Palsa Development and Associated Vegetation in Northern Sweden

Authors: Zuidhoff, Frieda S., and Kolstrup, Else

Source: Arctic, Antarctic, and Alpine Research, 37(1) : 49-60

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/1523-0430(2005)037[0049:PDAAVI]2.0.CO;2

Arctic, Antarctic, and Alpine Research, Vol. 37, No. 1, 2005, pp. 49–60

Palsa Development and Associated Vegetation in Northern Sweden

Frieda S. Zuidhoff† and Else Kolstrup**

*Physical Geography, Department of Earth Sciences, Uppsala University, Villavägen 16, S-752 36 Uppsala, Sweden.
†Present address: Hof der Toekomst 48, 3823 HX Amersfoort, The Netherlands.
f.zuidhoff@archeologie.nl

Abstract

Palsas in all stages of growth and decay were investigated for vegetation, snow depth, and thaw depth in summer in four bogs in northern Sweden. A field classification of successive palsa stages was developed based on palsa vegetation composition and morphology. The initial phase of the aggrading stage is characterized by low mound forms and vegetation with the same hydrophilous composition as in the bog, but somewhat dried out. In the stage of continued aggradation *Betula nana* colonizes from the surroundings and hydrophilous vegetation is poorly represented in the higher parts even though the mounds are still low. Stable palsas, which are usually the tallest mounds, have vegetation that tolerates drier conditions; *Empetrum hermaphroditum* is the vascular species with the highest coverage at this stage. Decay starts with block erosion and melting of the mound forms. Degrading palsas have taller shrub vegetation that causes significantly thicker snow reducing heat loss from the core in winter. Conversely, the shrub vegetation has a dampening effect on penetration of heat into the mounds in summer. The degraded stage bears no morphological resemblance to the mounds, but at this stage there is a higher diversity of species owing to additional moist and wet growing sites.

Introduction

Palsas are perennial mounds found in peat bogs in areas with discontinuous and sporadic permafrost (e.g., Lundqvist, 1969; Seppälä, 1988) and occasionally also in continuous permafrost areas (e.g., Åkerman, 1982, Washburn, 1983). They owe their existence to local accumulations of ice lenses formed by cryosuction within the peat, and sometimes also in underlying silty sediments, and require specific thermal and hydrological conditions for their growth (Wramner, 1973; Åhman, 1977; Pissart, 1983). The term palsa is discussed widely in the literature (e.g., Pissart, 1983; Harris, 1993; Gurney, 2001). In this paper it is used for perennial mounds formed from segregation ice in subarctic and subalpine wetlands whether they consist of pure peat or have a mineral core beneath peat.

Over the years a diversity of palsa forms—in particular mounds, ridges, and plateaus (e.g., Wramner, 1973; Åhman, 1977)—have been the subject of investigations in Scandinavia and other periglacial regions, and much information is available on their external and internal morphological characteristics, geographical distribution, and relation to climatic, hydrological, and lithological conditions. There is general agreement that a surface layer of peat is a prerequisite for the development of palsas and they are probably the periglacial landforms that are most dependent on vegetation. In spite of this, relatively few studies (e.g., Wramner, 1973; Worsley et al., 1995) have focused on vegetation cover and its relationship to palsa growth and decay.

This paper outlines vegetation characteristics for different stages of representative palsas in four Swedish palsa bogs along a northeast-southwest line; these are compared to a fifth site investigated by Wramner (1973). The linking of vegetation cover and composition with palsa morphological characteristics results in a revised scheme to classify palsa development.

Palsa Development

It has long been hypothesized that palsas go through a cycle of development (e.g., Du Rietz, 1921a; Svensson, 1962; Wramner, 1967, 1973; Railton and Sparling, 1973), and Seppälä (1986) outlined a general scheme for the cycle. This can be summarized as follows: initially there is local ice lens development with associated rise of the bog surface; then follows an embryo stage with continued and deeper freezing that raises the surface farther so that snow can be blown off in winter; subsequently the frost reaches the underlying silty sediments and the form has thereby reached the mature stage. At this stage the relief is usually at a maximum. Degradation follows, during which block erosion, collapse, deflation, and rain erosion takes place, or the palsa melts from below. Old palsas are more or less destroyed forms before they ultimately become dead palsas, which are unfrozen remnants, such as circular rims or open ponds (Seppälä, 1986). No vegetation development is given in relation to this outline.

To avoid confusion with the terminology above and also to allow for the possibility that a smaller palsa in one area may be older and further developed than a higher, less developed, form in another, the terminology of Cummings and Pollard (1989) of aggrading, stable, and degrading has been applied in this paper. In some cases it has been necessary to further subdivide the aggrading and degrading stages.

Study Areas

The four study areas are located in the discontinuous and sporadic permafrost zones in northern Sweden and are, from the northeast to the southwest, Keinovuopio, Seitajaure, Staloluokta, and Laivadalen (Fig. 1). The fifth site, Taavavuoma (Wramner, 1973), is located between Keinovuopio and Seitajaure. Geographical and meteorological data as well as information on timberline altitudes are given in Table 1.

Local weather data for Staloluokta and Laivadalen are integrated with data from nearby weather stations as presented in Westin and Zuidhoff (2001) and Zuidhoff and Kolstrup (2000), respectively. For Seitajaure local data from the bog are combined with data from Nikkaluokta (470 m). No local records exist from Keinovuopio; out of necessity a lapse rate of 0.6°C 100 m^{-1} altitude (in relation to Naimakka at 403 m) was chosen for calculating local temperature from reference normals at the meteorological station (Alexandersson et al., 1991). We realize that a different lapse rate might give slightly different local temperature data. For Taavavuoma a lapse rate of

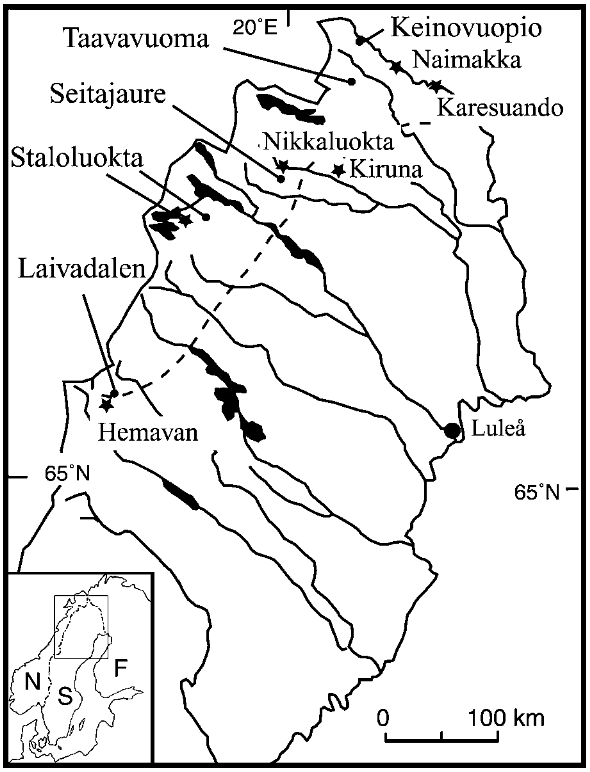


FIGURE 1. Part of Scandinavia with the localities Keinovuopio, Taavavuoma, Seitajaure, Staloluokta, and Laivadalen (dots) and the meteorological stations at Naimakka, Karesuando, Kiruna, Nikkaluokta, and Staloluokta (stars). The locality of Staloluokta includes the Vattenfall weather station. The zone of palsa distribution (dashed line) is drawn after Sollid and Sørbel (1998).

0.6°C 100 m^{-1} was also chosen in relation to weather stations at 325 and 475 m; in this case for the reference normals for the period 1931–1960 (Alexandersson et al., 1991), which is relevant to the work of Wramner (1973).

In Keinovuopio the topography is undulating with mountains up to 750 m a.s.l. In the palsa area the sediments beneath the 15- to 110-cm-thick peat is dominated by silt. The regional vegetation is birch forest with heath and mosses in the field layer (Von Sydow, 1983a). During field work it was noted that the palsa area is a bog, i.e., the conditions are waterlogged and acidic. For Keinovuopio no map is presented.

The Taavavuoma area is described in Wramner (1973: 19ff) and is an approximately 200-km^2 flat, east-west oriented depression. The palsa forms in this bog area are diverse but those that were investigated in relation to their vegetation form mounds. The peat is "thick" and the palsa areas seem mainly to be underlain by silty sediments. According to Von Sydow (1983a) the dominant vegetation in and around the area is birch forest together with bogs (see above) and fens (i.e., more alkaline moist/wet areas) with peat accumulation and hummock vegetation.

The palsa bog in Seitajaure (Fig. 2) is about 3 by 5 km (Zuidhoff, 2003). The sediments beneath the 75- to 160-cm-thick peat (Table 2) are mainly sandy till with a content of silt and stones. According to Rafstedt (1983) the regional vegetation belongs to the low alpine region and consists of wet and dry fens, willow shrub and wet heaths.

The palsas in Staloluokta are situated in two low-lying areas next to higher, windswept plateaus with thermal contraction polygons (Fig. 2) (Westin and Zuidhoff, 2001). The 10- to 55-cm-thick peat overlies silt and fine sand. The dominant vegetation is shrub-heath vegetation with *Betula nana*, *Empetrum hermaphroditum*, other Ericaceae, grasses, and sedges, as well as mosses and lichens and with willow shrub in sheltered places (Von Sydow, 1983b). In this area there might be a possibility that the palsa is a remnant of a former peat plateau; however, in the bog surrounding the palsa there were no signs of dead or drowned plants characteristic of drier areas as it was seen in bogs with many remnant palsas.

The palsa bog in Laivadalen is about 500 by 500 m and is located within a ca. 2-km-wide, north-south oriented valley (Fig. 2). The two embryo palsas in Laivadalen are situated outside the main palsa bog and are not shown in Figure 2. Beneath the 50- to 265-cm-thick peat the sediments are dominated by silt (Zuidhoff and Kolstrup, 2000). The vegetation in the surroundings belongs to the low alpine and birch forest region and in the lower part of the valley it is mainly dominated by fresh heath, bog, and fen hummock vegetation (Grundsten, 1979).

Methods

In the field, different palsa stages were recognized by vegetation, stability of palsas, and palsa height, to a large extent following the description by Wramner (1973), but with the emphasis on the vegetation composition and cover. The fieldwork took place over 5 yr between 1996 and 2001, too short a time-span to see full cycles of development and decay of individual forms. Out of necessity, a time-space substitution therefore had to been applied: i.e., the development stages of live vegetational composition on the palsas was related to vertical changes in macrofossil composition as seen in cuttings through the peat (Zuidhoff and Kolstrup, 2000). Besides, to further ascertain successive development stages, the development of palsas in Laivadalen was reconstructed from a comparison with Wramner (1967), use of aerial photographs of different age, as well as radiocarbon dating (Zuidhoff and Kolstrup, 2000). Following a general inventory of the palsa bogs, a representative selection of palsas in

TABLE 1

Latitude, longitude, altitude, treeline, mean annual temperature (MAAT), mean temperature of the warmest month (July), and mean temperature for the coldest month (January) for the investigation sites at Keinovuopio, Seitajaure, Laivadalen, Staloluokta, and Taavavouma (relevant for Wramner's [1973] investigation). Mean annual precipitation and mean winter precipitation (November–April) for the nearest meteorological station.

	Latitude (N)	Longitude (E)	Altitude (m a.s.l.)	Treeline (m a.s.l.)	Record period	MAAT (°C)	Mean July (°C)	Mean January (°C)	Meteorological station (m a.s.l.)	Mean annual precipitation (mm)	Mean winter precipitation (mm)
Keinovuopio	68°27′	21°02′	450	500–650	1961–1990	−2.9	11.5	−16.1	Naimakka (403)	429	130
Taavavuoma	68°30′	20°45′	540–570	600	1931–1960	−3 to −4			Karesuando (325)/Kiruna (475)	513/380	
Seitajaure	67°44′	18°52′	760	750	1961–1990	−3.0	11.4	−17.1	Nikkaluokta (470)	508	188
Staloluokta	67°17′	16°50′	725	600–700	1994–1998	−3.5	9.4	−8.8	Staloluokta (600)	549	239
Laivadalen	66°06′	15°30′	610	670–720	1961–1990	−1.5	9.9	−13.4	Hemavan (475)	737	343

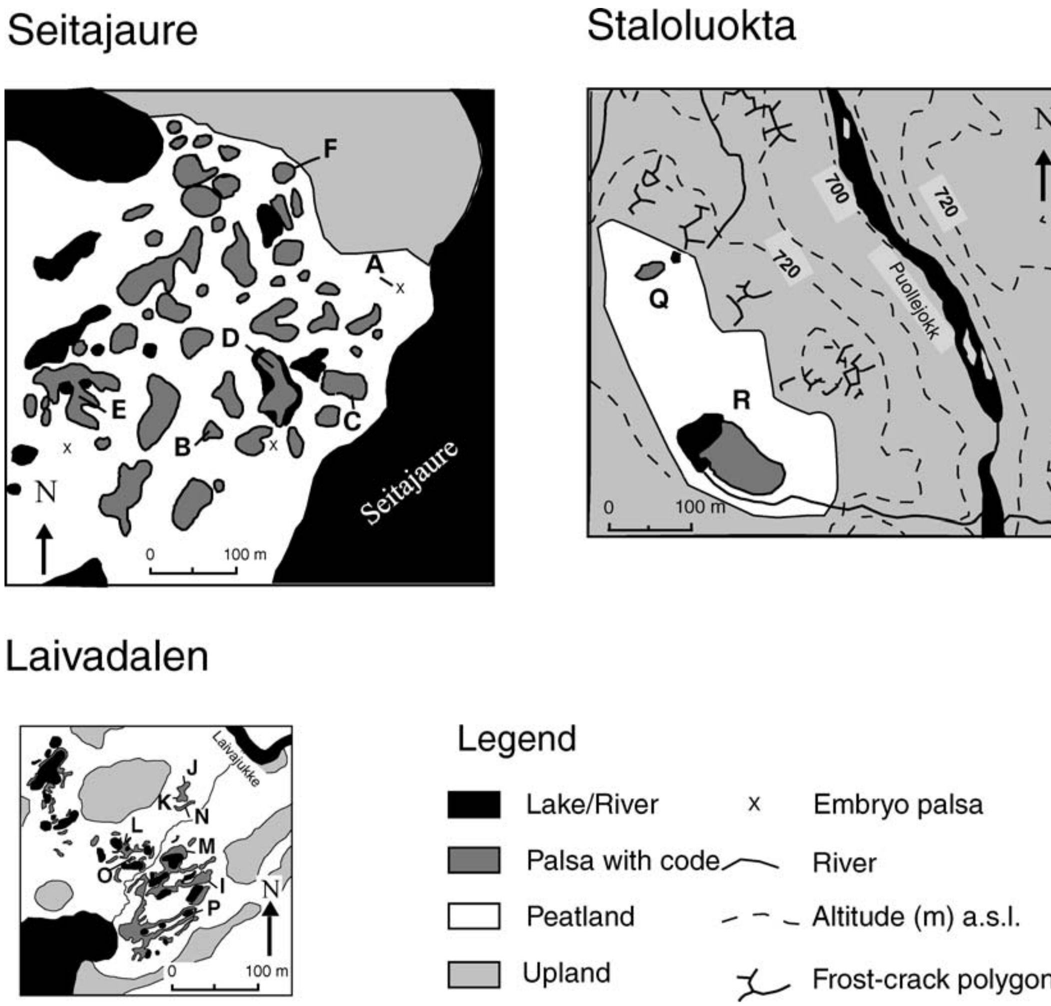


FIGURE 2. Detailed maps of the palsa bogs in Seitajaure, Staloluokta, and Laivadalen. The areas of Staloluokta and Laivadalen are rather flat, so no contour lines can be given on these maps.

different conditions was made in the different areas. The selection of forms given in Table 2 was determined by those available in the various bogs: for example, in Staloluokta there were relatively few palsas and in Laivadalen most palsas were degrading.

One to three representative vegetation plots were studied on the summit of each selected palsa: a single plot was made on palsas with homogenous vegetation and more plots where the plant cover varied. In addition, from three to seven vegetation plots were described in the bog next to the palsas. Plants were identified according to Nilsson (1991). The figures from Wramner (1973) for Taavavuoma, which were given according to the Hult-Sernander-Du Rietz five-grade scale (1: 0–6.25%, 2: 6.25–12.5%, 3: 12.5–25%, 4: 25–50%, 5: 50–100%) (Du Rietz, 1921b) were tentatively integrated with those of the Braun-Blanquet method (1: 0–5%, 2: 5–25%, 3: 25–50%, 4: 50–75%, 5: 75–100%) (Braun-Blanquet, 1964) used in this study. Both methods use 1-m^2 surface plots and distinguish between field layer vegetation (herb and shrub species) and ground layer (moss species, lichens, bare ground). In some cases mosses and lichens form vegetation beneath the canopy of taller, vascular species; in such cases the total vegetation cover can become more than 100%.

In the present study, aboveground biomass from different plants, excluding bryophytes and litter, within 0.25 m^2 or 0.5 m^2 areas was harvested from representative vegetation plots by clipping the vegetation at soil surface in order to obtain a measure of the vegetation structure. In the laboratory the plants from each plot were grouped into dominant species or types; the plants from each group were cut into vertical sections of 5 cm and subsequently dried at 70°C for 48 h before weighing.

In Seitajaure and Laivadalen the depth to the frozen ground was measured during late July 1997 with a 1.5-m-long steel rod. More than 30 measurements were made in relation to each of three main plant-cover types (dominance of *Betula nana*, *Empetrum hermaphroditum*, and lichens, respectively) as well as beneath patches of bare ground.

Snow depths were measured by probing with a 1-m-long cylinder during late winter visits along two or three profiles across each of the investigated palsas in the advanced aggrading, stable, and degrading stages, i.e., those stages that could be recognized while the bogs were snow covered but the palsas blown free of snow. In Laivadalen the snow depth was recorded automatically in the bog between palsas for every hour between September 1998 and July 1999 using an Aanderaa ultrasonic level sensor (USL) 3600 with an accuracy of 1%.

Results

PALSAS AND VEGETATION

Studies of the stratigraphies of palsas have shown that peat composed of vegetation, which is representative of the surrounding bogs, underlies peat from vegetation that developed on the palsas after their uplift (Fries and Bergström, 1910; Vorren, 1972; Zoltai, 1993).

TABLE 2

Morphological characteristics of the selected palsas also shown in Table 5 in Keinovuopio, Seitajaure, Staloluokta and Laivadalen together with the peat thicknesses and thaw depths. Five thaw depths were measured in Seitajaure on 31/07/97, in Laivadalen on 1–3/08/96, in Staloluokta on 25/08/97 and in Keinovuopio on 08/07/96.

Site	Stage	Max height (m)	Max width (m)	Max length (m)	Thickness of peat (m)	Depth of thawed layer (cm)
Seitajaure						
A	Initial aggrading	0.25	2.5	5.5	0.75	?
B	Continued aggrading	0.67	11	23	0.30	0.40
C	Stable	0.82	50	25	0.15	?
D	Degrading	1.39	27	60	1.60	0.40
E	Degrading	1.18	66	100	0.60–1.50	0.41
F	Degrading	0.56	26	32	1.10	0.43
Laivadalen						
G	Initial aggrading	0.20	2	5	?	37
H	Initial aggrading	0.20	1.5	5	?	34
I	Stable	0.80	10	26	1.20	37–48
J	Degrading	1.25	4	9	>1.25	39–42
K	Degrading	1.00	6	8	0.33	33–40
L	Degrading	1.60	12	20	1.20	42–48
M	Degrading	1.05	18	30	1.10	31–45
N	Degraded	0.70	5	16	0.70–0.95	30–50
O	Degraded	0.50	2	6	1.50	27–51
P	Degraded	0.60	10	50	1.45–2.20	27–55
Staloluokta						
Q	Continued aggrading	0.77	4	5.5	0.20	55
R	Stable	1.35	50	98	0.20–0.55	39–60
Keinovuopio						
S	Stable	1.02	22	35	0.80	22–31
T	Degrading	3.20	29	74	>1.00	25–41

Therefore this examination of palsa vegetation development starts with the vegetation in areas surrounding the palsas.

Hydrophilous species are present around the palsas: *Carex*, *Eriophorum angustifolium*, and, except for Staloluokta, also *Sphagnum* (Table 3): This vegetation has a low biomass, in which dead leaves dominate over live vegetation in the ground layer, but it is relatively tall, up to ca. 60 cm in height in Seitejaure (see Fig. 3). In Taavavuoma, Wramner (1973) noted that *Eriophorum palustre* and *Drepanocladus tundrae* were dominant.

The initial aggrading stage was only found in two of the areas. In both, the vegetation was poor in species with a little *Eriophorum angustifolium* and much *Sphagnum*, and in Laivadalen also a little *Carex*. The palsas were only slightly higher than the surroundings but the *Sphagnum* mosses were dry and wilted and the height of the plant species was lower than in the surroundings. This was also the case in Taavavuoma (Wramner, 1973).

The continued aggrading stage was only found in Seitajaure (two plots on the palsa B are presented in Table 3) and Staloluokta (one plot). Only *Betula nana* and *Eriophorum angustifolium* were found in the field layer, but both were fairly abundant; in the bottom layer *Polytrichum strictum* largely replaces *Sphagnum*. The vegetation was further reduced in height and the biomass was very low. In Taavavuoma, Wramner (1973) found a higher variety of species both in the field and bottom layer, in particular there were some Ericaceae, and *Rubus chamaemorus* made up an important component of the vegetation. That site may represent a transition between the aggrading and the stable stage.

One stable palsa was investigated in each of the four areas. All palsas had increased cover of *Betula nana* as compared to the previous stage, and there was colonization by abundant *Empetrum hermaphroditum* as well as some *Rubus chamaemorus*. Further, one or both of *Vaccinium uliginosum* and *Andromeda polyfolia* were present. *Eriophorum angustifolium* was found on two of the palsas pointing to moist spots within the generally dry conditions. New species of bryophytes had taken over in the bottom layer in most localities but generally speaking, the moss cover was reduced compared to the aggrading stage. Lichens comprised a higher degree of cover, and the overall biomass was greater than at the aggrading stage. On the summits of some forms, near-ground biomass of *Empetrum* dominated over *Betula nana*, while *Betula nana* contributed more on the slopes. The three species (*Betula nana*, *Empetrum hermaphroditum*, and *Rubus chamaemorus*) that were found on all the palsas of this stage were also present in Taavavuoma and so were representation of other ericaceous species. At this stage the palsas were usually higher than in the aggrading stage.

Degrading palsas were found in three of the localities. *Betula nana*, *Empetrum hermaphroditum*, and *Rubus chamaemorus* were present on all of the mounds and in Keinovuopio several *Betula pubescens* grew on the lee side and single low forms were even found on their tops. On some plots, *Betula nana* was more important while in others there was more *Empetrum*. *Vaccinium uliginosum* was present in all three areas and *Andromeda polyfolia* in two of them, but these species were not present on all parts of the palsas. *Vaccinium vitis-idaea* was present in the two southern of the localities and *Vaccinium myrtillus* was found on the palsa in Laivadalen. Bryophytes were present on all palsas but to varying extent, and even over the surface of a single palsa there were major differences in the coverage, most clearly seen in palsa M (plots M1 and M2) in Laivadalen. Also in relation to lichens, which were present on all palsas, there can be major differences between palsas and between different parts of the same palsa. The differences in relatively abundance of species were also reflected in the biomass. For example, out of three plots investigated in Seitajaure, *Betula nana* was best developed in plot D1, the two other plots were richer in *Empetrum*, and there were thus differences over the same palsa. On the other hand, on palsa E, *Empetrum* was more abundant over the whole palsa (Fig. 3d, 3e; Table 3). In Laivadalen a composition similar to the *Empetrum* rich plot in Seitajaure was found in one plot while in another (Fig. 3f) *Betula nana* was well developed. No descriptions of this and the remnant stage were given by Wramner (1973) for Taavavuoma.

Within or around ponds of degraded palsas, dead *Betula nana* and ericaceous shrubs may occasionally testify to the former palsa presence. In higher areas, *Betula nana* and *Rubus chamaemorus* were fairly abundant while *Empetrum* was less frequently present or even absent. Often there were Ericaceae species and in relatively moist parts there was *Eriophorum angustifolium*. *Sphagnum* was abundant locally and other mosses also cover part of the surface together with lichens. Depending on moisture conditions the amount and composition of the biomass can exhibit major differences both among the areas and within them. Figure 3g shows an example from Seitajaure where the amount of biomass was low and dominated by *Betula nana* with a minor admixture of *Empetrum* and other species nearest the ground and at this stage dead substance makes up part of the biomass also. In Laivadalen, *Betula nana*, *Empetrum*, other Ericaceae, and herbs had high biomass values and relatively high growth forms (Fig. 3h).

PALSA MORPHOLOGY

In most of the investigation sites the form of the palsas is oval to elongate. In Laivadalen and Keinovuopio, the palsas form palsa complexes, which consist mostly of several dome-shaped palsas. In Seitajaure all the selected stable and degrading palsas have a flat

TABLE 3A AND B

Plant species in the four investigated areas together with characteristics on mean palsa and vegetation height for (A) the bogs surrounding the palsas and (B) on the palsas at the different palsa stages. The cover of the vascular plants is given according to the Braun-Blanquet scale (Braun-Blanquet, 1964): 1: 0–5% cover, 2: 5–12.5%, 3: 12.5–25%, 4: 25–50%, 5: 50–100% cover. Due to overlapping leaves of vascular plants, bryophytes and lichens total cover could be more than 100%. Bare ground is given in percentage of the whole palsa. The letters of the palsas refer to Table 2.

A	Surrounding mire												
Study area	Seitajaure							Laivadalen			Keino	Staloluokta	
Mean height palsa (m)													
Mean height *Betula nana* (cm)													
Mean height dwarf shrubs and herbs (cm)	20	45	20	45	45	45	40	35	25	25	15	50	60
Vascular species													
Carex ssp.	4	2	1	3	1			1	1			2	
Carex rotundata				1	1	1	2			1			5
Eriophorum angustifolium			1	1	1			2	1	2	1	2	2
Betula nana													
Empetrum hermaphroditum													
Rubus chamaemorus													
Vaccinium uliginosum													
Andromeda polyfolia													
Vaccinium vitis-idaea													
Vaccinium myrtillus													
Vaccinium microcarpum													
Betula pubescens													
Bryophyte species													
Caliergon stramineum		4	1										
Sphagnum lindbergii		4		4	5	5	5						
Sphagnum fuscum								5	5	5			
Sphagnum ssp.	5		5	4	1	5					5		
Polytrichum strictum													
Ptilidium ciliare									1	1			
Dicranum ssp.													
Dicranum elongatum													
Lichens	1	1	1	1	1	1	1	1	1	1	1	1	1

TABLE 3

(Cont.)

B

Palsa stage	Initial aggrading			Continued aggrading			Stable				Degrading												Degraded				
Study area*	Seita	Laivadalen		Seitajaure		Stalo	Seita	Laiva	Keino	Stalo	Seitajaure						Laivadalen				Keino		Seita	Laivadalen			
Palsa/plot nr.	A	G	H	B1	B2	Q	C	I	S	R	D1	D2	D3	E1	E2	E3	J	L	M1	M2	T1	T2	F	P1	P2	O	N
Mean height palsa (m)	0.25	0.20	0.20	0.60			0.80	0.75	0.80	1.35	1.20			1.00			1.00	1.20	1.00		3.20		0.50	0.60		0.50	0.70
Mean height Betula nana (cm)				10	10		15	13	15		15	6	10	15	10	15	10	35	8	55	10	20	30	20	8	13	35
Mean height dwarf shrubs and herbs (cm)	25	30	15	10	7	12	4	3	4	5	4	2	5	5	5	5	4	12	4	8	5	3	10	5	2	5	12
Vascular species																											
Carex ssp.			1																				1				
Carex rotundata																										1	2
Eriophorum angustifolium	1	1	1	1	2	1			1	1													1				
Betula nana				2	2	1	2	2	2	2	3	2	2	2	2	2	2	3	1	4	2	4	2	3	1	2	3
Empetrum hermaphroditum							4	3	2	3	4	5	5	2	4	4	2	3	2	2	4	4		2	1	2	
Rubus chamaemorus							1	1	2	1	1	2	1	1	1	1	1	2	1	2	1	1	1	1	1	2	4
Vaccinium uliginosum							1		1	2	1	2	1		1	1	1	1	1	1	1			2		2	
Andromeda polyfolia							1	1	1		1	1		1	1	1	1		1					1		1	1
Vaccinium vitis-idaea														1	1	1	1		1	1							1
Vaccinium myrtillus																		2		1							2
Vaccinium microcarpum																								1		1	
Betula pubescens																				1**		1					
Bryophyte species																											
Caliergon stramineum																											
Sphagnum lindbergii																			1	2			3			5	
Sphagnum fuscum								1						3									2				
Sphagnum ssp.	5	5	5		1																			5			
Polytrichum strictum				5	5	1		1												5	4	2	4		1	2	5
Ptilidium ciliare							2	1		2	2	2	5		5	2	1	1	1		2	1					2
Dicranum ssp.							2		4	4	2	1	2		2			5	1	2		1				1	1
Dicranum elongatum										4				5		2	2		1						2		
Lichens				1	1		2	3	5	2	2	2	2	2	2	4	5	1	2	2	4	1	2	1	5	1	1
Bare surface of the whole palsa	0%	0%	0%	0%	0%	0%	?	2%	0%	0%	5%			3%			20%	40%	5%		5%		0%	1%		5%	3%

* Abbreviations of study areas:Seita = Seitajaure; Stalo = Staloluokta; Laiva = Laivadaten; Keino = Keinovuoplio.

** *Betula pubescens* was found on the palsa outside the vegetation plot.

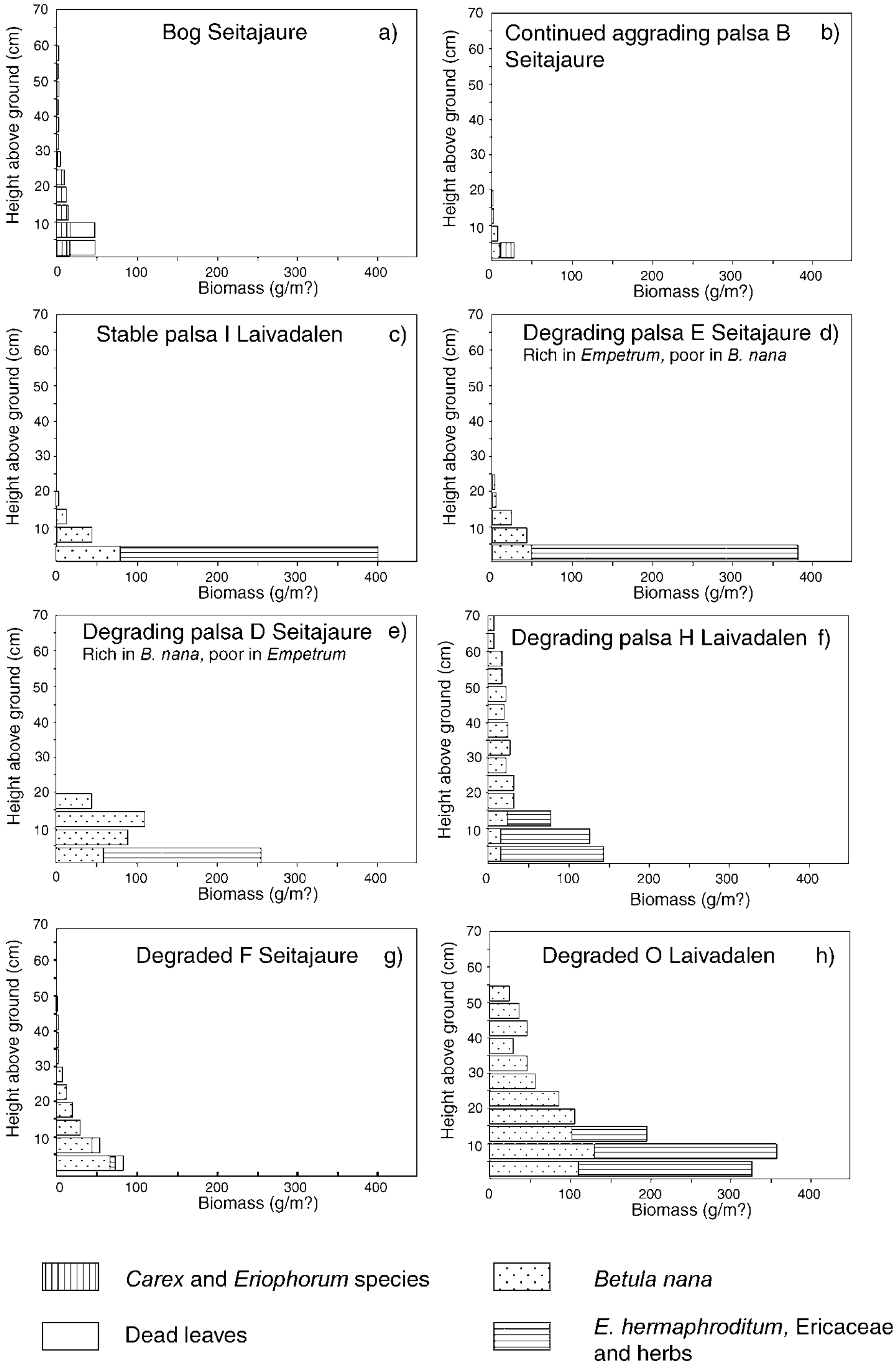
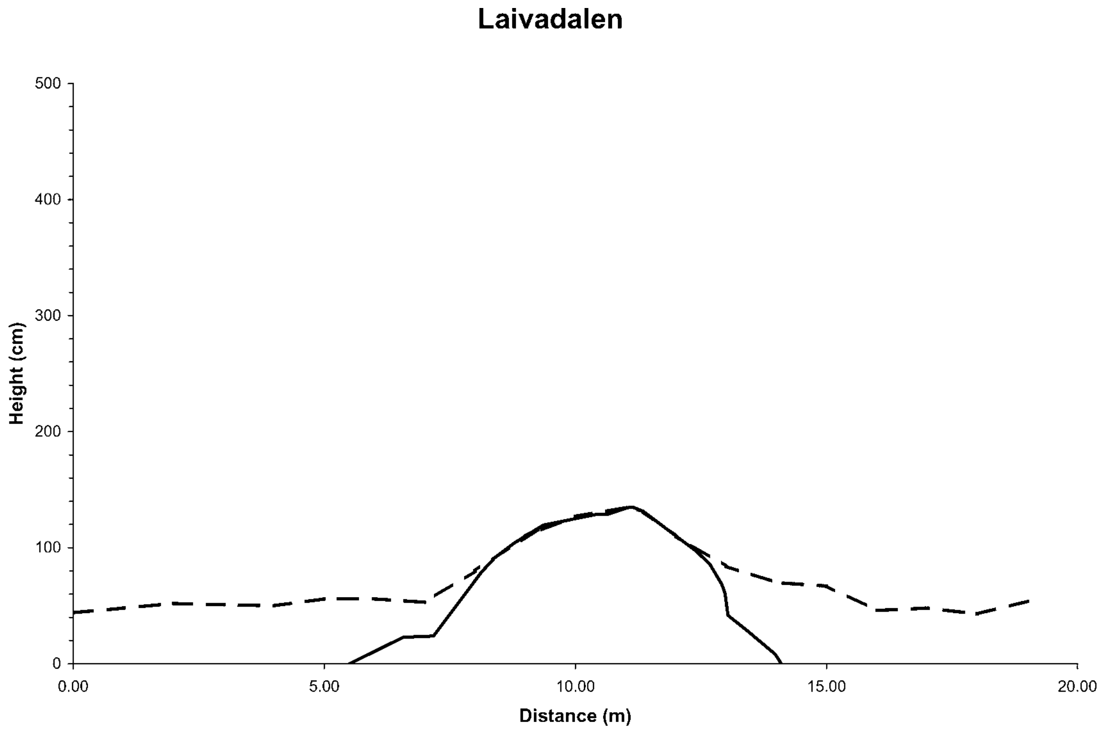


FIGURE 3. Aboveground biomass and its composition given in 5-cm intervals from (a) Bog between palsas in Seitajaure; (b) continued aggrading palsa (B) in Seitajaure; (c) stable palsa (I) in Laivadalen; (d) degrading palsa (E) rich in Empetrum *but poor in* Betula nana *in Seitajaure; (e) degrading palsa (D) with much* Betula nana *and less* Empetrum *in Seitajaure; (f) degrading palsas (M) in Laivadalen; (g) degraded palsa (F) in Seitajaure; (h) and degraded (O) in Laivadalen. See also Table 2.*

plateau-like surface with steep edges while there are domed forms in the other areas.

All palsas in the initial aggrading stage were small and low domes with smooth surfaces. In Seitajaure and Staloluokta the succeeding stage of continued aggradation is represented by 0.67- and 0.77-m-high forms, respectively (see Table 2 on the morphological characteristics for selected palsas). These palsas had gentle slopes, no ponds along the edges and had no signs of wind or block erosion. Cracks were not present on palsas in the aggrading stage except on the crest of palsas in Staloluokta where there was one large and two small cracks. On stable palsas cracks were observed in some cases especially along the edges and along adjacent ponds, but no block erosion occurred. Generally speaking the size and height of the palsas increased with the degree of development from the initial aggrading to the stable stage within individual bogs.

On the degrading palsas cracks up to several meters in length were observed dividing the peat layer in large blocks. Often more than one pond was found along the sides of these palsas and on top of the flat palsas in Seitajaure block erosion was observed adjacent to the ponds. Along these erosional edges the mineral soil was often visible, especially on palsas with a thin peat cover. On three degrading palsas in Laivadalen (palsa J, K, and L) wind erosion had disturbed the vegetation canopy and large spots with bare peat were found. In the degraded stage the palsas form ca. 0.5-m-high ridges or ring walls and



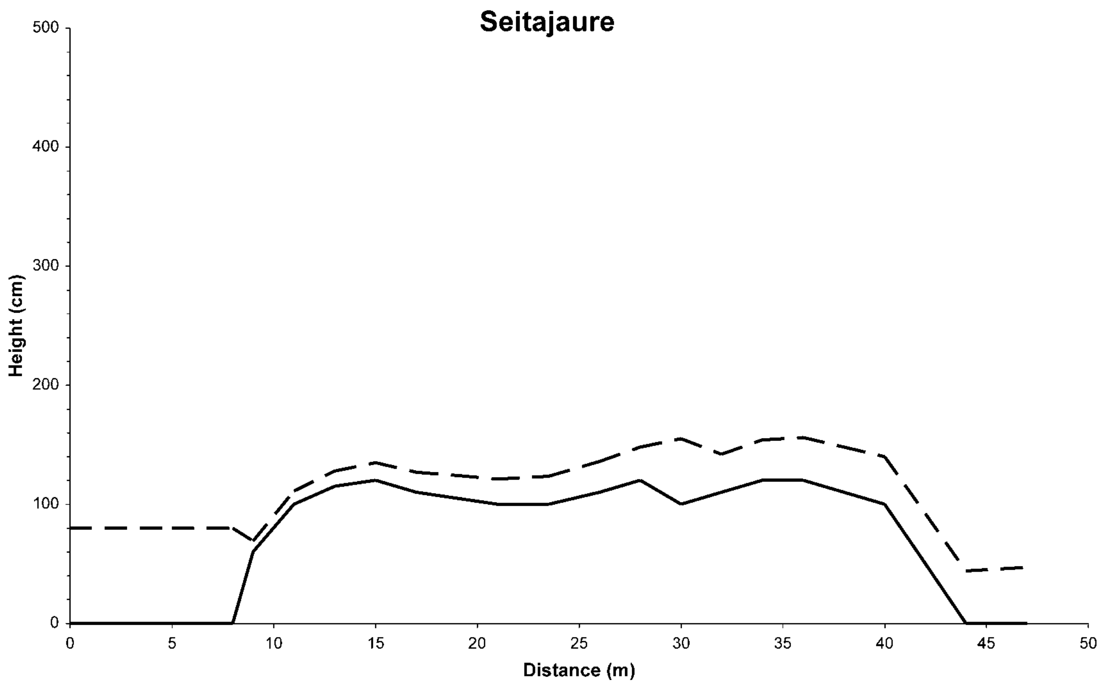


FIGURE 4. Snow surface (black line) in relation to palsas (gray lines) in Laivadalen and D in Seitajaure as measured on 24 March 1998 and 25 March 2001, respectively.

the height of the remnants was lower than degrading palsas within the same palsa bog.

SNOW COVER

Snow is present at all sites during the winter, but the snowpack evolution is not known in detail except for Laivadalen during 1998–99. At this site at least 10 cm snow was present from mid-October till late April with more than 20 cm (maximum 51 cm) between mid-December and mid-April. Snow-depths profiles measured across palsas in Laivadalen and Seitajaure on 24 March 1998 and 25 March 2001, respectively, show that the cover is thinnest upon the summits of the palsas (Fig. 4). There are major snowpack depth differences between palsa summits and the surrounding areas often with the summits without snow (Table 4). There was a difference in snow depth in relation to the type of vegetation and as a rule the taller the vegetation, the thicker its snow cover.

THAW DEPTH

In summer the thaw depth was significantly deepest under lichens and bare ground on palsas both in Laivadalen and Seitajaure (Table 5)

TABLE 4

Snow depths in Seitajaure and Laivadalen as measured on 25 March 2001 and 24 March 1998, respectively, on the most common vegetation types as well as for the surrounding bog areas. N is the number of measurements.

		Laivadalen				Seitajaure			
Snow depth (cm)		N	Mean	Minimum	Maximum	N	Mean	Minimum	Maximum
Surrounding bog		51	59	22	125	11	83	40	105
Palsa		67	24	0	97	45	35	20	70
Vegetation types on palsas	*Betula nana*	14	31	4.5	83	25	39	25	70
	Empetrum hermaphroditum	14	19	0	72	20	30	20	50
	Lichen	6	7	0	37	—	—	—	—
	Bare ground	14	5	0	12	—	—	—	—

and in Laivadalen also under *Empetrum hermaphroditum*. In both areas the thawed layer was shallower under dwarf birch than beneath other vegetation types, and the difference was statistically significant with a probability value $P < 0.05$ (Student's *t*-test). All stages of palsa development, including the remnant stage had frozen cores at the time of sampling.

Discussion

INITIATION

In the literature there is general agreement that initial development of palsas can be caused by differential frost penetration into the mire with associated local ice accumulation caused by cryosuction in frost sensitive sediments. Fries and Bergström (1910), and later Seppälä (1986), proposed that an absence of snow or only a thin snow cover in winter can cause local freezing and ice accumulation in the ground and thus cause a locally higher surface. In the present study it was found that the bog vegetation is not homogenous, neither in composition nor in height, and it is possible that local differences in vegetation might influence snow distribution and thus contribute to the location of future palsas. Alternatively, palsa formation might start in summer by local preservation of frozen ground under more insulating vegetation (Matthews et al., 1997). This possibility appears to be supported by a study by Kuhry (1998) who found that development of dry peat surfaces with *Sphagnum fuscum* was a trigger for palsa formation.

INITIAL AGGRADING STAGE

If the frozen core of an initial form remains frozen during the following summers, the mound can increase in height during the winters (Fig. 5). In this earliest phase, with a mound height of (a) single decimeter(s) the hydrological conditions are only slightly different from the those of the surrounding bog, and the vegetation to a large extent contains the same species as before. The most hydrophilous species may dry out but other species have not yet had time to colonize. It is proposed that the name of initial aggrading stage is used for this phase without major change of vegetation. This is a more restricted but clearer use for the start of palsa development than usually seen in the literature (e.g., Wramner, 1973; Seppälä, 1986; Worsley et al., 1995).

In northern Sweden individual species on palsas in the initial stage are shorter than the corresponding species in the surrounding bog. The plants at this stage of palsa development have a low biomass, so this could be one of the factors that might influence deflation of snow in winter and thus help to increase frost penetration into the mounds. It is also possible that an increase in albedo caused by the death of mosses in summer with associated change in color (Railton and Sparling, 1973; Worsley et al., 1995) could contribute to the persistence and continued growth, but in the study areas in Scandinavia such a major change in albedo was not observed.

CONTINUED AGGRADING STAGE

Following further ice accumulation, the palsas have risen sufficiently to become better drained even if they are not yet very high. Hydrophilous species are now only found along the wetter periphery while the central parts are colonized by the wind resistant and drought tolerant *Polytrichum* (Whittaker, 1973) and, where there is snow cover in winter, also by *Betula nana* (compare De Groot et al., 1997 for the ecology of *B. nana*). At this stage the vegetation on the palsa clearly differs from the composition of the bog.

The name of "continued aggrading stage" is proposed for this phase, independent of whether the frost has reached underlying silty soil (compare Seppälä, 1986). This proposal is in line with Wramner (1973) who found palsas within which the frozen core reached down into the silt already in his "embryo" stage owing to a very thin peat cover. The advantage of this definition is that it is independent of peat thickness and can be used directly in relation to field observations.

STABLE STAGE

With increasing growth the peat of the surface becomes drier until the palsas reach their maximum heights. During this stage the sides of the forms become steeper (compare also, e.g., Seppälä, 1986; Matthews et al., 1997) and the vegetation becomes entirely dependent on precipitation for its moisture supply (see also Seppälä, 1988). In the higher parts, relatively xerophilous plants take over with *Empetrum hermaphroditum* as the diagnostic species. It is noteworthy that *Empetrum*, which is normally regarded as a faster colonizer than *Betula nana* (Whittaker, 1993), does not develop before the surface has become sufficiently dry. *Rubus chamaemorus* and *Vaccinium uliginosum* are also immigrants at this stage, and they, like *Empetrum* (Wramner, 1973; Whittaker, 1993) are favored in the competition by their tolerance of strong winds and thin or absent snow cover. There is very little bare peat surface at this stage, but single cracks resulting from growth of the frozen core and/or thermal contraction can be present. The biomass has increased substantially and the vegetation now

TABLE 5

Mean thaw depths beneath different vegetation types on 21 July 1997 in Laivadalen and 6 August 1997 in Seitajaure. N is the number of measurements, SD is the standard deviation. The means were statistically tested by means of an ANOVA test.

Mean thaw depth beneath (cm)	Laivadalen (21-07-97)			Seitajaure (06-08-97)		
	N	Mean	Std	N	Mean	Std
Betula nana	31	32	7.2	33	35	3.6
Empetrum hermaphroditum	30	39	6.8	31	41	2.8
Lichen	31	38	5.7	33	44	2.8
Bare ground	31	40	6.9	30	43	2.3

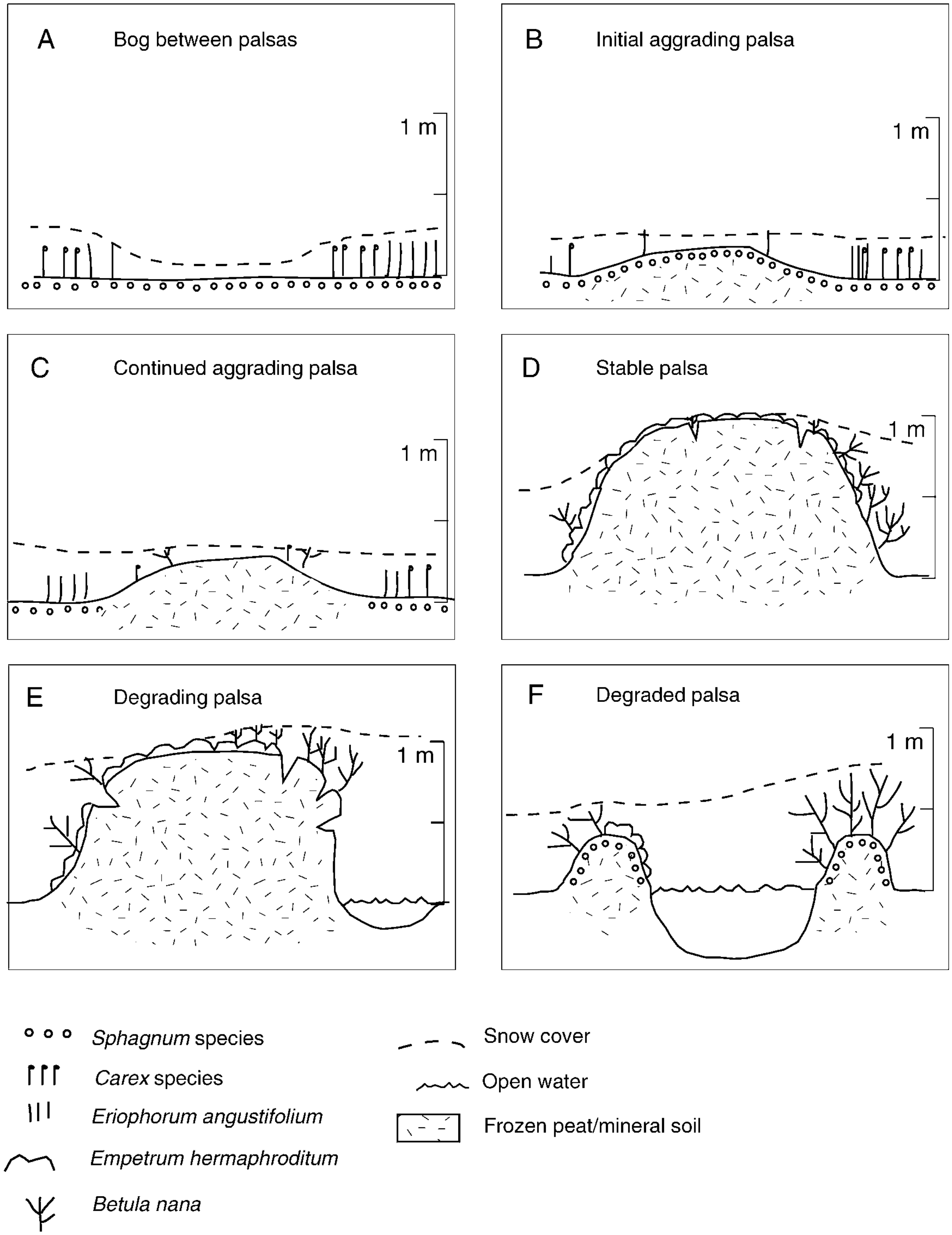


FIGURE 5. Vegetation and palsa development at successive stages: A gives one of the possible initial situations (the winter start scenario). B shows initial aggrading and C the continued aggrading palsa stage with increasing height of palsas and higher diversity of plant species. D shows the stable palsa with dwarf birch shrubs on the slopes and single cracks on top of the palsa. In E two possibilities are given with low (left hand side) and high vegetation upon the degrading palsa, respectively, both with unstable palsa slopes. In F ring walls around a pond indicate the degraded stage with increased diversity and height of vegetation. Note different vertical and horizontal scales with shortened horizontal scale for better overview.

forms a relatively dense mat of perennial and partly evergreen plants sometimes together with mosses. *Betula nana* regularly grows upon the higher parts yet prefers cracks where snow provides protection in winter (see also Oksanen, 2002). In this way *Betula* can help to preserve the peat by protecting the surface along the cracks against deflation and erosion and by binding the underlying peat with its roots.

There is a clear link between snow depth and plant species (Table 4) with the thickest snow over *B. nana* followed by *Empetrum* and thinnest over lichens and bare ground. Thus *B. nana* is capable of trapping the snow and preventing it from blowing away, and at the same time it grows preferably in places where snow accumulates, rather than on windswept summits. Many studies have stressed the importance of snow cover as an insulator in winter (Fries and Bergström, 1910; Seppälä, 1988), and Kershaw and Gill (1979) and Roche and Allard (1996) have pointed out the effect of vegetation structure on local differences in snow cover and associated soil temperatures. Furthermore snow trapped in vegetation has relatively low density and this further adds insulation capacity due to the low thermal conductivity of snow (Singh, 1999). It follows that the vegetation type can indirectly influence aggradation of the ice core in winter.

In summer there is also a relationship between plant species and thaw depth with less deep thaw under the taller vegetation (see Table 5). Similarly, Harris (1993) found colder conditions under taller vegetation in palsa-like mounds in Canada, and Kershaw and Skaret (1993) noted lower maximum summer temperatures at 5 cm depth under palsa surfaces with plant cover as compared to surfaces with bare peat. This is due to shading of the surface with reduced solar radiation upon the peat (e.g., Brown, 1970: 23; Williams and Smith, 1989: 72.) and thus the temperature fluctuations into the peat are dampened (Evans and Fonda, 1990).

The distinction between the aggrading and the stable palsa stage is defined here as the change to clearly drier conditions with colonization by heath plants, notably by *Empetrum*. This differentiation might also be of use as an indicator in Norway and Finland. Outside of Scandinavia, for example in Canada, other ericaceous species, for example *Ledum groenlandicum* (noted by Railton and Sparling, 1973; Cummings and Pollard, 1989), might be used as an indicator even if some stable palsas there carry trees.

DEGRADING STAGE

Increased stretching of the surface layer as well as exposure to wind and erosion makes the surface increasingly unstable. Existing cracks on the summit widen and deepen and cracks develop along the edges so that blocks slide down over the steep sides (e.g., French, 1996: 71; Svensson, 1962; Wramner, 1973; Zuidhoff, 2002).

The increased irregularity of the surface increases the diversity of ecological niches (see also Worsley et al., 1995) and most forms have a higher diversity of plants, occasionally including hydrophilous species together with continued presence of plants that prefer the dry habitat of the higher parts of the palsas. It can be noted that *Vaccinium vitis-idaea* and *V. myrtillus* were found on degrading palsas in Seitajaure and Laivadalen. Both species require a moderate to thick snow cover in winter (Carlsson et al., 1999) as does the birch, which has become taller than in the previous stage. At the same time, areas with bare ground have increased.

DEGRADED STAGE

In the degraded stage, there is no morphological similarity to the previous mounds; instead elongated ridges or ring walls alternate with pools (compare, e.g., Wramner, 1973). Ecological diversity increases further, particularly in hydrophilous species because water-filled pools now form part of the complex. Heath vegetation and birch persist, even if the height of the palsas is usually less than in the previous stage. In some places this vegetation can be relatively tall and the highest biomass at any stage was found on remnants. Within ramparts that support relatively dry vegetation and high biomass it was found that the ground was still frozen near the end of the summer (Table 2) (see also Meier, 1996; Walger, 1998) and such ramparts could occasionally contain and represent perennially frozen ground.

The degraded stage is the final phase of palsa development. If there is only peat in the palsa the morphologic expression of the remnant may be very limited (Lundqvist, 1969) whereas forms relatively rich in silt may leave traces that can last for thousands of years (Pissart, 2000).

Conclusions

Investigations in four Swedish palsa bogs show that there is interaction between palsa stage, hydrology, vegetation species composition and structure, snow cover, and thaw depth. During growth of palsas there is a change from hydrophilous vegetation to more drought tolerant species. With increasing palsa height there are more ecological niches and more plant species, the tallest of which, *Betula nana*, becomes taller from the aggrading to the degraded stage of palsa development. In turn this affects trapping and retainment of snow in winter. The composition and structure of the plant cover also affects the insulating capacity of the top layer of the palsas in the summer. A cause-effect relationship between plant cover and palsa morphology is found in several stages of development: the vegetation with a low biomass during the aggrading stage results in low snow accumulation in winter, tall shrubs on degrading palsas traps snow and hampers growth of the ice lenses and in the degraded stage vegetation may help to preserve frozen ground during summer.

Vegetation, together with palsa morphology, can be used to classify palsa stages. A very wet initiation phase is followed by an initial aggrading stage with the same species although in poor conditions. A drier plant composition with few species marks the continued aggrading stage and once the surface of palsas has become sufficiently dry to support ericaceous species, the stable stage is reached independent of whether underlying silt is included in the frozen core or not. *Empetrum hermaphroditum* is the most characteristic species of the stable stage. The breakdown of palsas is primarily characterized by block erosion that gives rise to an increase in microhabitats before the forms are transformed into morphologically different degraded forms with a relatively broad representation of plant species that reflect a wide range of available hydrological conditions.

Acknowledgments

Financial support for the fieldwork was provided by the Swedish Society for Anthropology and Geography, Sernanders Stiftelse, Linnéstipendium, Rektorsfond, Geografiska Föreningens Minnesfond, Otterborgs donationsfond, and Bjurzons resestipendium. Support from the Swedish Natural Science Research Council (NFR) (grant to Else Kolstrup, nos. G-AA/GU 11684-300 and G-AA/GU 11684-301) covered equipment and some of the travel costs. We want to thank Vattenfall for permission to use the meteorological data. The constructive comments from two anonymous reviewers and Hugh M. French, Ottawa, are gratefully acknowledged. We are especially grateful for the excellent field assistance from Jeroen van Steenis, Tage Thyrsted, Mats Walger, Menno Faber, and Thomas Matzen. Mats Walger also analyzed some of the vegetation samples from Laivadalen.

References Cited

Åhman, R., 1977: Palsar i Nordnorge. En studie av palsars morfologi, utbredning och klimatiska förutsättningar i Finnmarks och Troms fylke. *Meddelanden från Lunds Universitets Geografiska Institution Avhandlingar,* 78. 165 pp.

Åkerman, J., 1982: Observations of palsas within the continuous permafrost zone in eastern Siberia and in Svalbard. *Geografisk Tidsskrift,* 82: 45–51.

Alexandersson, H., Karlström, C., and Larsson-McCann, S., 1991: Temperaturen och nederbörden i Sverige 1961–1990 referensnormaler. *SMHI Reports Meteorology* 81. 88 pp.

Braun-Blanquet, J., 1964: *Pflanzensoziologie. Grundzüge der Vegetationskunde.* 3 Aufl. Wien/New York: Springer. 865 pp.

Brown, R. J. E., 1970: *Permafrost in Canada: Its influence on northern development.* Toronto: University of Toronto Press. 234 pp.

Carlsson, B. Å., Karlsson, P. S., and Svensson, B. M., 1999: Alpine and subalpine vegetation. *In*: Rydin, H., Snoeijs, P., and Diekman, M. (eds.), *Swedish Plant Geography*: *Dedicated to Eddy van der Maarel on his 65th Birthday.* Acta Phytogeographica Suecica, 84. Svenska Växtgeografiska Sällskapet, Uppsala, 75–89.

Cummings, C. E. and Pollard, W. H., 1989: An investigation of palsas in the Schefferville area, Quebec. *Musk-ox,* 37: 8–18.

De Groot, W. J., Thomas, P. A., and Wein, R. W., 1997: *Betula nana* L. and *Betula glandulosa* MichX. *Journal of Ecology,* 85: 241–264.

Du Rietz, G. E., 1921a: Några iakttagelser över myrar i Torne Lappmark. *Botaniska notiser* 1921: 3–14.

Du Rietz, G. E., 1921b: *Zur methodischen Grundlage der modernen Pflanzensoziologie.* Dissertation Uppsala University. 272 pp.

Evans, R. D. and Fonda, R. W., 1990: The influence of snow on subalpine meadow community pattern, North Cascades, Washington. *Canadian Journal of Botany,* 68: 212–220.

French, H. M., 1996: *The Periglacial Environment.* 2nd ed. Harlow, U.K.: Addison Wesley Longman. 341pp.

Fries, T. and Bergström, E., 1910: Några iakttagelser öfver palsar ock deras förekomst i nordligaste Sverige. *Geologiska Föreningen i Stockholms Förhandlingar,* 32(1): 195–205.

Grundsten, C., 1979: *Vegetationskarta över de svenska fjällen, Kartblad nr 11 Gräsvattnet/Umfors (25E/F) Skala 1:100 000.* Naturgeografiska institutionen Stockholms universitet, Statens naturvårdsverk.

Gurney, S. D., 2001: Aspects of the genesis, geomorphology and terminology of palsas: perennial cryogenic mounds. *Progress in Physical Geography,* 25: 249–260.

Harris, S. A., 1993: Palsa-like mounds developed in a mineral substrate, Fox Lake, Yukon Territory. *Sixth International Conference on Permafrost. July 5–9, 1993 Proceedings,* Beijing, China, 238–243.

Kershaw, G. P. and Gill, D., 1979: Growth and decay of palsas and peat plateaus in the Macmillan Pass – Tsichu River area, Northwest Territories, Canada. *Canadian Journal of Earth Sciences,* 16: 1362–1374.

Kershaw, G. P. and Skaret, K. D., 1993: Microclimatic characteristics of palsas along an altitudinal gradient, Mackenzie Mountains, NWT, Canada. *Sixth International Conference on Permafrost. July 5–9, 1993 Proceedings,* Beijing, China: 338–343.

Kuhry, P., 1998: Late Holocene Permafrost Dynamics in Two Subarctic Peatlands of the Hudson Bay Lowlands (Manitoba, Canada). *Eurasian Soil Science,* 31(5): 529–534.

Lundqvist, J., 1969: Earth and ice mounds: a terminological discussion. *In* Péwé, T. L. (ed.), *The Periglacial Environment. Past and Present.* Montreal: McGill-Queen's University Press, 205–215.

Matthews, J. A., Dahl, S.-O., Berrisford, M. S., and Nesje, A., 1997: Cyclic Development and Thermokarstic Degradation of Palsas in the Mid-Alpine Zone at Leirpullan, Dovrefjell, Southern Norway. *Permafrost and Periglacial Processes,* 8: 107–122.

Meier, K.-D., 1996: *Studien zur Periglaziärmorphologie der Varanger-Halbinsel, Nordnorwegen.* Norden 11. Bremen. 405 pp.

Nilsson, Ö., 1991: *Nordisk fjällflora.* Bonniers. 272 pp.

Oksanen, P. O., 2002: Holocene permafrost dynamics in palsa and peat plateau mires of continental Europe. A study based on plant macro fossil analysis, radiocarbon dating and reviews of literature. Licentiate thesis. University of Oulo, Department of Biology. 30 pp.

Pissart, A., 1983: Pingos et palsas: Un Essai de Synthèse des Connaissances Actuelles. *In* Poser, H. and Schunke, E. (eds.), *Mesoformen des Reliefs im heutigen Periglazialraum.* Abhandlungen der Akademie der Wissenschaften in Göttingen, Mathematisch - Physikalische Klasse Dritte Folge, 35, 48–69.

Pissart, A., 2000: Remnants of lithalsas of the Hautes Fagnes, Belgium: a summary of present-day knowledge. *Permafrost and Periglacial Processes,* 11: 327–355.

Rafstedt, T., 1983: *Vegetationskarta över de svenska fjällen. Kartblad nr 5 Kebnekaise (29I). Skala 1:100 000.* Naturgeografiska institutionen Stockholms universitet, Statens naturvårdsverk.

Railton, J. B. and Sparling, J. H., 1973: Preliminary studies on the ecology of palsa mounds in northern Ontario. *Canadian Journal of Botany,* 51: 1037–1044.

Roche, Y. and Allard, M., 1996: L'Enneigement et la dynamique du pergélisol: l'exemple du Détroit de Manitounuk, Québec Nordique. *Géographie physique et Quaternaire,* 50: 377–393.

Seppälä, M., 1986: The origin of palsas. *Geografiska Annaler,* 68A: 141–147.

Seppälä, M., 1988: Palsas and related forms. *In* Clark, M. J. (ed.), *Advances in Periglacial Geomorphology.* Chichester: Wiley & Sons, 247–278.

Singh, A. K., 1999: An investigation of the thermal conductivity of snow. *Journal of Glaciology,* 45(150): 346–351.

Sollid, J. L. and Sørbel, L., 1998: Palsa bogs as a climate indicator: examples from Dovrefjell, Southern Norway. *Ambio,* 27: 287–291.

Svensson, H., 1962: Några iakttagelser från palsområden. *Norsk Geografisk Tidsskrift,* 18: 212–227.

Von Sydow, U., 1983a: *Vegetationskarta över svenska fjällen. Kartblad nr 1 Treriksröset/Naimakka* (*31J/31K/32J/32K*). *Skala 1:100 000.* Naturgeografiska institutionen Stockholms universitet, Statens naturvårdsverk.

Von Sydow, U., 1983b: *Vegetationskarta över svenska fjällen. Kartblad nr 6 Virihaure/Västra Sarek (28G/28H). Skala 1:100 000.* Naturgeografiska institutionen Stockholms universitet, Statens naturvårdsverk.

Vorren, K.-D., 1972: Stratigraphical investigations of a palsa bog in Northern Norway. *Astarte,* 5: 39–71.

Walger, M., 1998: *Palsas in Laivavagge. A field study of the vegetation structure on palsas, palsa stages and the depth to the ice layer.* Msc. Thesis, Uppsala University, Department of Earth Science. 96 pp.

Washburn, A. L., 1983: Palsas and continuous permafrost. *Permafrost: Fourth International Conference, Proceedings.* Washington, D.C.: National Academy Press, 1372–1377.

Westin, B. and Zuidhoff, F. S., 2001: Ground thermal conditions in a frost-crack polygon, a palsa and a mineral palsa (lithalsa) in the discontinuous permafrost zone, northern Sweden. *Permafrost and Periglacial Processes,* 12: 325–335.

Whittaker, R. J., 1993: Plant population patterns in a glacier foreland succession: pioneer herbs and later-colonizing shrubs. *Ecography,* 16: 117–136.

Williams, P. J. and Smith, M. W., 1989: *The Frozen Earth, Fundamentals of Geocryology.* Cambridge: Cambridge University Press, 306 pp.

Worsley, P., Gurney, S. D., and Collins, P. E. F., 1995: Late Holocene 'mineral palsas' and associated vegetation patterns: a case study from Lac Hendry, Northern Quebec, Canada and significance for European Pleistocene thermokarst. *Quaternary Science Reviews,* 14: 179–192.

Wramner, P., 1967: Studier av palsmyrar i Laivadalen, Lappland. *Teknik och Natur*, Festskrift tillägnad professor Gunnar Beskow, Meddelanden från Göteborgs Universitets Geografiska Institution, 86, 435–449.

Wramner, P., 1973: Palsmyrar i Taavavuoma, Lappland (Palsa bogs in Taavavuoma, Swedish Lapland). Göteborgs Universitet Naturgeografiska Institutionen, *Guni rapport*, 3. 140 pp.

Zoltai, S. C., 1993: Cyclic development of permafrost in the peatlands of northwestern Alberta, Canada. *Arctic and Alpine Research,* 25: 240–245.

Zuidhoff, F. S., 2002: Recent decay of a single palsa in relation to weather conditions between 1996 and 2000 in Laivadalen, northern Sweden. *Geografiska Annaler,* 84A: 103–111.

Zuidhoff, F. S., 2003: Physical properties of the surface peat layer and the influence on thermal conditions during the development of palsas. *Proceedings of the Eight International Conference on Permafrost, Zürich, Switzerland, 21–25 July 2003.* Lisse: Balkema, 1313–1317.

Zuidhoff, F. S. and Kolstrup, E., 2000: Changes in palsa distribution in relation to climate change in Laivadalen, Northern Sweden, especially 1960–1997. *Permafrost and Periglacial Processes,* 11: 55–69.

Revised ms submitted January 2004