Supplement of The Cryosphere, 17, 1803–1819, 2023
https://doi.org/10.5194/tc-17-1803-2023-supplement

The Cryosphere
Open Access

Supplement of

Permafrost degradation at two monitored palsa mires in north-west Finland

Mariana Verdonen et al.

Correspondence to: Mariana Verdonen (mariana.verdonen@uef.fi)

Table S1. Dates of active layer thickness (ALT) measurements, number of points at which the ALT was ≤ 1m (all, and within top-of-palsa (TOP) areas), and mean ALTs ± 1SD. Note that in 2018, the active layer was not measured at the same points as in other years due to an RTK-GNSS malfunction. Therefore, we interpolated the 2018 ALT values using the Natural Neighbour method and extracted the values from the interpolated raster layers at the locations of points measured in 2019.

Site	Date	N. of points (all)	Mean ALT in cm (all) ± SD	N. of points (TOP)	Mean ALT in cm (TOP) ± SD
Peera	27.08.2007	89	59.0 ± 7.2	31	59.6 ± 6.5
	27.08.2008	193	55.2 ± 8.9	68	54.0 ± 6.3
	31.08.2009	104	55.5 ± 8.4	31	56.9 ± 6.6
	30.08.2010	147	56.1 ± 8.8	52	56.3 ± 6.8
	28.08.2011	145	63.5 ± 8.2	55	61.9 ± 5.7
	26.08.2012	128	51.7 ± 9.9	36	53.4 ± 4.7
	09.09.2013	116	65.6 ± 10.5	36	62.8 ± 6.0
	29.08.2014	96	71.7 ± 10.6	42	69.6 ± 8.6
	26.08.2015	142	65.9 ± 11.1	64	63.8 ± 8.8
	24.08.2016	136	66.5 ± 11.0	68	65.3 ± 9.9
	31.08.2017	142	65.5 ± 13.0	68	63.6 ± 8.5
	26.08.2018	98	63.0 ± 9.4	68	62.4 ± 5.7
	24.08.2019	140	53.1 ± 10.5	68	54.9 ± 7.4
	23.08.2020	115	62.2 ± 12.2	68	61.2 ± 10.1
	27.08.2021	107	60.1 ± 14.4	68	57.7 ± 11.2
Laassaniemi	27.08.2007	110	56.7 ± 8.7	35	55.7 ± 4.1
	27.08.2008	180	60.4 ± 16.3	46	52.2 ± 3.6
	29.08.2009	145	53.8 ± 10.4	43	52.2 ± 3.9
	30.08.2010	99	56.5 ± 12.2	36	54.9 ± 4.5
	28.08.2011	117	57.6 ± 9.0	46	57.2 ± 5.5
	25.08.2012	134	50.5 ± 11.6	46	48.3 ± 6.8
	10.09.2013	117	59.4 ± 10.4	46	57.5 ± 4.7
	27.08.2014	71	58.3 ± 10.0	46	55.6 ± 5.7
	29.08.2015	95	48.7 ± 11.7	46	46.1 ± 7.0
	26.08.2016	98	54.6 ± 14.9	46	47.7 ± 6.1
	01.09.2017	92	45.8 ± 14.4	46	40.5 ± 5.3
	25.08.2018	88	50.7 ± 12.8	46	45.3 ± 3.5
	25.08.2019	81	43.6 ± 8.0	46	41.3 ± 4.2
	24.08.2020	78	42.6 ± 7.2	46	40.5 ± 4.5
	28.08.2021	75	43.9 ± 11.9	46	40.5 ± 3.9

Table S2. Aerial data from the National Land Survey of Finland (NLS) used in this work. Data accessed through the NLS WCS-service: https://www.maanmittauslaitos.fi/ortokuvien-ja-korkeusmallien-kyselypalvelu (in Finnish)

Data	Date	Cell size (cm)	Spectral resolution
Aerial	13.08.1959	50	Panchromatic
Aerial	07.07.1985	50	Panchromatic
Aerial ortho	25.07.2000	50	Multispectral
Aerial ortho	14.08.2012	50	Multispectral

Table S3. UAS RGB data that were used in this work. The DSM cell sizes are provided for the data that were used for analysing palsa changes from the UAS DSMs. XYZ -errors (cm) refer to ground control points (GCPs) RMSEs if they were used. Without GCPs, the errors refer to camera location errors. Cell sizes are in centimetres.

Site	Date	Cell size ortho	Cell size DSM	Platform	Sensor	GCPs	X-error	Y-error	Z-error	Pixel error
Peera	24.08.2016	3.3	6.7	DJI Phantom 3	DJI FC300X	3	1.8	1.8	0.8	1.4
	02.09.2017	1.5		Trimble - ZX5	E-PL7	10	0.9	0.6	0.4	0.4
	19.06.2018	2.5		DJI Phantom 3	DJI FC300X	5	0.06	0.03	0.05	0.4
	26.08.2019	1.6		DJI Phantom 4 RTK	DJI FC6310R	9	0.9	0.9	0.3	0.6
	25.08.2020	2.4		DJI Phantom 4 RTK	DJI FC6310R	6	0.6	0.5	0.8	0.4
	28.08.2021	1.4	2.8	DJI Phantom 4 Pro	DJI FC6310	5	1.0	1.4	1.3	0.5
	29.08.2021	1.5		DJI Matrice 300	ZenmuseP1	5	0.8	0.9	1.0	1.5
Laassaniemi	26.08.2016	3.4	6.9	DJI Phantom 3	DJI FC300X	4	4.9	9.8	19.4	2.3
	01.09.2017	1.4		Trimble ZX5	E-PL7	8	0.06	0.06	0.04	0.4
	19.06.2018	2.5		DJI Phantom 3	DJI FC300X	6	0.9	1.5	1.1	0.5
	25.08.2019	1.1		DJI Phantom 4 Pro	DJI FC6310S	5	0.3	0.6	5.1	0.5
	24.08.2020	2.5		DJI Phantom 4 RTK	DJI FC6310R	0	0.04	0.03	0.09	-
	28.08.2021	1.6	3.1	DJI Matrice 300	ZenmuseP1	4	1.6	1.5	4.1	1.4

Application of SnowModel to estimate snow depth on Peera and Laassaniemi palsas

SnowModel (Liston and Edler, 2006) is a Fortran77 based program to simulate snow depth, snow water equivalent and other snow conditions at time intervals from 10 min to 24 h. SnowModel (Fig. S1) is an aggregation of four submodels, which were originally developed for non-forested arctic and alpine conditions: (1) SnowPack to simulate changes in snow depth based on temperature, precipitation, melting, and sublimation processes; (2) SnowTran-3D to simulate the effects of wind, suspension, saltation, snow erosion on slopes, accumulation at the end of hill slopes, and vegetation; (3) MicroMet to simulate the basic distribution of meteorological input for the investigation area; and (4) EnBal to simulate the energy balance of the surface based on the meteorological inputs of the MicroMet model. Each submodel is described in detail in Liston and Edler (2006) and in the references therein.

Although, the highest recommended spatial resolution for SnowModel results is 1 m (Liston and Edler, 2006), higher resolution of 0.3 m resulted in better snow depth estimations at Peera palsa mire based on Störmer’s (2020) analyses, where he compared SnowModel results using various settings to the observations in situ 8.1.–3.3.2019. Therefore, we decided to use a 0.3 m spatial resolution.

SnowModel requires information about meteorological conditions, vegetation cover, and topography as inputs to model snow depth. As meteorological data, we used daily values of mean air temperature (°C), precipitation (mm), relative humidity (%), wind direction (°), and wind speed (m s^{-1}) measured at the Kilpisjärvi weather station. Digital Surface Models (DSMs), based on Unoccupied Aerial System (UAS) RGB data from August 2018, were resampled to 0.3 m cell size and used as input elevation models for Peera and Laassaniemi palsa mires. As vegetation affects the DSMs, some errors in SnowModel results may be introduced, especially in areas of very dense shrub cover.

For the vegetation classification of Peera (Fig. S2 a), we used the vegetation cover map produced by Tomhave (2018), which was validated in the field in August 2019. The vegetation classes used by Tomhave (2018) were adapted to predefined vegetation types with different snow-holding depths provided in SnowModel (see Table 1 in Liston and Elder, 2006). A similar classification was performed for Laassaniemi (Fig. S2 b) for use in this study.

We generated daily snow depths at Peera and Laassaniemi for the snow periods starting from October 2006 until the end of May 2021. We then extracted the average top-of-palsa (TOP) values from the snow-depth raster layers produced by SnowModel using the *terra* package (v1.7-3; Hijmans, 2023) in R (R Core Team, 2021). The TOP snow depths at the end of March were then used as explanatory variables in linear regression to analyse their effect on the annual active layer thicknesses.

We also compared the snow depth values estimated by SnowModel with the values measured in situ at four points on Peera palsa 8.1.–3.3.2019 (Table S4 and Fig. S3). In general, the model performed well in estimating the values until the 14th of February (DOY 45), when a heavy snowfall occurred. After mid-February, SnowModel overestimated especially the values at the higher parts of the palsa (P1 and P5). Nevertheless, the RMSEs were 40–85 % lower between the observed and estimated values than between the in situ observations and the observations at the Kilpisjärvi weather station (Table S4).

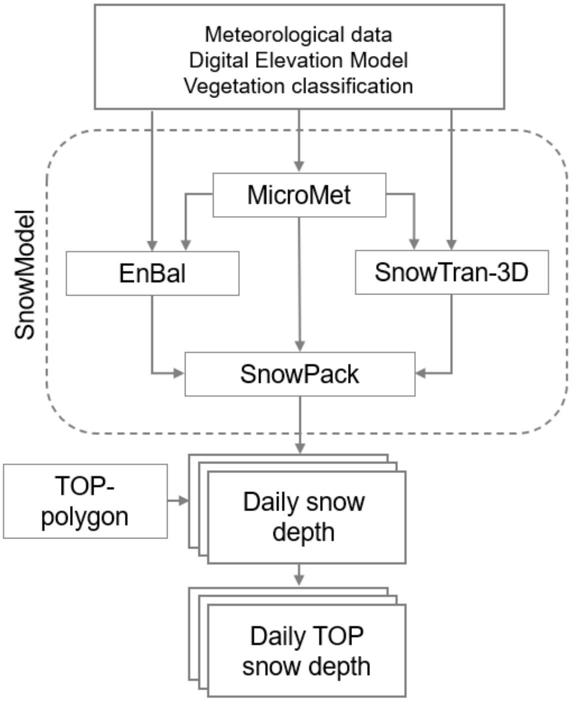

Figure S1. Flowchart of the SnowModel application to estimate daily snow depth within top-of-palsa (TOP) areas of Peera and Laassaniemi palsas.

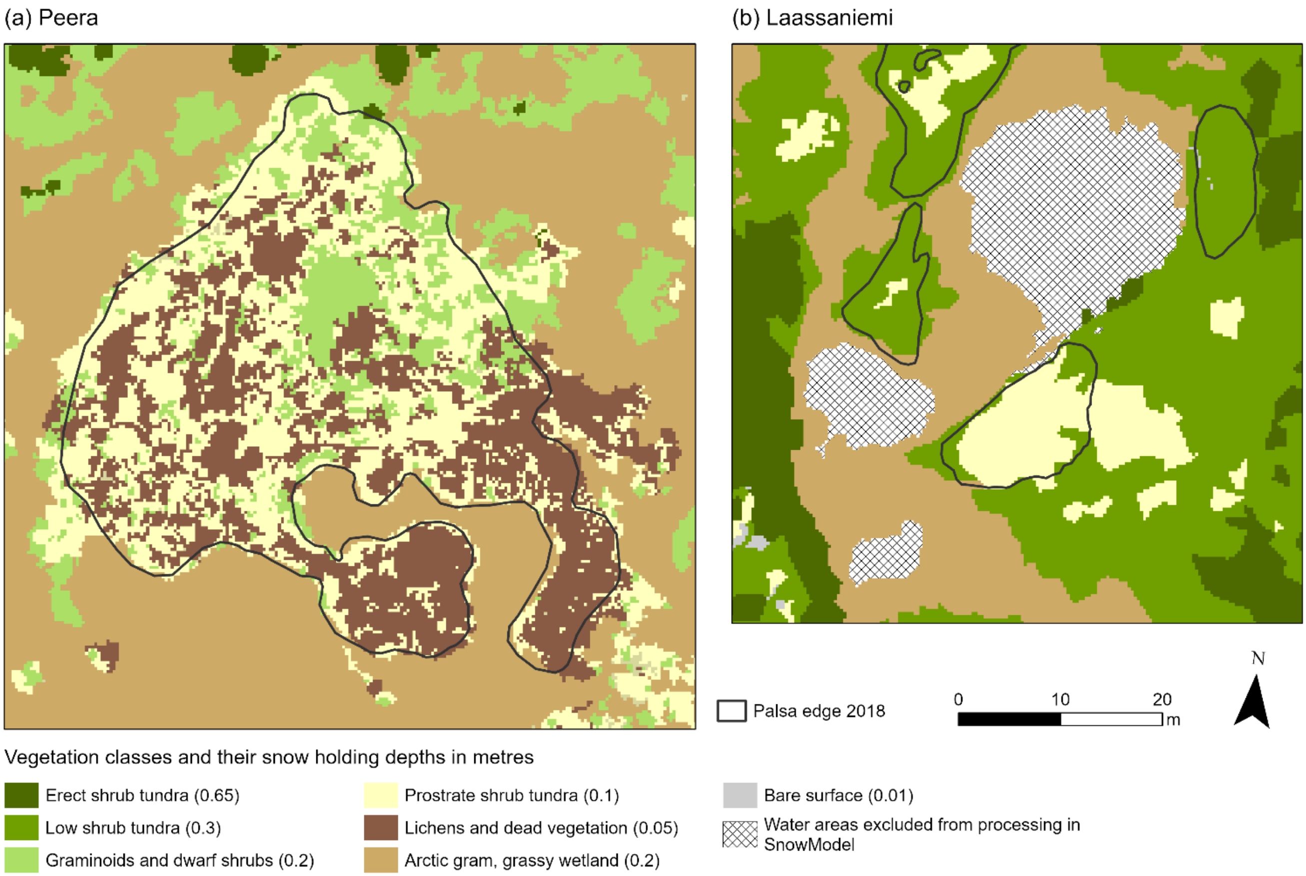

Figure S2. Vegetation classifications of UAS RGB orthomosaics from 2018 used as input layers in SnowModel. Numbers in brackets indicate snow-holding depths (m) associated with respective vegetation type in SnowModel.

Table S4. RMSEs (cm) between observed snow depth values at four points at Peera and snow depth estimated by SnowModel, and between the observed values and snow depth measured at the Kilpisjärvi weather station (FMI).

	SnomModel	FMI
P1	25.4	42.0
P5	9.1	21.5
P6	7.9	15.8
LTP3	6.9	48.1

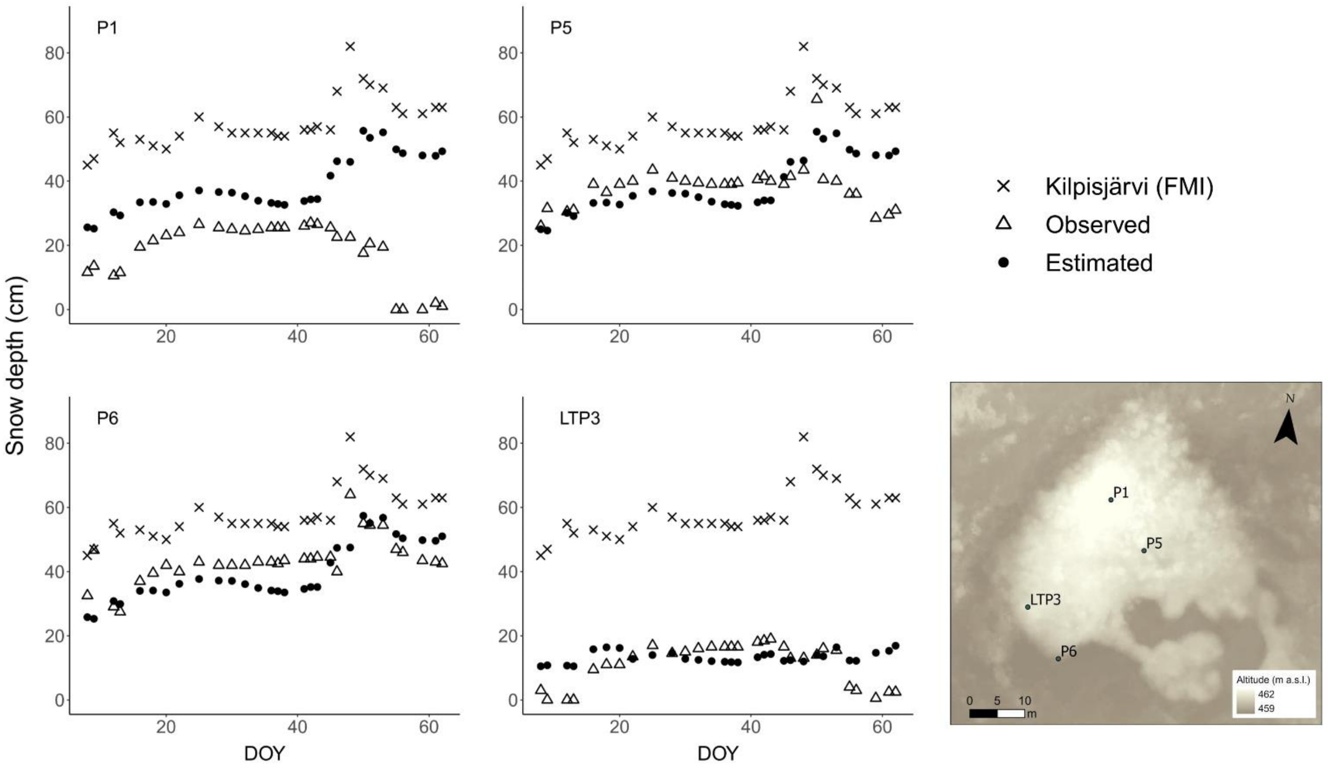

Figure S3. Observed and estimated snow depth at Peera 8.1.–3.3.2019, and the snow depth values measured at the Kilpisjärvi weather station (FMI).

References

FMI: Download observations, https://en.ilmatieteenlaitos.fi/download-observations, last access: 7.2.2022

Hijmans R.: terra: Spatial Data Analysis. R package version 1.7-3, https://CRAN.R-project.org/package=terra, 2023.

Liston, G.E. and Elder, K. A.: Distributed Snow-Evolution Modeling System (SnowModel), J. Hydrometeorol., 7, 1259–1276, https://doi.org/10.1175/JHM548.1, 2006.

R Core Team: R: A Language and Environment for Statistical Computing (Vienna, Austria: R Foundation for Statistical Computing) Online at http://R-project.org, 2021

Störmer, A.: Modelling snow distribution over discontinuous permafrost related to climate change in Kilpisjärvi, Finnish-Lapland, M.S. thesis, Faculty of Natural Sciences, Gottfried Wilhelm Leibniz University of Hannover, Germany, 2020.

Tomhave, L.: Palsa Development and Associated Vegetation in Northern Finland, (in German), B.S. thesis, Faculty of Natural Sciences, Gottfried Wilhelm Leibniz University of Hannover, Germany, 2018.

Table S5. Annual subsidence within the top-of-palsa areas (cm) based on the RTK-GNSS measurements 2007–2021.

Year	Peera	Laassaniemi
2008	-0.48	-4.41
2009	-1.12	-6.83
2010	-0.60	-6.29
2011	-1.73	-7.73
2012	-2.99	-8.57
2013	-1.31	-6.74
2014	-3.90	-6.94
2015	-1.33	-6.30
2016	-3.85	-6.68
2017	-2.29	-4.94
2018	-2.44	-2.38
2019	-2.44	-2.38
2020	-2.12	-1.03
2021	-3.96	-2.97

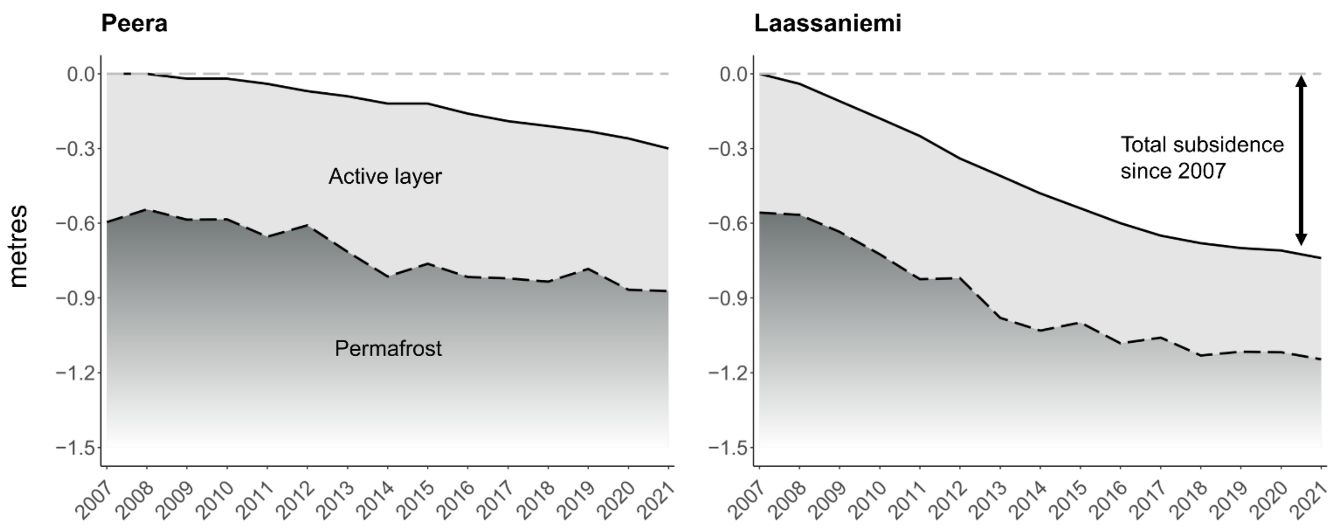

Figure S4. Top-of-palsa surface (solid line) and bottom of the active layer (black dashed line) positions relative to the 2007 level (grey dashed line) based on the RTK-GNSS measurements.