates observed in this study continue. On the other hand, the existence of palsas in coastal areas with MAAT above 0 °C leaves the possibility open that a small portion of these permafrost landforms may survive also in a future climate, so that a definite conclusion on the fate of palsas and peat plateaus in Finnmark in the 21st century cannot be drawn yet.

5.3 Degradation of palsas and peat plateaus through lateral erosion

Palsas and peat plateaus are complex permafrost features, and the environmental factors governing their formation and degradation are not yet fully understood. Since all stages of palsa development can be found in the same mire, Seppälä (1982, 1986) suggested that changes in climate are not necessarily the reason for the collapse of individual palsas, but a natural part of the cyclic development of palsas. Results of studies by Zoltai (1993) and Matthews et al. (1997) support this view. In contrast, we detected neither new palsas larger than 10 m diameter nor palsas that increased in areal extent in the investigated 60-year-period, although detection of small new embryo palsas can be difficult in aerial images. Other studies confirm this general pattern of degradation of palsas (Hofgaard and Myklebost, 2015, 2014; Sollid and Sørbel, 1998; Zuidhoff and Kolstrup, 2000), or present evidence of a wider abundance of palsas in the past (Luoto and Seppälä, 2003) which is an indication that the climatic factors are a primary control on the distribution of palsas and peat plateaus. The two different views are not necessarily in conflict, as both processes can be important for different time-periods and for different spatial scales (Aalto and Luoto, 2014). Cyclical evolution of palsas as observed by Seppälä (1982, 1986) could e.g. occur for a certain range of climatic conditions, while aggradation or degradation could be dominant during colder and warmer periods, respectively.

In addition to climatic factors, the mean areal loss rates appear to be related to shape and geometry of individual palsas and peat plateaus. The results in *Suossjavri* show a clear difference between the mean annual loss rate for large peat plateaus and smaller palsas, with smaller palsas degrading significantly faster than larger peat plateaus. A potential explanation is that dome palsas are higher than peat plateaus, resulting in more block erosion, while low peat plateaus are mostly eroded by thermal erosion from water (Sollid and Sørbel, 1998). However, many of the delineated palsas are probably "residual" palsas from the disintegration of larger peat plateaus and are therefore not necessarily higher than the adjacent peat plateaus, while still featuring large degradation rates. The explanation may thus simply be that smaller and more fractionated features have a longer perimeter on which lateral erosion can act relative to their area. If the absolute rates of lateral retreat (in m a^{-1}) are on average of similar magnitude for all features, the areal loss rate (in % a^{-1}) would indeed be larger for smaller palsas, in agreement with the findings of this study.

Fig. 13 shows an aerial image of a peat plateau near *Suossjavri* highly affected by block erosion, as common for palsas and peat plateaus in this area. At the actively degrading margins, the mire vegetation is not yet established and a water-filled depression forms, indicating that the retreat of the margin occurs at higher velocity than the regrowing of the mire vegetation. However, the water bodies become overgrown and many of them eventually disappear which is evident from both the aerial images and field observations. The proximity between the standing water and the ice-rich core of the peat plateaus and palsas most likely contributes to thermal undercutting and eventually block erosion at the margins (Kurylyk et al., 2016), but a variety of factors, such as the height of the palsa and the ground ice content can be expected to play a role for this process.

On the other hand, the interior of palsas and peat plateaus can also experience thaw subsidence resulting in thermokarst depressions and suprapermafrost taliks, as seen for peat plateaus in northern Sweden (Åkerman and Johansson, 2008, Sjöberg et al., 2015). Based on calculated thaw rates and an instant increase in air temperature of 2 °C, **Sjöberg et al. (2015) estimated that it will take 175-260 years for the permafrost at their investigated peat plateaus to completely thaw. However, much more rapid degradation has been observed in the same region (Zuidhoff, 2002), which could be an indication that lateral erosion considerably increases the degradation rates. A recent study in south-central Alaska found that 85 % of the degradation of forested permafrost plateaus was due to lateral degradation along the margins (Jones et al., 2016).**

5.4 Implications for permafrost modelling and mapping

Grid-based modelling of the ground thermal state suggests that several thousand square kilometers in Finnmark could be covered by permafrost in mires areas (Farbrot et al., 2013; Gisnås et al., 2013; **Gisnås et al., 2016**), which is significantly more than the area of palsas and peat plateaus of 110 km^2 estimated in this study. However, the model results are based on 1 km^2 grid cells without accounting for the considerable subgrid variability of the ground thermal regime. In this study, on average only 13 % of the area of grid cells of 250 m^2 size (i.e. 16 times smaller than 1 km^2 grid cells) proved to be actually covered by clear permafrost features, and this fraction is necessarily even lower for 1 km^2 grid cells. Therefore, it seems possible to console at least the orders of magnitude obtained with the two approaches: the modelling result refers to the area with climatic conditions that make the presence of permafrost and thus palsas and peat plateaus possible, if further conditions e.g. related to the ground thermal properties (Farbrot et al., 2013; Gisnås et al., 2013) are met. The latter, however, only occur for a rather small fraction within each grid cell where palsas and peat plateaus are actually observed in aerial images in this study. Although it is possible that permafrost in mire areas in Finnmark can also exist outside of palsas and peat plateaus, we suggest using the lower number of 110 km^2 as a conservative estimate for the permafrost area in mires in Finnmark in the future. We conclude that it is not possible to model the occurrence and thermal regime of palsa and peat plateaus in grid-based approaches without taking subgrid variability of environmental factors explicitly into account. There exist a variety of approaches how such small-scale variability of different factors can be included in modelling (e.g. Fiddes et al., 2015; **Kurylyk et al., 2016;** Westermann et al., 2015; Zhang et al., 2012). As exemplified by Gisnås et al. (2014) for mountain permafrost environments in Norway, redistribution of snow due to wind drift could be a governing factor for the ground thermal regime also in palsa mires, especially since palsas and peat plateaus are elevated landscape elements which feature lower snow depths than the surrounding mire area (Seppälä, 1982). Tiling approaches that facilitate a statistical representation of subgrid variability of snow depths have been implemented in a regional permafrost model for the Norwegian mountain areas (Gisnås et al., 2015), but the concept has not yet been applied to mire areas.

Up to now, a physically-based model approach for the evolution of palsas and peat plateaus is lacking, which is not surprising considering that the environmental factors giving rise to their formation, stability and degradation are not fully understood yet (Sect. 5.1). Changes in vegetation and surface properties accompanying the disappearance of palsas and peat plateaus (Fig. 2) further complicate modelling efforts. This study is clear evidence that lateral erosion is a dominant pathway for degradation of permafrost features in the sporadic permafrost zone in northern Norway. On the other hand, it is unclear if the areal loss has been accompanied by systematic elevation changes of the surface due to melting of excess ground ice in the palsas and peat plateaus, followed by the drainage of the meltwater. One-dimensional model approaches for ground subsidence and thermokarst pond formation (Lee et al., 2014; Westermann et al., 2015) are a first step towards physically-based modelling of thaw processes in ice-rich permafrost ground, but they must be included in a model framework that facilitates representing small-scale redistribution of heat, water and snow. Furthermore, fully coupled 3D-models have been demonstrated for larger thermokarst lakes (Kessler et al., 2012), and similar concepts may also be applicable to model palsa and peat plateau dynamics. We conclude that this study constitutes a solid baseline that can help to guide and validate future model improvements regarding peat plateaus and palsas.

6 Conclusion

Using high-resolution (**0.2-0.5 m^2**) aerial imagery, we systematically map the occurrence of palsas and peat plateaus **on 250 m grids** in the sporadic permafrost zone in northern Norway. Furthermore, we delineate the exact boundaries of palsas and peat plateaus at four study areas along a NE-SW transect covering both coastal and more continental inland areas (in total about 2% of the palsa mires and peat plateaus in northern Norway). Using repeat aerial images from the 1950s to the 2010s, changes in areal extent over time are investigated.

- We estimate that about 110 km^2 of the county of Finnmark are currently covered by palsas and peat plateaus, corresponding to 0.2 % of the land surface. The largest concentrations occur in the plains in the inner parts of Finnmark at elevations of 300 to 500 m a.s.l. and mean annual air temperatures between -3 and -4 °C. However, palsas/peat plateaus also exist in coastal areas below 100 m a.s.l. with mean annual air temperatures as high as +1 °C.
- Since the 1950s, the area covered by palsas and peat plateaus steadily decreased at all study areas through lateral erosion and formation of thermokarst ponds, with a total decrease in area between 33 % and 71 %. Newly formed palsas of diameter of more than 10 m were not observed **in the study areas**. In the same period, air temperatures increased by 1.0 to 1.5 °C in the study areas.
- Combining the change rates with the areal mapping, we estimate that half of the area covered by palsas and peat plateaus in the 1950s in northern Norway, i.e. an area of more than 100 km^2, has disappeared in the last 50 years.
- Signs of degradation, such as thermokarst lakes, observed in the earliest available aerial images suggest that the degradation of palsas and peat plateaus was already an ongoing process in the 1950s.
- In two study areas, the change rates can be resolved in three different time periods covering 10 to 25 years each. The mean annual loss rate is remarkably constant over the last 50 years, although a moderate acceleration during this period is observed at one of the sites. However, a direct correlation of change rates with increasing air temperatures, precipitation **or snow depth** does not exist.

The study is evidence of the highly dynamic evolution that subarctic permafrost environments can experience in relatively short time periods. Such fast changes are related to the melting of excess ground ice in palsas and peat plateaus triggering changes of microtopography that result in significant modifications of e.g. vegetation, hydrology and the carbon cycle. Model projections on the future state of such permafrost environments in general cannot account for the underlying physical processes and must therefore be regarded as highly uncertain. However, if the present-day loss rates continue in the future, palsas and peat plateaus will largely disappear in northern Norway in the course of the 21st century.

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Table 1. Key information about the aerial images utilized in this study. The images are either gathered from Norgeibilder (2015) or ordered directly from the Norwegian Mapping Authority, Norway, through an aerial image archive (Kartverket, 2015a). **GSD: ground sample distance, i.e. the distance between the centres of adjacent pixels measured on the ground.**

	Date	Source	Image scale	GSD, m	Film type
Karlebotn	28.07.1957	Aerial image archive*	1:20 000	0.42	Panchromatic (black-white)
	04.07.2005	Norgeibilder.no	ND	0.5	Analog RGB
	19.08.2008	Norgeibilder.no	ND	0.5	Digital RGB
Lakselv	20.07.1959	Aerial image archive*	1:20 000	0.26	Panchromatic (black-white)
	11.09.2008	Norgeibilder.no	ND	0.50	Digital RGB
Suossjavri	16.08/08.09 - 1956	Aerial image archive*	1:20 000	0.24	Panchromatic (black-white)
	21.07.1959	Aerial image archive*	1:20 000	0.24	Panchromatic (black-white)
	01.07/15.07 - 1982	Aerial image archive*	1:25 000	0.36	Analog RGB
	01.07.2003	Norgeibilder.no	ND	0.5	Panchromatic (black-white)
	17.08.2011	Norgeibilder.no	ND	0.4	Digital RGB
Goatheluoppal	21-22.08.1958	Aerial image archive*	1:20 000	0.24	Panchromatic (black-white)
	18-20.07.1980	Aerial image archive*	1:25 000	0.31	Analog RGB
	01.07.2003	Norgeibilder.no	ND	0.5	Panchromatic (black-white)
	14.08.2012	Norgeibilder.no	ND	0.4	Digital RGB

* http://159.162.103.4/geovekst/Flybildearkiv/ (© Norwegian Mapping Authority, Norway).

Table 2. Data of **mean annual air temperature** (MAAT), **mean annual precipitation** (MAP), **mean annual maximum snow depth** (MASD), **mean annual days of dry snow** (**MADDS)** and **mean snow fraction of total precipitation (MSFr)** during the period 1961-1990 and 1991-2014 at the four study areas, including linear trends **for MAAT, MAP and MASD** based on simple linear regression. The data are based on the seNorge (2016) dataset.

	MAAT			MAP			**MASD**			**MADDS**	**MSFr**
	1961-1990 (°C)	1991-2014 (°C)	Trend (°C(10a)$^{-1}$)	1961-1990 (mm)	1991-2014 (mm)	Trend (%(10a)$^{-1}$)	**1961-1990 (mm)**	**1991-2014 (mm)**	**Trend (%(10a)$^{-1}$)**	**1961-1990 (days)**	**1961-1990 (%)**
Karlebotn	-1.3	-0.1	+0.34	440	477	+2.6	**644**	**718**	**+16.8**	**150**	**40**
Lakselv	+0.1	+1.1	+0.25	377	392	+0.6	**436**	**401**	**-24.7**	**140**	**35**
Suossjavri	-1.9	-0.9	+0.23	492	510	+0.2	**593**	**711**	**+12.1**	**186**	**37**
Goatheluoppal	-2.9	-1.8	+0.32	354	428	+5.8	**488**	**599**	**+34.5**	**187**	**39**

Table 3. Area of all palsas and peat plateaus in *Suossjavri* for 1956/1959, 1982, 2003 and 2011, with total differences of the area between 1956/1959 and 2011.

	Total all palsas
1956/1959 (m^2)	739817
1982 (m^2)	648695
2003 (m^2)	553342
2011 (m^2)	494507
Total difference (m^2)	**-245310**
Total difference (%)	**-33**

Table 4. Area of all palsas in *Goatheluoppal* for 1958, 1980, 2003 and 2012, with total differences of the area between 1958 and 2012.

	Total all palsas
1958 (m^2)	501659
1980 (m^2)	348973
2003 (m^2)	212879
2012 (m^2)	146834
Total difference (m^2)	**-354825**
Total difference (%)	**-71**

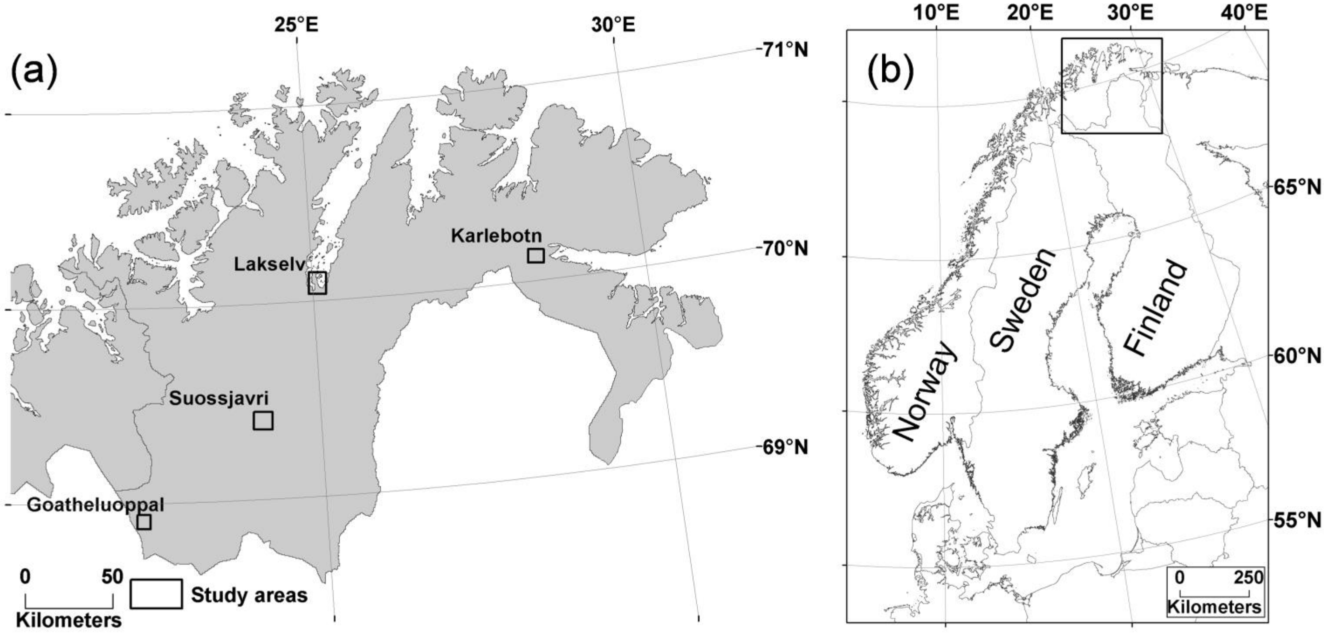

Figure 1. The county of Finnmark with the four study areas marked.

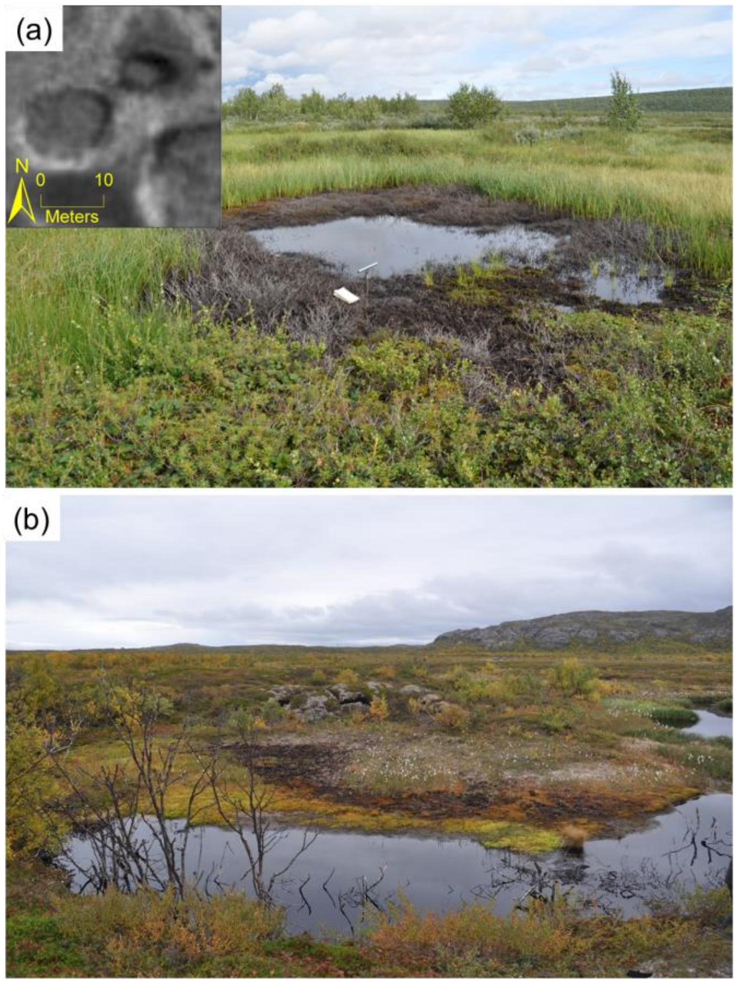

Figure 2. (a) Small thermokarst lake with recently dead vegetation at palsa mire 7 in *Suossjavri*, August 2014, situated at the location of a former small palsa (visible in aerial image from 2003, see inlet). (b) Degrading palsa and recently submerged birch trees at palsa mire 2 in *Karlebotn*, September 2015.

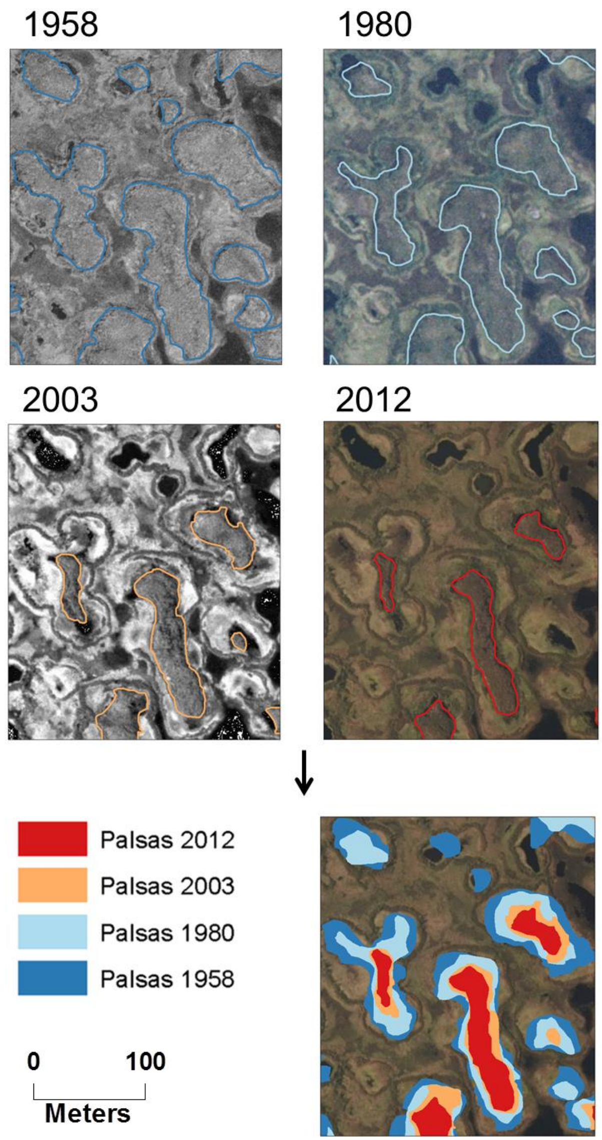

Figure 3. Example of polygons from the delineation of palsas at four different times in *Goatheluoppal*.

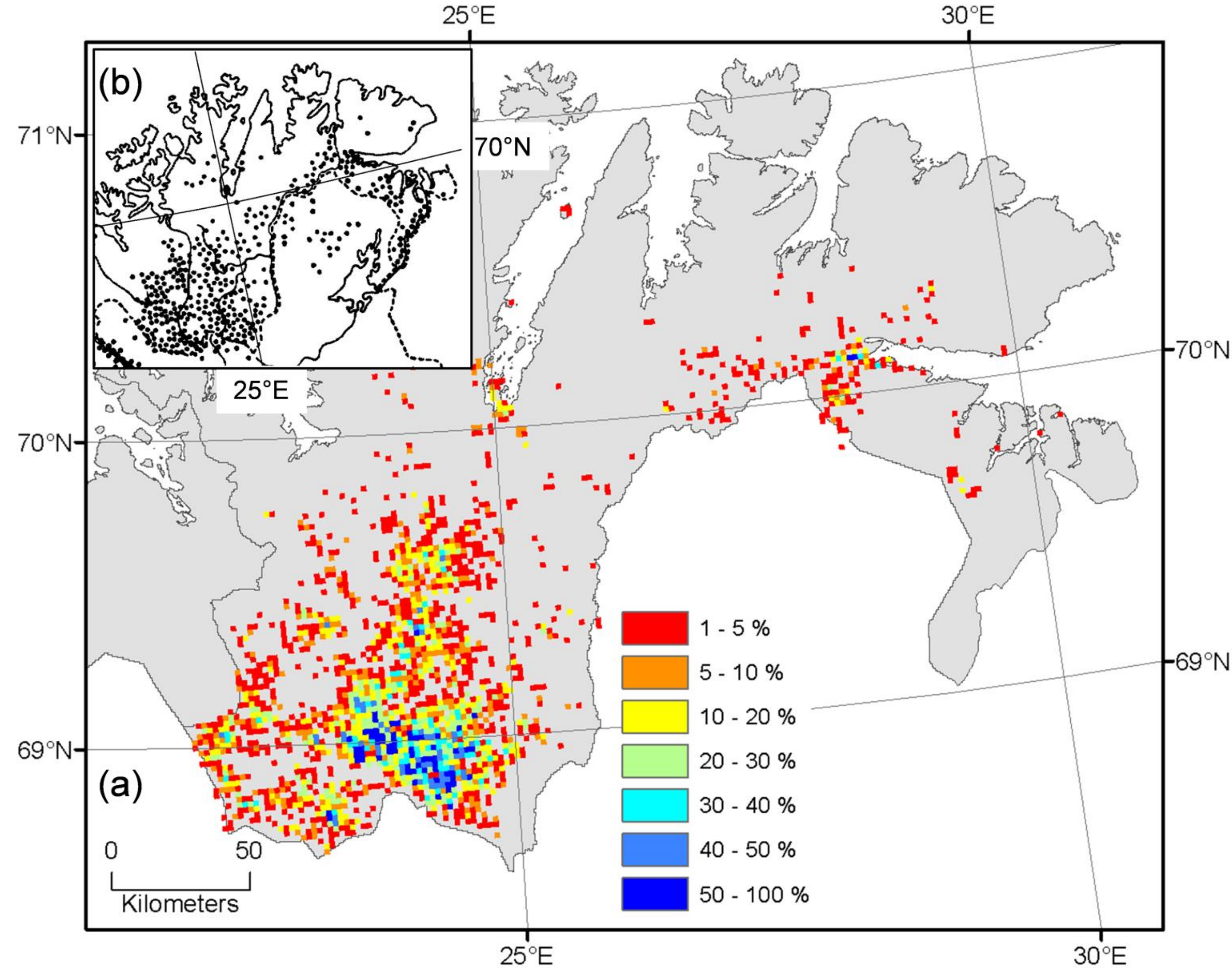

Figure 4. Distribution of palsas and peat plateaus in Finnmark at 2 km resolution. The concentration reflects the proportion (in percent) of 250 m^2 grid-cells that have presence of palsas in 2 km^2 grid-cells. The inlet map (b) shows the distribution of palsa mires mapped by Sollid and Sørbel (1998) based on work from the 1960s-1970s (Sollid and Sørbel, 1974).

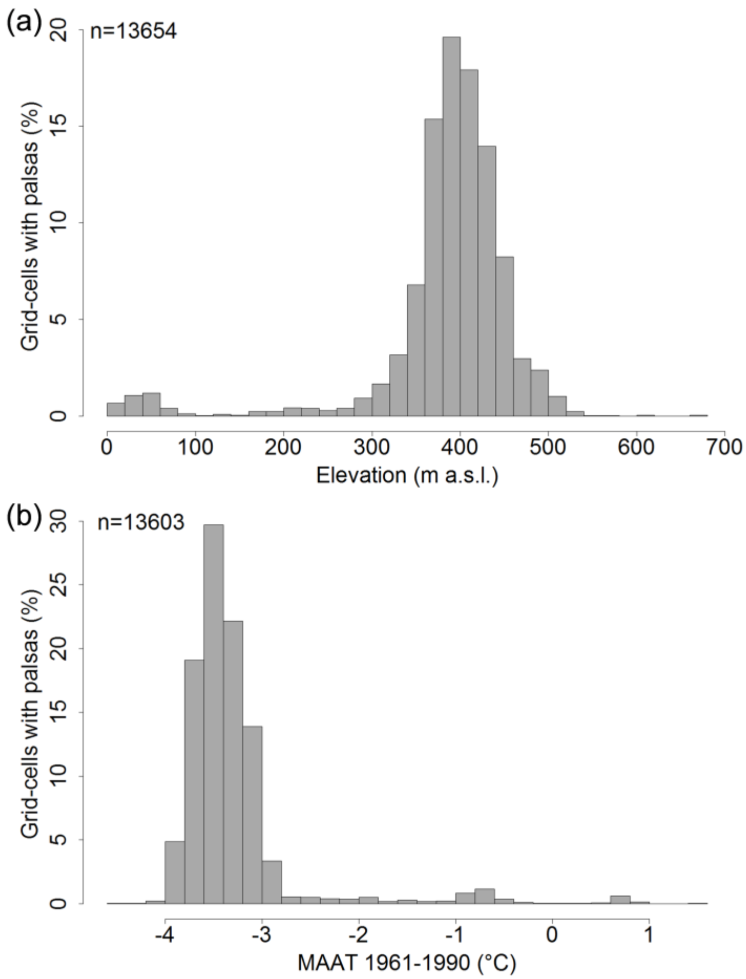

Figure 5. Histograms based on the location of the 250 m^2 grid-cells with presence of palsas and peat plateaus for (a) gridded data of the minimum elevation (Kartverket, 2015b) in each grid cell and (b) gridded data of **mean annual air temperature (MAAT) for 1961-1990** (seNorge, 2016). The number of grid-cells used in the histograms deviate slightly from the mapped number of grid-cells with palsas due to insufficient covering close to the coast and to the Norwegian border of the gridded layers of MAAT and the **digital elevation model**.

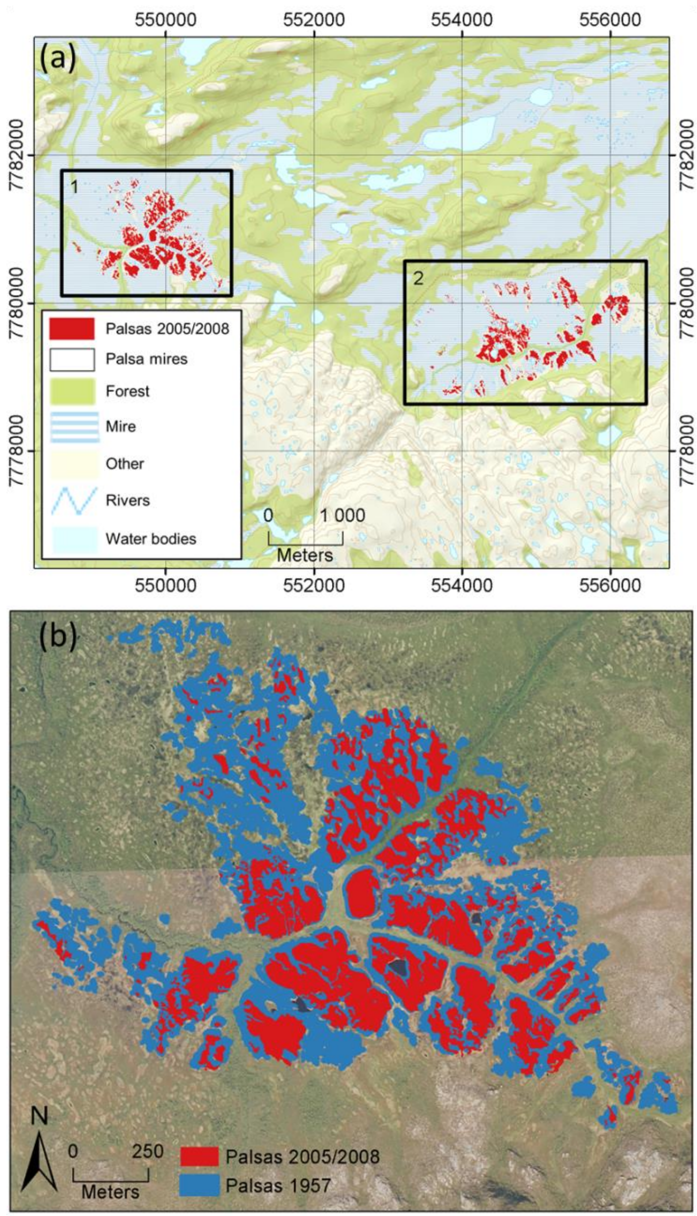

Figure 6. (a) Palsa mires mapped in *Karlebotn*. Background map from Kartverket (2015b) with projection in UTM 35N. (b) Palsas and peat plateaus mapped in mire 1. Background image from 2008 through Norgeibilder (2015).

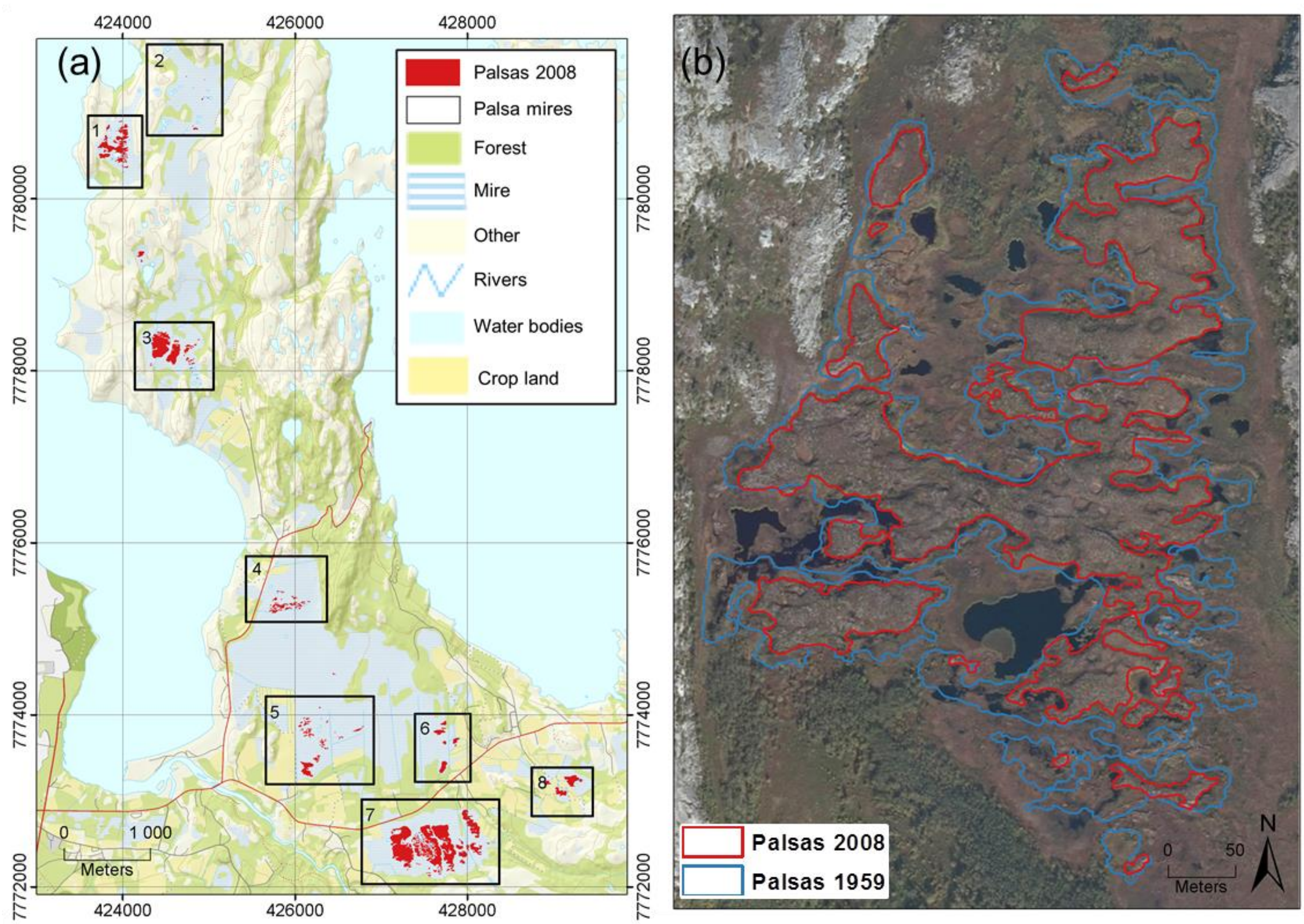

Figure 7. (a) Palsa mires mapped in the study area *Lakselv*. Some smaller palsas are outside these eight palsa mires. Background map from Kartverket (2015b) with projection in UTM 35N. (b) Palsas mapped in palsa mire 1 in *Lakselv*. Background image from 2008 through Norgeibilder (2015).

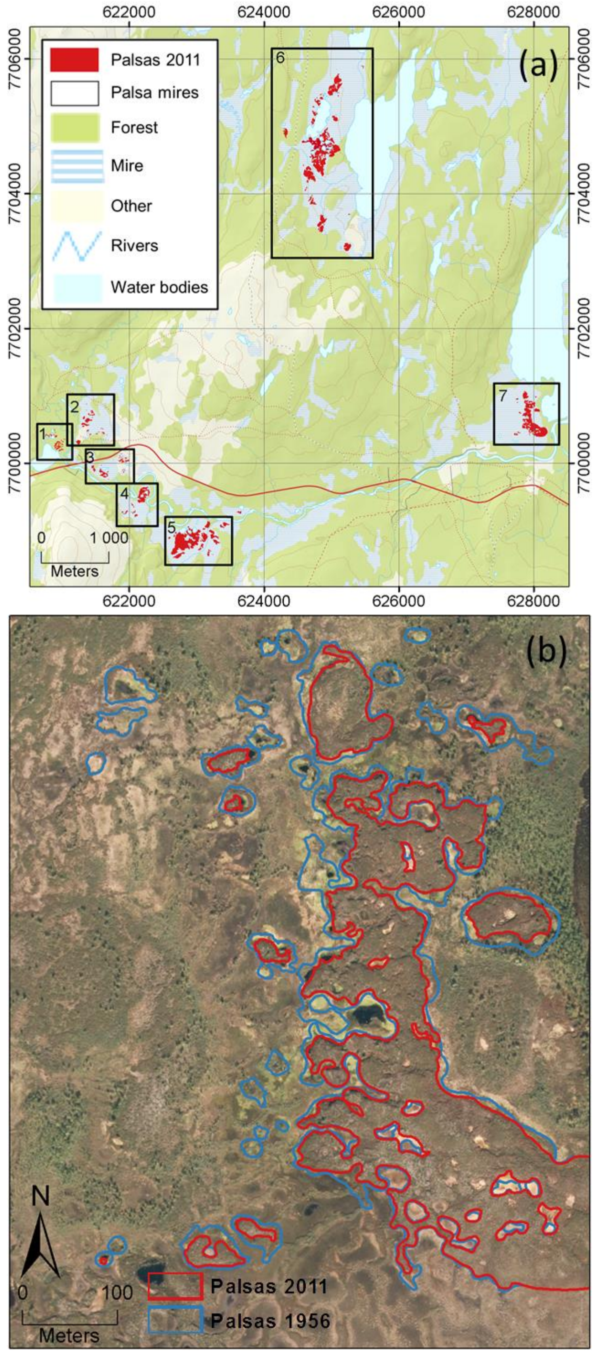

Figure 8. (a) Palsa mires mapped in the study area *Suossjavri*. Background map from Kartverket (2015b) with projection in UTM 34N. (b) Palsas and peat plateaus mapped in palsa mire 7 in *Suossjavri*. To increase the visibility of this figure, only the delineation of palsas from 1956 and 2011 is included. Background image from 2011 through Norgeibilder (2015).

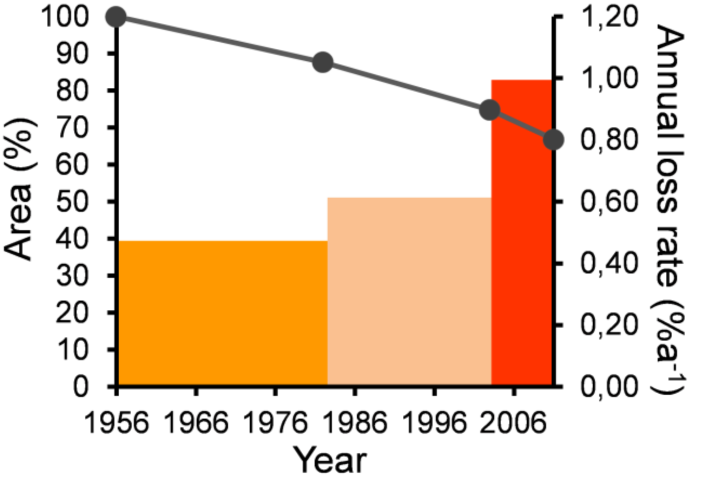

Figure 9. Areal extent of palsas and peat plateaus in *Suossjavri* relative to the area in 1956 **(dots)**, and mean annual loss rates **(bars)** for the different time periods.

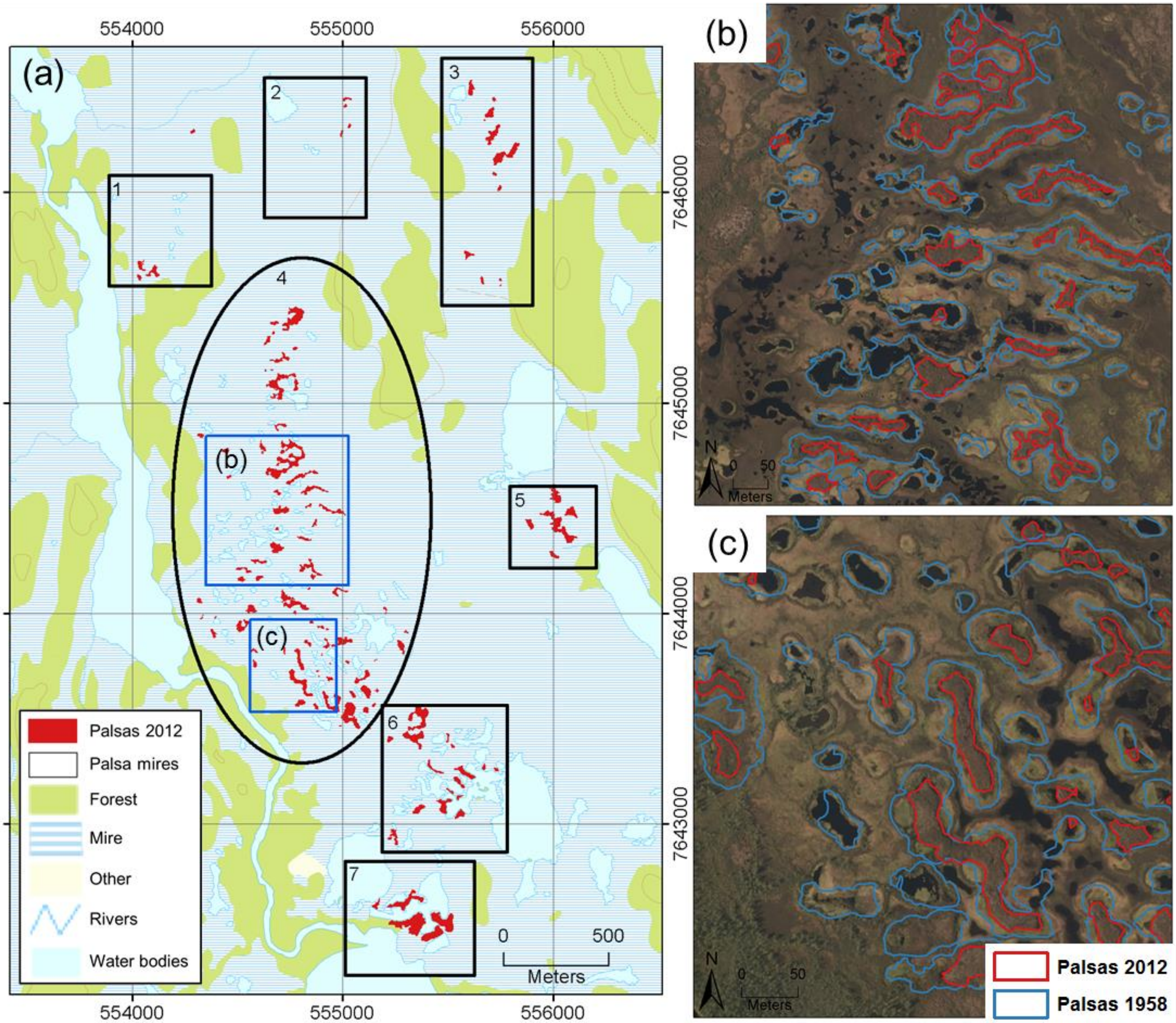

Figure 10. (a) Palsas mires mapped in the study area *Goatheluoppal*. Background map from Kartverket (2015b) with projection in UTM 35N. The images in (b) and (c) show examples of some palsas mapped in the palsa region 4 in *Goatheluoppal*. To increase the visibility of this figure, only the delineation of palsas from 1958 and 2012 is included. Background images from 2012 through Norgeibilder (2015).

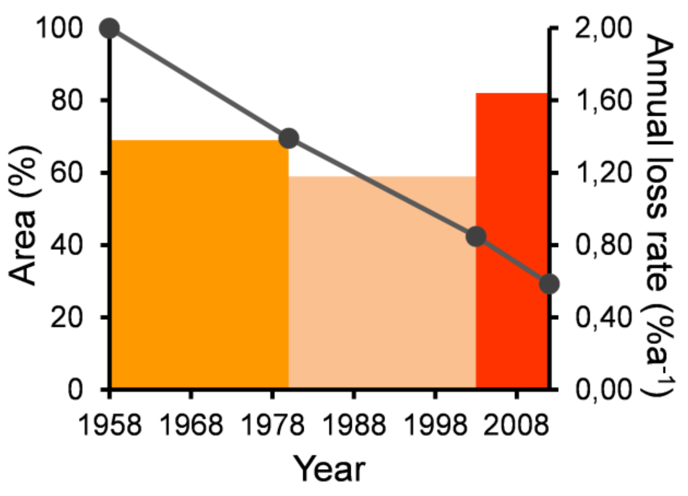

Figure 11. Areal extent of palsas and peat plateaus in *Goatheluoppal* relative to the area in 1958 **(dots)**, and mean annual loss rates **(bars)** for the different time periods.

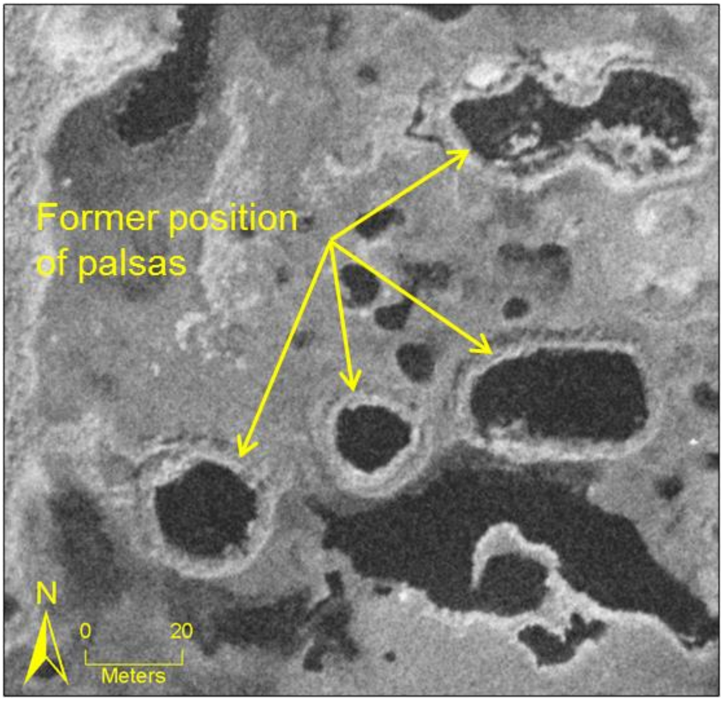

Figure 12. Examples of thermokarst lakes encircled by rim ridges in an image from 1958 of the palsa region 4 in *Goatheluoppal*.

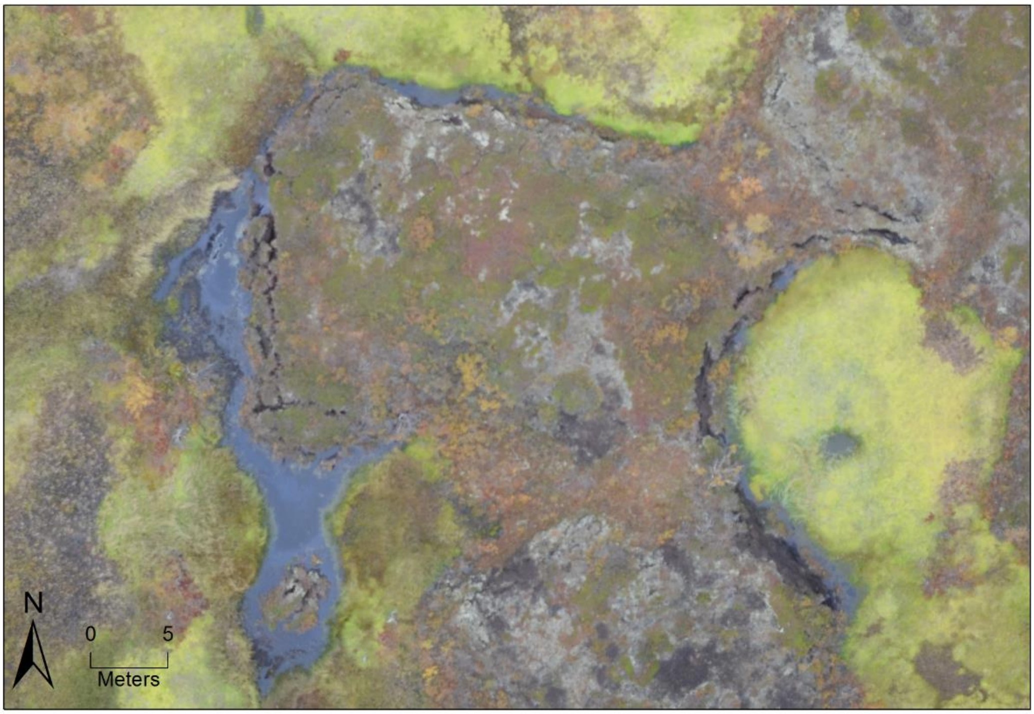

Figure 13. High-resolution aerial image of a peat plateau in mire 7 at *Suossjavri*. Note the ongoing block erosion at the margins where blocks of peat collapse in the thermokarst ponds flanking the eroding edge. The more stable margins do not feature ponds and mire vegetation grows directly at the edge of the peat plateau.