The impact of elevation, topography and snow load damage of trees on the position of the actual timberline on the fells in central Finnish Lapland

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This study examines the impact of selected environmental variables on the position of the limit of continuous forest (actual timberline) on three fells situated in central Finnish Lapland, namely Aakenustunturi, Yllästunturi and Pyhätunturi. The factors studied are elevation, topography and snow load damage to coniferous trees. The potential for ascending timberlines in the region is discussed. The limit of continuous forest in the study area is hardly ever composed of a single species but rather features alternating occurrences of spruce, pine and mountain birch. The average altitudinal position of the actual timberline is highest on the southern and western slopes (366–428 m a.s.l.), while the lowest altitudes are recorded on the northern and eastern slopes (336–403 m a.s.l.). Prevalence of block fields and slope gradient are the most significant and visible factors controlling the position of the actual timberline. On the studied fells, from 10% to more than 50% of the total length of the actual timberline is controlled by block fields. The lowest occurrence of the limit of continuous forest, at 270 m a.s.l., results from an extremely high proportion of block fields and steep slopes. Snow patches and delayed snow melting also hamper the upward advancement of the forest. Continuous forest reaches its highest altitudes at 440 m a.s.l. on slopes with gentle inclination and land cover other than block fields, and 460 m a.s.l. in sheltered furrows. Average snow load damage to spruce and pine at the actual timberline varies in the ranges 15–58% and 30–76%, respectively. Snow load damages on trees undoubtedly impede the advance of the actual timberline to higher elevation in all exposures. Seedling density (number/ha) on south-facing slopes near the actual timberline is ca. 5 times greater than on the north-facing slopes. Recent regeneration and seedling establishment is almost absent at the treeline near the fell tops. Results suggest that there is potential for actual timberline advance on south-facing slopes with gentle inclination and missing block fields. It is uncertain, however, whether natural regeneration will take place on felltops with few or no trees.

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Introduction

Actual timberline is a generic term denoting to continuous, altitudinal mountain timberline, which is more or less distinguishable from other parts of the terrain and which can be attributable to a number of local factors (see Holtmeier 2003). This line has also been called an empirical forest line/timberline (Hustich 1966; Dahl 1998), and physiognomic forest line (Hustich 1966; Tuhkanen 1993; Autio 1995; Heikkinen et al. 2002; Autio & Hicks 2004). Areas above the actual timberline are characterised by smaller trees, which grow in groups or alone. The *treeline* is established by the furthest individual trees that have a tree-like form and whose minimum height is 2 metres (Hustich

1966; Tuhkanen 1993; Heikkinen et al. 2002). The terrain between the treeline and the actual timberline is called the *treeline ecotone* (Holtmeier et al. 2003). The *timberline ecotone*, in turn, denotes to the transitional zone between the *economic timberline* and the *tree-species line* (Heikkinen et al. 2002).

A widespread idea is that the present and future global climate warming process will raise the altitudinal forest limit (see Skre 1990; Kellomäki 1996; Kellomäki et al. 1997) especially as the trend seems to be that the climate is warming up with higher altitudes (Diaz & Bradley 1997). The advance of the coniferous treeline has already been documented on the Swedish Scandes Mountains (Kullman 2000; Kullman & Kjällgren 2001). New trees have emerged in timberline forests in Finnish Lapland, too (Juntunen et al. 2002). There are major local differences in the way in which the timberline reacts to climatic changes. Local differences of this kind are attributable to factors such as the varied topography of fells, which in turn is reflected in local differences in snow accumulation and temperatures (Kullman 1979; Holtmeier 1997).

No detailed regional picture is available on the relation between edaphic and topographic factors, the location of the actual timberline and the almost complete treelessness of felltop areas (bare fell heath regions above the treeline) on the fells in Central Lapland. Although the timberline phenomenon and its regulating factors have already been examined for more than 200 years (Holtmeier 2003), there still is no uniform theory that would exhaustively account for it. This is one reason why there is still evident need to investigate the timberline phenomenon at the local (100 m–1 km) and regional level (1–100 km) (Holtmeier 2000, 2003; Kjällgren & Kullman 2002).

The purpose of this paper is to provide, by interpreting the results of fieldwork and aerial photographs, a maximally accurate, regionally comprehensive picture of the positions of the actual timberline, the orographical and topographical factors affecting these positions, and snow load damage to trees on the fells Aakenustunturi, Yllästunturi and Pyhätunturi. An account is also given of the extent to which the warm periods of the 20th century are reflected in the actual timberline and how the favourable seed years of the early 1970's are visible on the actual timberline, treeline ecotone and treeline. Finally, the question of the potential of the actual timberline to advance vertically is also dealt with. The present paper addresses the following five main questions:

1. What are the altitudinal positions of the actual timberline on the studied fells in Central Lapland?
2. To what extent is the position of the actual timberline attributable to the presence of block fields?
3. How does slope inclination affect the position of the actual timberline?
4. What is the impact of delayed snow deposits and snow load damage on the position of the actual timberline?
5. How does climatic change affect the position of the actual timberline and treeline?

Study area

The fells Aakenustunturi (67°41′N, 24°29′E; 570 m a.s.l.) in Western Lapland and Yllästunturi (67°34′N, 24°15′E; 718 m a.s.l.) and Pyhätunturi (67°01′N, 27°09′E; 540 m a.s.l.) in Central Lapland (Fig. 1) are among the oldest residual mountains in the world that contain rock types of age approximately 2000 million years (Manner & Tervo 1988). Most of the rock is quartzite (Mielikäinen 1979; Rastas 1984), which effectively endures chemical weathering. After the latest retreat of the ice sheet, this quartzite has been broken into jagged boulders, or block fields, by freezing water. The fells are characterised by round felltops that result from a long-term erosion effect. Visible features connected with the melting of the continental ice sheet are lateral meltwater channels and glaciofluvial overflow channels (Kujansuu 1967; Mäkinen & Maunu 1984). There are patterned grounds (Haapasaari 1988; McCarroll et al. 1996) on their felltops, representing the effect of frost action.

The fells Aakenustunturi and Yllästunturi are situated in an old-growth forest protection area, apart from Yllästunturi's westernmost top Ylläs, where most of the area's downhill skiing slopes are located (Ylläs-Levi… 2003). Most parts of Pyhätunturi, in turn, are included in the Pyhätunturi National Park that was established in 1938. It is only the Pyhäkero area, reserved for downhill skiing, that lies outside the National Park.

According to Köppen's climate classification (Köppen & Geiger 1936), the areas examined here represent the snow forest climate, and more specifically the humid short-summer type, i.e. Betula climate (Dfc). The mean annual temperature at

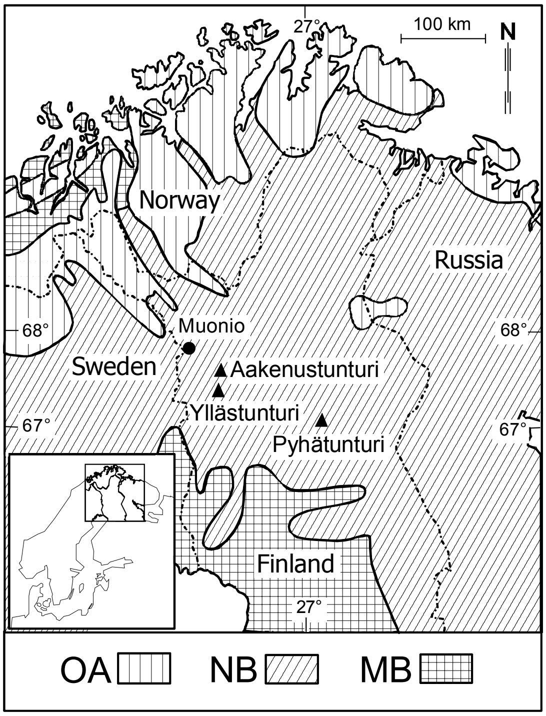

Fig. 1. Location of the areas of investigation, i.e. Aakenustunturi, Yllästunturi and Pyhätunturi in the northern boreal zone (NB) between the middle boreal (MB) and oroarctic (OA) vegetation zones.

Aakenustunturi and Yllästunturi, as recorded by the nearest official meteorological station in Muonio (67°58′N, 23°40′E; 254 m a.s.l.), was –1.7 °C in the period 1961–1990. For Pyhätunturi, the respective figure was –1.0 °C as recorded at the Sodankylä observatory station (67°22′N, 26°37′E; 179 m a.s.l.). Mean precipitation in both areas was approximately 500 mm (Climatological… 1991). It should be noted, however, that the climate conditions on slopes and felltop areas differ considerably from those of the surrounding low-lying areas, mainly due to orographic and topographic reasons (Autio & Heikkinen 2002).

In the classification of northwest Europe's vegetation into zones and sections, the fells Aakenustunturi, Yllästunturi and Pyhätunturi represent the northern boreal vegetation zone. In terms of its continental–marine correlations, the area is situated in the indifferent section group OC (Ahti et al. 1968; Hämet-Ahti 1988). The actual timberline on the above fells is mainly composed of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*), though timberline forests can also be rich in mountain birch (*Betula pubescens* ssp. *czerpanovii*). Actual timberlines lying considerably below the average can also contain downy birch (*Betula pubescens*) (Autio 1997).

Material and methods

Data collection

The location of the actual timberline on Aakenustunturi was determined from 367 observation points (Fig. 2) and on Yllästunturi from 76 points (Fig. 3). Other parameters measured at the points were exposure, slope inclination, presence of block fields, degree of snow load damage to spruce and pine, and relations between tree species. The observations were made in summer 2000. On Pyhätunturi's westernmost bare felltop, Peurakero, exposition and the location of the actual timberline were measured from a total of 344 points (Fig. 4) in summer 2001. At the actual timberline, the crown coverage of the continuous forest was still approximately 30% (Holtmeier 1974; Påhlsson 1995). The geographical position was recorded on a handheld GPS receiver GARMIN 12XL using the average position function, which calculates a moving average of the coordinates until the average stabilises, in approx. five minutes (Owner's… 1998). The number of satellites visible is usually six to eight on these exposed open mountain tops, producing on average five to ten metre accuracy. Due to the fact that GPS measurement of the vertical component is less accurate we decided to obtain altitude from the digital elevation model (25 metre resolution raster, one decimetre resolution altitude). The elevations of the actual timberline points were determined using the overlay analysis in ArcGis programme, and the DEM of National Land Survey of Finland. The points indicating the actual timberline were transformed into a line representing the actual timberline for each fell. The method devised by Perttu (1972) was employed in order to find out the exposures of the actual timberline points. The method divides the felltop or felltops into four sectors each of which stands for one cardinal point (Figs. 2–4). The various sectors are delimited by boundaries drawn according to half-cardinal points. Thus each sector covers 90° of the circular perimeter. The ranges of influence between the felltops were delimited by gullies and

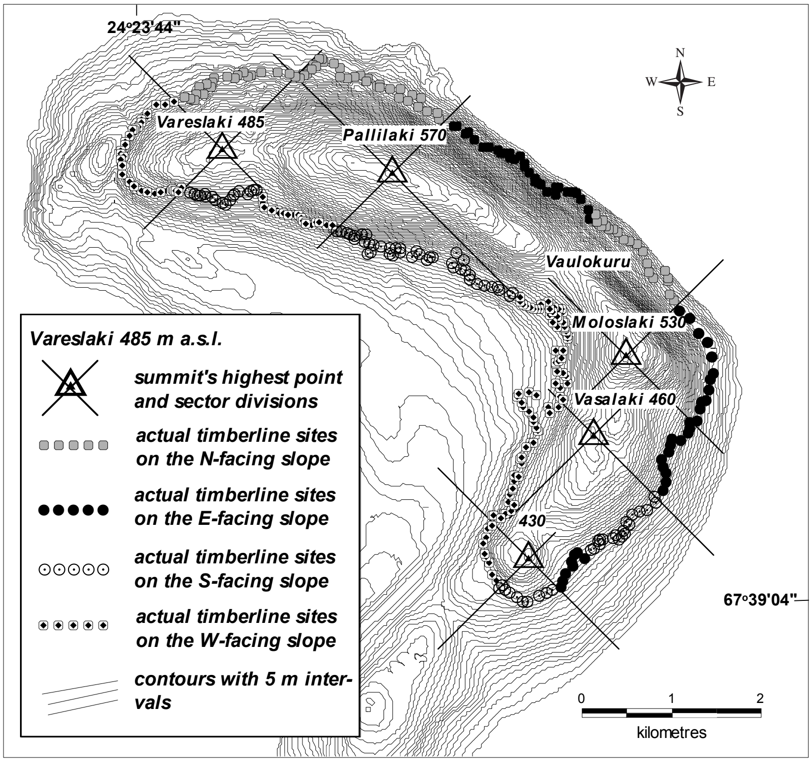

Fig. 2. Timberline points by points of the compass on five felltops of Aakenustunturi. Copyright National Land Survey of Finland 2004. Unauthorised copying prohibited.

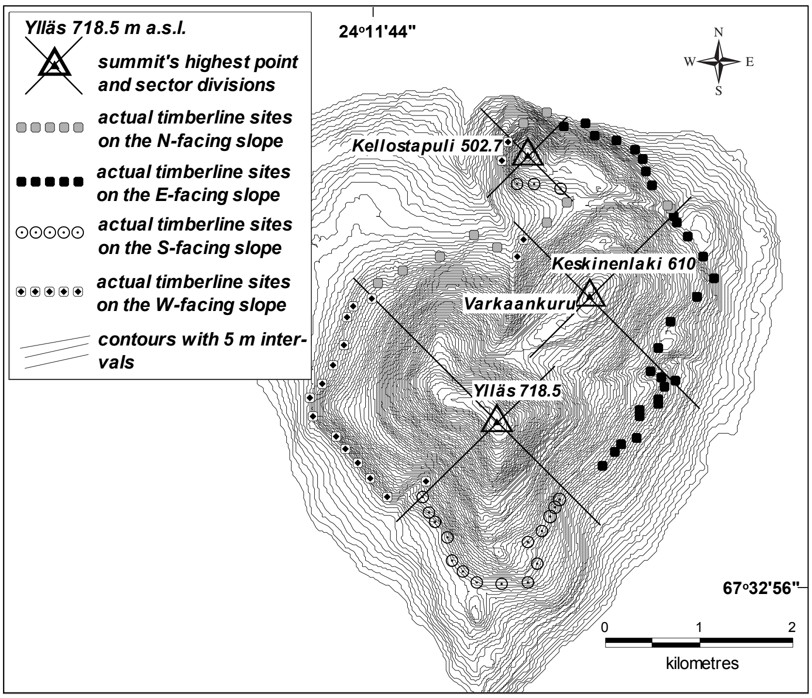

Fig. 3. Timberline points by points of the compass on Yllästunturi. Copyright National Land Survey of Finland 2004. Unauthorised copying prohibited.

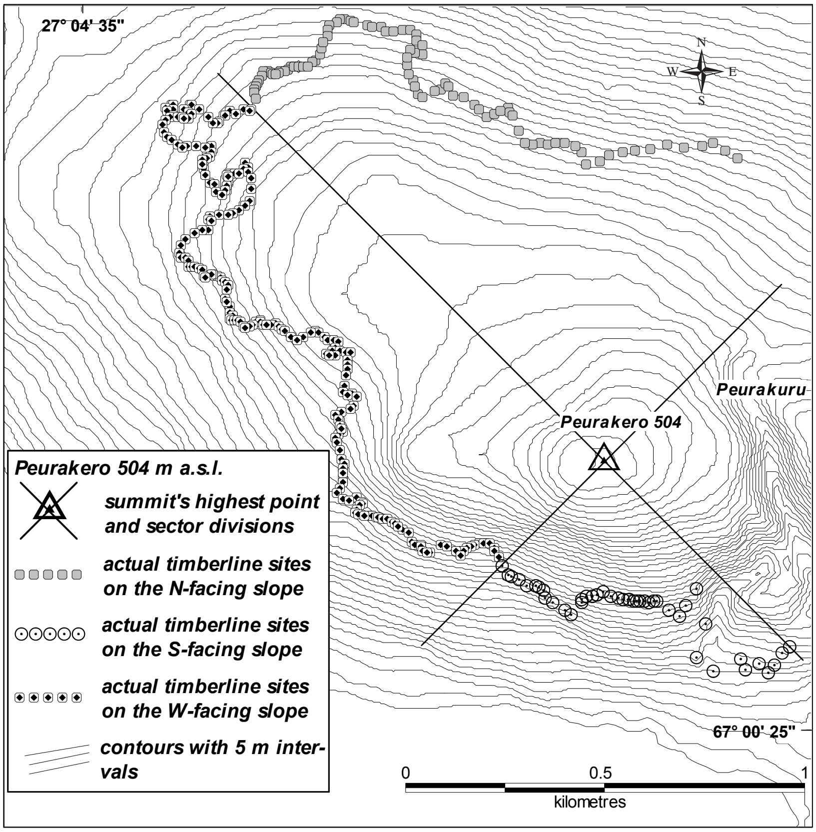

Fig. 4. Timberline points by points of the compass on Peurakero on Pyhätunturi. Copyright National Land Survey of Finland 2004. Unauthorised copying prohibited.

depressions that separate the felltops. The elevation curves could also be used for assessing the range of influence of each felltop (Figs. 2–4). In addition, the length of the border lines that stand for the sectors indicate the boundaries of the ranges of influence between the felltops. Thus the points of compass of the timberline points were established in relation to the nearest felltop. The final exposition of each timberline point was determined on the basis of the cardinal point of the sector in which the target was situated.

Slope inclination at the actual timberline was measured using an optical hypsometer, model PM-5/1520. The proportion of block fields was measured by assessing the part of the land area that was covered by block fields at the actual timberline. Snow load damage was assessed by calculating, in percentages, how many of the spruces and pines making up the actual timberline had broken crowns, or branches in the crown, and ramified crowns. Snow load damage to birches was not examined. The relative proportions of tree species making up the actual timberline were also examined.

The numbers of spruce and pine seedlings and young growth (height less than 2 m) per hectare were calculated immediately above the actual timberline and from the middle of treeline ecotone on the southern and northern slopes, and from Aakenustunturi's Vareslaki at the treeline (Fig. 5). The term seedling is used for small individuals knowing that young growth nearly 2 metres high might be several decades old. The mortality of conifer seedlings was also calculated on the same sites. Circular experimental plots of size 300 m^2 (radius 9.8 m) at the actual timberline, and of 500 m^2 (radius 12.5 m) at the treeline ecotone and at the treeline were established totalling 15 in number. There were three parallel experimental plots at each measurement point. The distance between the central points of two adjacent plots was 40 m (see Juntunen et al. 2002).

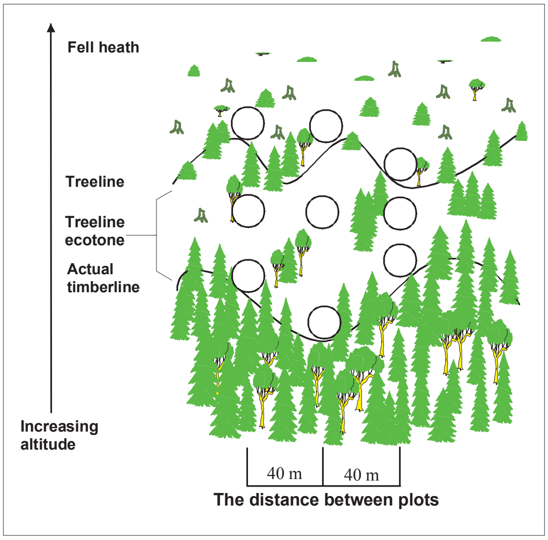

Fig. 5. Experimental design of spruce and pine seedlings density (number/ha) measuring. The distance between the circular plots was measured from centre to centre.

Statistical analyses

Differences in average altitudinal location of the actual timberline in different exposures were tested using the non-parametric Mann-Whitney's U test. The direction and intensity of the correlation between the elevations of the actual timberline, the proportion of block fields on the slopes, slope inclination and snow load damage to spruce and pine were examined using a non-parametric Spearman's correlation coefficient (SPSS… 1998). Before testing, the validity of the normal distribution assumption for the material was checked using the Kolmogorov-Smirnov test (SPSS… 1998). As the data did not follow the normal distribution, it was decided to use the non-parametric Mann-Whitney U test and Spearman's correlation coefficient.

Aerial photographs

The proportions of the actual timberline where it converges with the lower limits of the block fields were detected using digital infrared orthographic colour aerial photos for all the three fells. The same principle was employed for measuring the proportions of convergence between delayed snow deposits and the actual timberline on Aakenustunturi. In addition, the infrared orthographic images were used to illustrate the relation between the actual timberline and various environmental factors that drop or elevate the timberline position. The digital images were scanned from aerial photographs taken from an altitude of approximately 4600 metres, and had a ground resolution of one metre.

Results

Altitudinal position of the actual timberline

The length of the actual timberline is 28 km on Aakenustunturi (Fig. 2), 17 km on Yllästunturi (Fig. 3) and 6 km on Peurakero at Pyhätunturi (Fig. 4). The altitudinal position of the actual timberline on Pyhätunturi is higher (400 m a.s.l.), on average, than on other fells (Table 1). The altitudinal position is by far lowest on Aakenustunturi, but on average higher on the south-facing slopes of Aakenustunturi and Yllästunturi, as compared with the other slopes. The continuous forest reaches its highest vertical limit at ca. 460 metres on the west-facing slope of Yllästunturi. On Pyhätunturi, the average and absolute altitudinal positions of the actual timberline are highest on the west-facing slopes and lowest on the south-facing slopes. The lowest location is ca. 270 m a.s.l., situated on the north-facing slope of Yllästunturi. The differences between the highest and lowest altitudinal positions of the actual timberline on Aakenustunturi and Yllästunturi are greatest at the northern exposure.

This difference is greatest on Yllästunturi, where the actual timberline at the southern exposure is situated on average 62 metres higher than at the northern exposure (Table 2). The smallest elevation difference is 2 metres between the northern and eastern exposures and the southern and western exposures on Aakenustunturi.

Average elevation differences are not statistically significant between the actual timberlines situated at the northern and eastern exposures and southern and western exposures on Aakenustunturi (Table 2). However, the elevation differences between other exposure combinations are statistically very significant ($p < 0.001$) on Aakenustunturi. On Yllästunturi, in turn, the average elevation differences between timberlines situated at the northern and eastern exposures is statistically insignificant. In other respects the elevation differences are statistically very significant ($p < 0.01$) or almost significant ($p < 0.05$). On Pyhätunturi, the

Table 1. Average elevation of the actual timberline, it's standard deviation (STDV), minimum and maximum elevations, and maximum elevation difference on Aakenustunturi, Pyhätunturi and Yllästunturi by points of the compass. The highest values are indicated in bold and the smallest in italics and underlined. The number of timberline points (n) is also given.

Exposure	Average (m a.s.l.)	STDV	Min (m a.s.l.)	Max (m a.s.l.)	Range (vertical m)
Aakenustunturi					
N (n = 62)	338	**24.1**	*<u>284</u>*	391	**107**
E (n = 72)	*<u>336</u>*	22.8	299	*<u>384</u>*	85
S (n = 91)	**390**	23.7	347	**440**	92
W (n = 143)	388	*<u>19.3</u>*	**353**	432	*<u>79</u>*
Average	370	22.5	321	410	89
Yllästunturi					
N (n = 19)	*<u>376</u>*	**43.7**	*<u>272</u>*	429	**157**
E (n = 23)	366	38.5	276	*<u>411</u>*	135
S (n = 16)	**428**	*<u>12.2</u>*	**413**	453	*<u>40</u>*
W (n = 18)	410	17.6	380	**456**	76
Average	395	28.0	335	437	102
Pyhätunturi					
N (n = 116)	403	*<u>8.0</u>*	**387**	416	*<u>29</u>*
S (n = 87)	*<u>375</u>*	**14.8**	*<u>335</u>*	*<u>403</u>*	**68**
W (n = 137)	**418**	11.0	383	**435**	52
Average	402	11.3	368	415	47

Table 2. Differences in average altitudinal position of the actual timberline in different exposures. Statistical tests on the elevation differences between the exposures were performed using the Mann-Whitney U-test. Abbreviations: p-value is probability. Statistical significance: *** highly significant, ** significant, * almost significant and 0 insignificant.

Exposure	Difference in height (m)	P-value	Significance
Aakenustunturi			
N - E	2	0.565	0
N - S	–52	0.000	***
N - W	–50	0.000	***
E - S	–54	0.000	***
E - W	–52	0.000	***
S - W	2	0.562	0
Yllästunturi			
N - E	10	0.167	0
N - S	–52	0.000	***
N - W	–34	0.023	*
E - S	–62	0.000	***
E - W	–44	0.000	***
S - W	18	0.002	**
Pyhätunturi			
N - S	28	0.000	***
N - W	–15	0.000	***
S - W	–43	0.000	***

elevation differences are statistically very significant in all exposition combinations.

Tree species and snow load damage at the actual timberline

The relations between the various tree species were examined on all points of the actual timberline on Aakenustunturi and Yllästunturi. The results obtained for this feature on Pyhätunturi, are based on Autio (1997). On Aakenustunturi, the actual timberline is composed mainly of spruce (Table 3), with ca. 30% proportion of mountain birch of, rising to as much as 60% on east-facing slopes. The proportion of pine on Aakenustunturi timberline is negligible. On Yllästunturi, however, pine is the most common species (41%) to form the actual timberline (Table 4). The proportion of mountain birch is 33% and that of spruce 26% of the tree species making up the actual timberline.

The most common species on the west-facing measurement points of the actual timberline on

Table 3. Proportions of mountain birch, pine and spruce, and their standard deviations (STDV) of the trees forming the actual timberline on Aakenustunturi by points of the compass. The figures are average values. The highest values by tree species are indicated in bold and the smallest in italics and underlined. The number of timberline points (n) is also given.

Exposure	Birch (%)	STDV	Pine (%)	STDV	Spruce (%)	STDV
N (n = 62)	34.2	29.5	*<u>0.2</u>*	0.5	65.0	29.6
E (n = 72)	**60.0**	30.7	4.8	15.9	*<u>35.1</u>*	29.4
S (n = 91)	22.5	19.2	3.3	7.9	74.0	21.1
W (n = 143)	*<u>13.9</u>*	15.5	**5.2**	3.4	**82.1**	17.6
Average	32.6	23.7	3.4	6.9	64.0	24.4

Table 4. Proportions of mountain birch, pine and spruce, and their standard deviations (STDV) of the trees forming the actual timberline on Yllästunturi by points of the compass. The figures are average values. The highest values by tree species are indicated in bold and the smallest in italics and underlined. The number of timberline points (n) is also given.

Exposure	Birch (%)	STDV	Pine (%)	STDV	Spruce (%)	STDV
N (n = 11)	35.6	24.1	55.7	31.4	<u>*5.0*</u>	5.6
E (n = 29)	<u>*26.6*</u>	14.7	<u>*19.0*</u>	25.4	**54.6**	30.4
S (n = 18)	**41.8**	15.0	28.0	25.9	31.6	27.3
W (n = 18)	28.7	24.1	**60.4**	33.0	12.8	19.1
Average	33.2	19.5	40.8	28.9	26.0	20.6

Peurakero at Pyhätunturi is mountain birch (37%), which is also most common at the actual timberline of the northern slopes of Peurakero (47%). On the southern slopes of Peurakero, the actual timberline is composed mostly of pine. Common for all three fells is that the actual timberline is composed of not just a single species, but alternating occurrences of spruce, pine and mountain birch (cf. Autio 1997).

Snow load damage is more common phenomenon with pines than spruces on Aakenustunturi (Table 5) and Ylllästunturi (Table 6). In this study, damages were not examined on Pyhätunturi. Snow load damage to pine and spruce is most common on the south-facing and west-facing slopes of Aakenustunturi. On Ylllästunturi, pines suffer from snow load damage particularly on west-facing and east-facing slopes, whereas spruces are damaged mostly on east-facing and south-facing slopes.

Table 5. Average snow damage to pine and spruce, and their standard deviations (STDV), at the actual timberline on Aakenustunturi by points of the compass. The highest values by tree species are indicated in bold and the smallest in italics and underlined. The number of timberline points (n) is also given.

Exposure	Pine (%)	STDV	Spruce (%)	STDV
N (n = 62)	62.5	47.9	<u>*15.4*</u>	9.3
E (n = 72)	<u>*59.4*</u>	31.7	17.6	19.3
S (n = 91)	**75.9**	30.0	25.0	9.0
W (n = 143)	67.4	23.2	**27.1**	8.6
Average	66.3	33.2	21.3	11.5

Table 6. Average snow damage to pine and spruce, and their standard deviations (STDV), at the actual timberline on Ylllästunturi by points of the compass. The highest values by tree species are indicated in bold and the smallest in italics and underlined. The number of timberline points (n) is also given.

Exposure	Pine (%)	STDV	Spruce (%)	STDV
N (n = 19)	<u>*31.1*</u>	12.9	37.5	8.3
E (n = 23)	**73.1**	29.0	**57.5**	23.2
S (n = 16)	42.5	19.2	39.7	23.0
W (n = 18)	45.6	24.9	<u>*27.8*</u>	25.9
Average	48.1	21.5	40.6	20.1

A statistically very significant correlation ($p < 0.01$) was observed between snow load damage to spruce and the altitudinal positions of the actual timberline on all the slopes of Aakenustunturi (Table 7). As for pine, the same positive correlation is statistically significant ($p < 0.01$) on the east-facing and west-facing slopes only. On Ylllästunturi, snow load damage to pine correlate positively and statistically significantly ($p < 0.01$) with the actual timberline altitude on the east-facing slopes and south-facing slopes ($p < 0.05$) (Table 8).

Block fields and slope inclination at the actual timberline

Block fields and slope inclination at the actual timberline correlate positively with each other, i.e. as the inclination increases, so do usually the block fields (Table 9), and vice versa. The slopes at the actual timberline on Ylllästunturi are steeper and contain more block fields than do those on Aakenustunturi. In spite of this, the average altitudinal position of the actual timberline on Ylllästunturi is higher than on Aakenustunturi. This indicates that on Ylllästunturi, block fields start to occur higher, on average, than on Aakenustunturi. The higher position of the actual timberline on Ylllästunturi may also be attributable to the mass-elevation effect (cf. Hustich 1937). On the east-facing slopes of Aakenustunturi, the slope inclination at the actual timberline is greater than on other slopes, there are more block fields, and the average altitudinal position of the actual timberline is lower than in other points of the compass. On the western slope, however, the inclination of the actual timberline is

Table 7. Correlations between the actual timberline elevation, slope inclination, block fields, and snow load damage (S.l.d.) to spruce and pine on Aakenustunturi. Statistically significant correlations at risk level $p < 0.01$ are indicated in bold.

	m a.s.l.	Inclination	Block fields	S.l.d. of spruce	S.l.d. of pine
North-facing slope					
m a.s.l.	1.000	0.078	**–0.718**	**0.776**	–0.316
Inclination	0.078	1.000	–0.114	0.144	0.056
Block fields	**–0.718**	–0.114	1.000	**–0.517**	0.316
S.l.d. of spruce	**0.776**	0.144	**–0.517**	1.000	–0.316
S.l.d. of pine	–0.316	0.056	0.316	–0.316	1.000
East-facing slope					
m a.s.l.	1.000	**–0.560**	**–0.398**	**0.604**	**0.591**
Inclination	**–0.560**	1.000	**0.455**	**–0.510**	0.208
Block fields	**–0.398**	**0.455**	1.000	–0.012	0.093
S.l.d. of spruce	**0.604**	**–0.510**	–0.012	1.000	0.627
S.l.d. of pine	**0.591**	0.208	0.093	**0.627**	1.000
South-facing slope					
m a.s.l.	1.000	**0.478**	**0.612**	**0.746**	–0.014
Inclination	**0.478**	1.000	**0.626**	**0.496**	0.172
Block fields	**0.612**	**0.626**	1.000	**0.606**	0.228
S.l.d. of spruce	**0.746**	**0.496**	**0.606**	1.000	0.115
S.l.d. of pine	–0.014	0.172	0.228	0.115	1.000
West-facing slope					
m a.s.l.	1.000	**0.310**	**0.221**	**0.431**	**0.501**
Inclination	**0.310**	1.000	**0.637**	**0.387**	–0.174
Block fields	**0.221**	**0.637**	1.000	**0.435**	–0.119
S.l.d. of spruce	**0.431**	**0.387**	**0.435**	1.000	0.244
S.l.d. of pine	**0.501**	–0.174	–0.119	0.244	1.000

Table 8. Correlations between the actual timberline elevation, slope inclination, block fields, and snow load damage (S.l.d.) to spruce and pine on Yllästunturi. Statistically significant correlations at risk level $p < 0.01$ are indicated in bold.

	m a.s.l.	Inclination	Block fields	S.l.d. of spruce	S.l.d. of pine
North-facing slope					
m a.s.l.	1.000	0.092	–0.577	0.562	0.465
Inclination	0.092	1.000	0.373	–0.116	–0.556
Block fields	**–0.577**	0.373	1.000	0.103	–0.455
S.l.d. of spruce	0.562	–0.116	0.103	1.000	**0.856**
S.l.d. of pine	0.465	–0.556	–0.455	**0.856**	1.000
East-facing slope					
m a.s.l.	1.000	**–0.704**	**–0.645**	–0.041	**0.536**
Inclination	**–0.704**	1.000	**0.705**	0.005	–0.397
Block fields	**–0.645**	**0.706**	1.000	0.335	–0.286
S.l.d. of spruce	–0.041	0.005	0.335	1.000	0.087
S.l.d. of pine	**0.536**	–0.397	–0.286	0.087	1.000
South-facing slope					
m a.s.l.	1.000	0.098	–0.307	0.337	**0.511**
Inclination	0.098	1.000	–0.043	0.289	–0.039
Block fields	–0.307	–0.043	1.000	–0.302	–0.405
S.l.d. of spruce	0.337	0.289	–0.302	1.000	**0.911**
S.l.d. of pine	**0.511**	–0.039	–0.405	**0.911**	1.000
West-facing slope					
m a.s.l.	1.000	–0.411	–0.468	0.092	0.265
Inclination	–0.411	1.000	**0.847**	0.233	–0.421
Block fields	–0.468	**0.847**	1.000	0.466	–0.342
S.l.d. of spruce	0.092	0.233	0.466	1.000	0.390
S.l.d. of pine	0.265	–0.421	–0.342	0.39	1.000

lowest and the block fields are smallest. The average altitudinal position of the actual timberline on the west-facing slopes is almost the same as on the south-facing slopes. On Yllästunturi, however, slope steepness and the presence of block fields do not reduce the altitudinal position of the av-

Table 9. Average block field coverage of the ground area, inclinations and standard deviations (STDV) at actual timberline points (n) on Aakenustunturi and Yllästunturi by points of the compass. The highest block field and inclination values are shown in bold and the lowest in italics and underlined.

Exposure	Block fields (%)	STDV	Inclination (o)	STDV
Aakenustunturi				
N (n = 62)	8.0	13.1	15.2	7.7
E (n = 72)	**21.7**	18.0	**21.8**	10.5
S (n = 91)	8.2	13.5	10.5	6.4
W (n = 143)	*7.9*	13.3	*9.1*	5.0
Average	11.5	14.5	14.2	7.4
Yllästunturi				
N (n = 11)	*24.5*	25.1	*15.1*	11.7
E (n = 29)	25.8	29.0	19.9	10.0
S (n = 18)	30.4	20.0	16.8	3.9
W (n = 18)	**45.9**	38.9	**24.7**	11.2
Average	31.7	28.3	19.1	9.2

erage actual timberline to such an extent as they do on Aakenustunturi. The actual timberline on Yllästunturi extend higher, on average, on the steep western slope with extensive block fields, than on the gentler and less rocky northern and eastern slopes.

In cases where the actual timberline borders a block field (Fig. 6A Point 1 and Fig. 6B Point 4), its elevation remains below the average (Fig. 7). The lowest timberline points on the fells are dictated by slope gradient and block fields in particular. On the lowest actual timberline point on the northern slope of Yllästunturi (272 m a.s.l.), for instance, the block field percentage is 80% and inclination 32°. Of the total length of the actual timberline on Aakenustunturi (27.9 km), at only 9.7% (2.7 km) does the actual timberline run alongside the lower edge of a block field, as compared with 52.5% on Peurakero at Pyhätunturi and 28.4% on Yllästunturi. In the latter case, 36.5% of all timberline points sit in areas where block fields make up 40% or more of the ground area, as compared with only 10.9% on Aakenustunturi (Table 10).

On gentle slopes with small block fields, the forest turns into barren fell heath gradually making the actual timberline difficult to perceive accurately in the field or on aerial photographs (Fig. 6A Point 2 and Fig. 6B Point 5, Fig. 8). On such slopes as well as in steep gullies (such as Varkaankuru at Yllästunturi, see Fig. 3), the timberline lies higher than elsewhere (Fig. 6A Point 3). On the other hand, in some locations, e.g. on the north-facing and east-facing slopes of Aakenustunturi, the actual timberline remains at low altitude despite a gentle slope inclination. The reasons for this are

Table 10. Classification of block field coverage (%) into five class intervals at actual timberline points on Aakenustunturi and Yllästunturi. The frequency of observations in each interval and their relative (%) proportion of the entire material are shown. Block fields coverage 40% or more is indicated as a dash line in the table.

Class intervals (%)	Frequency	(%)
Aakenustunturi		
0–19	261	71.1
20–39	66	18.0
40–59	36	9.8
60–70	3	0.8
80–100	1	0.3
Yllästunturi		
0–19	35	47.3
20–39	12	16.2
40–59	10	13.5
60–70	4	6.8
80–100	12	16.2

sudden kinks in the slope gradient, which form favourable zones for delayed snow beds. The deposits lead to a sharp actual timberline and lower than average altitudinal position (Fig. 6C Point 6 and Fig. 9). Forests do not occur above delayed snow beds, and individual trees only survive in places moister than their surroundings (Fig. 10). In excessively wet places, such as paludified sites, the timberline occupies a lower elevation (Fig. 6D Point 8). In addition, delayed snow deposits typically accumulate in depressions, such as lateral drainage channels, which prevent the timberline from reaching higher elevations (see Autio & Heikkinen 2002). Of the total length of the actual timberline on Aakenustunturi, 4.8% involved cases where the lower edge of delayed snow deposits adjoined the

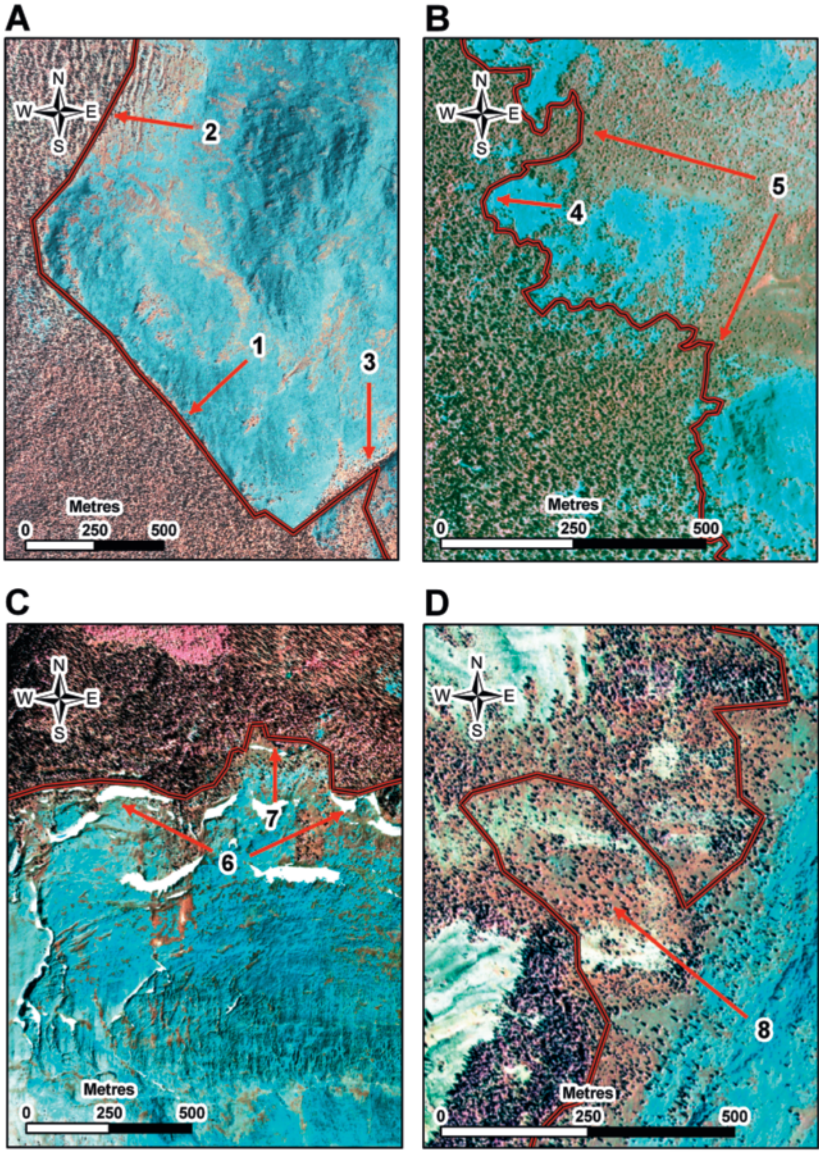

Fig. 6. Four aerial photographs of Yllästunturi, Pyhätunturi and Aakenustunturi. A thick red line with a thin black line in the centre and edges indicates the actual timberline. Copyright FM-kartta Oy. Publication number for all photographs is FMK002_1/2004.
(A) Aerial photograph of the western and southern slope of Yllästunturi (718 m a.s.l.). The brownish forest at Point 1 borders sharply on the bluish lower edge of a block field. The actual timberline lies at Point 1 at 403 m a.s.l. In the left-hand upper corner the actual timberline runs in a forest (Point 2), indicating the gradual thinning of the forest on the gentle slope into a treeless felltop. In gullies (Point 3) the continuous forest rises above the surroundings. The highest actual timberline on Yllästunturi is situated at 456 m a.s.l. at Point 3. Photographed on 30th July 1995.
(B) Aerial photograph of the western slope of Peurakero on Pyhätunturi (504 m a.s.l.). The greenish forest clearly borders on the bluish lower edge of a block field as in Point 4 at ca. 400 m a.s.l. Where block fields do not hamper the advance of forest, and the slope is gentle, the forest gradually becomes thinner and the actual timberline rises above the surroundings. At the tip of the southward arrow at Point 5, the actual timberline reaches its highest elevation on Peurakero, Pyhätunturi, i.e. 435 m a.s.l. Photographed on 8th July 1989.
(C) Aerial photograph of the northern slopes of Pallilaki (570 m a.s.l.) and Vareslaki (485 m a.s.l.) on Aakenustunturi. Delayed snow deposits accumulate in suitable points of the terrain on the northern and eastern slopes of Aakenustunturi (indicated by white colour in the photographs) that prevent the advance of the forest, as in places indicated by the arrow at Point 6. At those points the actual timberline is situated at 354 m a.s.l. The timberline occupies lower elevations in places indicated by the arrow at Point 7, due to frequent avalanches. At lowest the actual timberline in the avalanche slope was situated at 313 m a.s.l. Photographed on 24th June 1998.
(D) Aerial photograph of the western slope of Vasalaki on Aakenustunturi (460 m a.s.l.). The lower elevation of the actual timberline in the place indicated by the arrow at Point 8 is due to paludification. At lowest the actual timberline is situated at the lower edge of a mire at 355 m a.s.l. Before the mire the actual timberline runs at 372 metres. Photographed on 24th June 1998.

Fig. 7. Actual timberline on Kellostapuli, Yllästunturi. The view is from the west to the east. The actual timberline, which borders on a steep slope with block fields, is clearly and sharply visible even in the remote landscape, as shown in the centre and left-hand corner of the photograph. Steep slope and block fields together reduce the elevation of the actual timberline. (Photo Jyrki Autio, 09/1996).

Fig. 8. Thin, park-like treeline ecotone forest on the gentle western slope of Peurakero, Pyhätunturi. The forest gradually becomes thinner and the actual timberline is not sharp. (Photo Jyrki Autio, 08/2001).

actual timberline. Another factor leading to lower timberline elevations is the occurrence of local avalanches on the north-facing slopes of Kellostapuli at Yllästunturi and of Pallilaki at Aakenustunturi (Fig. 6C Point 7 and Fig. 11).

At Aakenustunturi, the altitudinal position of the actual timberline correlate statistically significantly ($p < 0.01$) with block fields regardless of the slope aspect. The correlation is negative on the north-facing and east-facing slopes, but positive on the south-facing and west-facing slopes (Table 7). In other words, the low altitudinal position of the actual timberline on the northern and eastern slopes correlates with the proportion of large block fields. On the southern and western slopes, however, the altitudinal position of the actual timberline is high, but there are also large block fields. The correlation between slope steepness and timberline elevation is negative and statistically significant on the east-facing slopes ($p < 0.01$), but positive and statistically significant on the south-facing and west-facing slopes (Table 7).

Statistical correlation between the altitudinal positions of the actual timberline, the proportion

Fig. 9. Sharp actual timberline on the northern slope of Pallilaki on Aakenustunturi, caused by a delayed snow deposit. The view is from the same place as that shown by the left-hand arrow at Point 6 in Figure 6C. (Photo Jyrki Autio, 08/2004).

Fig. 10. Spreading of trees above the actual timberline on both sides of the seeping surface of a small spring on the eastern slope of Pallilaki on Aakenustunturi. (Photo Jyrki Autio, 08/2000).

of block fields on the slope, and slope inclination is smaller on Yllästunturi (Table 8) than on Aakenustunturi (Table 7). A negative, statistically significant correlation ($p < 0.01$) was observed between block fields, slope steepness and the altitudinal position of the actual timberline on the east-facing slopes. According to Autio (1997), block fields occupy as much as 50% of the ground cover at the actual timberline on the southern slope of Laakakero at Pyhätunturi but only 3% at the timberline on the northern slope of Laakakero and 10% on the western slope of Peurakero. The altitudinal

Fig. 11. Trees on the northern slope of Pallilaki on Aakenustunturi suffer from frequent avalanches, which prevent the forest from advancing. The view shows an avalanche accumulation site. Avalanches originate at higher points on the slope where the inclination is approximately 35°. They stop at the actual timberline shown in the background (see Fig. 6D Point 7). (Photo Jyrki Autio, 08/2000).

position of the actual timberline is lowest on the south-facing slopes, which are characterised by large block fields and steep gradient, while on the gentle western and northern slopes, where also the block fields are smallest, it reaches the highest altitudinal position on Pyhätunturi.

Seedling density and mortality at the treeline ecotone

The number of spruce seedlings decline dramatically from the actual timberline to the treeline (Table 11). The southern and northern slopes also differ greatly in this respect: on southern slopes, the number of spruce seedlings at the actual timberline and in the middle of the treeline ecotone is ca. 5 times higher than on northern slopes. Pine seedlings are quite scarce at the timberline and in the middle of treeline ecotone dominated by spruce. In relative terms, the proportion of pine seedlings of the conifer new growth increase with elevation so that on the treeline, for instance, pine account for half of all conifer seedlings, as opposed to zero occurrences at the actual timberline on the southern slope. The proportion of dead conifer seedlings is 4.4% of all seedlings at the actual timberline of the south-facing slope, 16.7% in the middle of treeline ecotone and 52.6% at the treeline, as compared with 28.0% at the actual timberline of the northern slope, which exceeds the figure recorded for the treeline ecotone (22.5%). An opposite trend was observed on the southern slope.

Table 11. Number of spruce and pine seedlings per hectare at the actual timberline, in the middle of treeline ecotone and tree line on the southern and northern slope of Vareslaki on Aakenustunturi. Conifer seedling mortality per hectare is also given.

Exposure	Zone	Altitude (m a.s.l.)	Spruce seedling density (number/ha)	Pine seedling density (number/ha)	Seedling mortality (number/ha)
South	Actual timberline	435	4961	0	231
	Treeline ecotone	460	1672	88	352
Summit	Tree line	475	12	6	20
North	Treeline ecotone	395	297	44	99
	Actual timberline	365	891	11	351

Discussion

Actual timberline elevation

The average and maximum actual timberline elevations on Aakenustunturi and Yllästunturi discussed here and those obtained by Hustich (1937) differ quite notably in that the present ones are clearly below those presented by Hustich. The measuring instruments (barometer) and topographic maps at his disposal were not as accurate and furthermore, the method that Hustich (1937) used for delimiting the actual timberline is not known. The actual timberline positions recorded here by means of a GPS receiver can be considered quite accurate (see Colpaert 1998), as indicated by the fact that on the aerial photographs the actual timberline adjoins the lower edges of the block fields (see for example Fig. 6A Point 1), which indicate the highest timberline elevation.

According to Holtmeier (1974, 2003), the actual timberline elevation varies from 400 metres up to 600 metres in the "high fjeld" area situated in Western Lapland. On Aakenustunturi and Yllästunturi, however, the average elevations remain below 400 metres, apart from Yllästunturi's south-facing and west-facing slopes, where the average actual timberline elevation exceeds 400 m a.s.l., with a maximum of 460 metres. Earlier investigations (e.g. Norokorpi 1994) have suggested that the coniferous timberline is situated at approximately 440 m a.s.l. in the Pyhätunturi area. The results obtained here indicate, however, that although the actual timberline on Pyhätunturi can reach a maximum elevation of 440 metres, the average remains at 405 metres. The actual timberline elevations recorded by Autio (1997) for Aakenustunturi, Pyhätunturi and Yllästunturi also differ from the results obtained here. This is mainly due to the fact that the results from Autio (1997) were derived from single-transect observations whereas those discussed here are based on a much more comprehensive sample.

Tree species at the actual timberline

On the studied fells, the relations between tree species at the actual timberline turned out to be typical for fells situated to the south of the northern timberline (see Autio 1995, 1997; Holtmeier 2003) in that the limit composed of alternating compositions of spruce (*Picea abies*), pine (*Pinus sylvestris*) and mountain birch (*Betula pubescens* ssp. *czerpanovii*). On Aakenustunturi, for instance, the actual timberline is composed entirely of spruce in only 1.5% of all cases. The birch proportion is greatest on the east-facing and north-facing slopes, attributable to a thicker snow cover (see Solantie 1974; Kullman 1979; Autio 1997). According to Solantie (1974), the thick snow cover results from the dynamics of air flows crossing the fells. In addition, snow melts from these slopes later than from slopes facing other directions (Autio 1997). According to Kullman (1979), considering the snowy conditions of this kind, mountain birch is better capable of seed-based reproduction than is spruce or pine.

Usually, shade-tolerant species, such as spruce, tend to form abrupt timberlines, while light-demanding species, such as pine, tend to produce open stands near the vertical limit for continuous forest with a wide transition zone (Walter 1968). In the current study, however, the tree species did not have an impact on the nature of the actual timberline: the forest always turns gradually into a treeless or almost treeless fell heath region regardless of tree species expect in cases where the limit is determined by soil-related and topographic factors such as block fields, delayed snow deposits and avalanches.

Factors affecting snow load damage at the actual timberline

Snow load damage to spruce turned out to be smaller than to pine, which is in accordance with earlier investigations (Heikinheimo 1920; Norokorpi & Kärkkäinen 1985; Norokorpi 1994; Mustonen 1997; Korpi 2001). Although the narrow-crowned spruce is well capable of withstanding snow masses, pine is still more common than spruce at the actual timberline for example on Yllästunturi. It is therefore likely that the species composition at the actual timberline is determined by soil-related factors, such as moisture and texture of soil, more than by the ability of the tree to withstand snow load damage. The combined percentages of snow load damage to spruce and pine at the upper limit of continuous forest are markedly higher than on the limit where snow starts to accumulate on trees (30% damage) so the latter limit on Aakenustunturi and Yllästunturi is situated below the actual timberline (cf. Norokorpi 1994). It should be noted, however, that on Aakenustunturi, the snow load damage at the actual timberline to spruce alone is under 30% on average, indicating that the snow accumulation limit for spruce is above the actual timberline. The snow accumulation limit for spruce is known to be higher than for pine (Norokorpi & Kärkkäinen 1985). In addition, the amount of snow load damage varies considerably, mainly due to major variation in the actual timberline elevation.

The fact that snow load damage to spruce is less severe on Aakenustunturi than on Yllästunturi is mainly attributable to the fact that on Yllästunturi the actual timberline is situated higher than on Aakenustunturi. According to earlier investigations (Heikinheimo 1920; Norokorpi & Kärkkäinen 1985; Korpi 2001), the amount and frequency of snow load damage increase with higher elevations. The finding is also supported by the fact that on Aakenustunturi, snow load damage to spruce and pine is more severe on the south-facing and west-facing slopes with higher actual timberline elevation, as compared with northern and eastern slopes. Also Heikinheimo (1920), Nykänen et al. (1997) and Päätalo (2000) point out that snow loads are largest on south-facing and west-facing slopes. In earlier studies in Kuusamo by Norokorpi and Kärkkäinen (1985), however, the amount of snow load damage was not found to be dependent on slope aspect. On Yllästunturi, the average snow load damage is largest on the east-facing slopes, probably reflecting the impact of artificial snowing practiced in Yllästunturi's skiing resort in early winter. Rime formation is extensive in early winter, too (Tammelin & Säntti 1992). Yllästunturi's east-facing slopes are also well positioned for receiving the humid air masses spreading from the south so the resulting humidity tends to condensate readily on the trees.

On Yllästunturi, snow load damage to pines is less extensive than on Aakenustunturi, possibly due to the fact that on the latter pines make up a small proportion of the timberline's growing stock, thus increasing the proportion of random fluctuations in the results. On the other hand, pine crowns on Aakenustunturi may be more asymmetric and broader, thus accumulating more snow than those on Yllästunturi (see Nykänen et al. 1997). Scattered pines on Aakenustunturi suffer from snow load damage more than pines that occur in denser growths. Individual pines growing in spruce-dominated timberline forests may accumulate larger snow loads than those standing in pine-dominated growths (cf. Kangas 1959). The relationship between slope angle and snow load damage is apparent on the south-facing and west-facing slopes of Aakenustunturi, where damage is most widespread on steep slopes (cf. Nykänen et al. 1997). On the other hand, at these points also the timberline elevation is higher and hence, it is possible that the amount of the snow load damage is partially due to higher timberline elevation.

Orographic and topographic factors affecting the position of the actual timberline

The *mass-elevation effect* resulting from a large mass of broad, high mountains (Hustich 1937; Holtmeier 1974, 2003) may indeed affect the maximum elevation of the actual timberline in the study area, as the highest occurrence of continuous forest limit was found on the highest fell, Yllästunturi. The mass-elevation effect does not seem to have as obvious impact on the average actual timberline elevation, however, as the actual timberline reaches its highest average elevation on Pyhätunturi, which is lower than Yllästunturi.

The proportion and distribution of block fields on the slope have an impact on timberline elevation, as indicated in previous research, too (Hustich 1937; Piirola 1969; Holtmeier 1974; Autio 1995, 1997). It is difficult for trees to become rooted in a nutrient-poor, rocky soil (Heikkinen et al. 1995), and they are also sensitive to wind damage (Eronen 1979). Thin humus layer and thin soil horizon (Autio & Kinnunen 1992) give rise to high temperatures and low moisture content in summer (Tranquillini 1979; Holtmeier 2000; Holtmeier et al. 2003). Areas above the actual timberline are exposed to high wind speeds (Lehtonen 1992; Tammelin 1998), which also accelerates the drying of the surface soil. Excessive drying of the soil surface in areas above the actual timberline is enhanced by coarse, highly permeable soils, particularly on steep slopes (Mäkitalo et al. 1994). The low soil moisture content hampers or even prevents the sprouting of tree seeds and the ability of trees to obtain nutrients (Kallio & Lehtonen 1973; Holtmeier 2000, 2003).

The formation of the actual timberline is affected also by slope inclination. On gentle slopes, the uppermost vertical limit of continuous forest usually alters into a treeless area gradually through a transition zone (Fig. 8; see also Autio 1995; Holtmeier 2003). It may be difficult to indicate the actual timberline under such conditions. The actual timberline is usually sharpest on steep slopes (Fig. 7) where the uppermost vertical limit of continuous forest is also fairly easy to point out. On steep slopes in the fells of Lapland, freeze-thaw cycles have often caused quartzite to crack, giving rise to block fields. Steep gradient seems to encourage the occurrence of block fields, a situation also noted elsewhere (Piirola 1969; Autio 1995). Holtmeier (2003) named the timberline dictated by rocky fields and steep topography as the orographic timberline. If we use a block field limit value of 40% or more of the ground area covered with blocks, these make up 36.5% of the timberlines on Ylläs-tunturi and 10.9% on Aakenustunturi. These limits, regulated by block fields and steep topography, are thus orographic timberlines. On Peurakero at Pyhätunturi, the proportion of orographic timberlines is over 50%. Steep inclination and the presence of block fields together force the actual timberline to remain at lower elevations. On sheltered north-facing slopes with steep topography, the local timberline elevation is also reduced by avalanches (Fig. 11; see also Autio & Heikkinen 1999). On gentle slopes, mires have the same impact (Fig. 6D; see also Holtmeier 1973, 1974; Wardle 1993).

Local landforms have an impact on the structure of the actual timberline. Depressions, such as lateral meltwater channels, are treeless and may accumulate several metres of snow. In these landforms, the absence of trees is due to excessive snow cover that only melts in late summer and the resulting short growing season (Autio & Heikkinen 2002).

The varied topography of fells is also closely reflected in their microclimate, snow distribution and mass movements. Topographically induced microclimatic variations have been found to have an impact on the location of the actual timberline and treeline (Autio 1995).

In parallel with earlier investigations (Perttu 1972; Mayer & Ott 1991; Odland 1996; Autio 1997; Kjällgren & Kullman 2002), the timberlines in the study area reach their maximum elevations on the south-facing and west-facing slopes while the lowest elevations were recorded on the north-facing and east-facing slopes. The only expection to this rule is Pyhätunturi, where the actual timberline elevation is lowest on the south-facing slopes.

Factors affecting seedling density and mortality at the treeline ecotone

On the south-facing slope of Aakenustunturi, spruce seedlings form vital, dense growths immediately above the actual timberline and in the treeline ecotone (Fig. 12). Yet the number of spruce seedlings is slightly below that recorded by Juntunen et al. (2002) on Pallastunturi (68°00′N, 24°09′E) but well above that in the corresponding zones on Pyhätunturi. The number of spruce seedlings is much smaller at the actual timberline and in the middle of treeline ecotone on the northern slope of Vareslaki at Aakenustunturi than on Pallastunturi (Juntunen et al. 2002). Their number is larger on the south-facing slope of Aakenustunturi than on the north-facing slope, which is attributable to a more favourable local climate, earlier snow melt and higher effective temperature sum (Autio & Hicks 2004). Delayed snow deposits accumulate immediately above the actual timberline on the northern slope (see Fig. 6C Point 6). In these points, the local growing season is shorter, the ground becomes waterlogged and ground temperatures are low at the beginning of the growing season. In addition, pockets of descending cold air are likely to form at the dense, continuous actual timberline on Aakenustunturi during the growing season, causing damage to tree seedlings and annual shoots. The reasons for the small number of seedlings at the treeline and for their high mortality and fading on Aakenustunturi might be multiple, including the occurrence of sub-zero temperatures at the beginning of the growing season, variation in temperature factors, unfavourable soil temperature conditions, drought and poor nutrient supply, minor or non-existent snow protection in winter, reindeer grazing in a sensitive environment, and mechanical abrasion and drought caused by harsh winds (see Holtmeier et al. 2003). Many of the above factors also contribute to the scantiness of seedlings in the treeline ecotone of the northern slopes.

Potential advance of the actual timberline

The size of spruce seedlings and young growth on Aakenustunturi varies from 10 cm to almost 2 m. It is likely that the smallest seedlings date back to the 1980's and 1990's when according to Juntunen et al. (2002) spruce seedling regeneration was successful on the fells of Lapland. Summer seasons warmer than usual with conditions favourable for seedling regeneration occurred in 1994–2001 on Aakenustunturi. The best years with this respect were 1997 and 1999–2001, when temperatures stayed above the long term average and high pollen deposition at the actual timberline was recorded (Autio & Hicks 2004). Most of the seedlings germinated in 1972–1973, which is known to be one

Fig. 12. To the front in the picture are spruce seedlings and young growth having started their growth in the past three decades, which are situated at 435 metres and above the actual timberline on the southern slope of Aakenustunturi. (Photo Jyrki Autio, 08/2004).

of the most favourable conifer regeneration years of the last century (Sirén 1993), thanks to warm summer seasons (Juntunen et al. 2002). Conifer seedlings seem to be able to react vividly to climatic changes (cf. Kellomäki et al. 1997), which is reflected by the strongly stocked young growth at the actual timberline and treeline ecotone of south-facing slopes. The rapid reaction of conifer seedlings to climate warming indicates a potential for the advance of the treeline and subsequently also of the actual timberline.

It is possible that climate warming will be reflected in just a few decades in the position of the actual timberlines that lie at topographically and edaphically favourable sites on Aakenustunturi, Pyhätunturi and Yllästunturi. This is suggested by the fact that there are several places on Aakenustunturi (Aho 1999) and on Pyhätunturi and Yllästunturi (Sonninen 1993; Tuovinen 1997) where spruces and pines having started their growth in the warm years of the 1920's and 1930's form vital actual timberlines. At the treeline, the situation

Fig. 13. Most of the trees shown in the background are mountain birches of height less than 2 metres, with some spruces and pines, above the actual timberline at 450 metres on Peurakero, Pyhätunturi. (Photo Jyrki Autio, 08/2001).

is somewhat different, as the spruces and pines of the same favourable generation almost invariably show signs of suffering mainly as a result of damage caused by snow, wind-blown ice crystals, extreme climate and soil temperature fluctuations (Heikkinen et al. 2002). According to Holtmeier (1974, 1993) and Kullman (1983), many of the trees from the exceptionally warm period of the 1920's and 1930's have already died or suffer from damage caused by harsh, extreme climate.

Decisive with regard to the successful advance of the actual timberline is that there are sufficiently many successive years with conditions that favour the development of tree seedlings and seeds, as was apparently the case in the 1920's, 1930's, early 1940's, and again during the past three decades. Treelines climates are characterised by extreme, fluctuating temperatures and soil conditions, which in part impair the possibilities of seedlings and adult trees to survive. The mere rise in air temperature alone does not guarantee the advance of the altitudinal forest limit, not to mention the stocking of treeless or almost treeless felltop areas with young stock. On the contrary, many phenomena introduced by climate change slow down or may even prevent the advance of the actual timberline (see Holtmeier et al. 2003).

As summer seasons become warmer and maximum temperatures rise (Carter & Saarikko 1996; Holopainen et al. 1996), the already high temperature fluctuations on the ground surface and in the soil may give rise to drying of the soil surface and thus impair the ability of tree and seedling roots to obtain water and nutrients from the ground (Holtmeier 2003; Holtmeier et al. 2003) and the sprouting of seeds (Kallio & Lehtonen 1973; Holtmeier 2003) in the treeline ecotone and at the treeline. The projected possible increase in the occurrence of harsh winds and storms (Holopainen et al. 1996) from the already high level would accelerate evaporation and enhance wind damage in felltop areas. The reduction of protective snow cover due to higher winds would increasingly expose seedling roots to frost damage in winter (cf. Holtmeier et al. 2003).

The predicted increase of winter precipitation due to global cimate change (Holopainen et al. 1996) may accelerate the accumulation of snow on trees, and thus slow down or even prevent the advance of the actual timberline. The ice-free waters of Bothnian Bay release warm humid air particularly in early winter, giving rise to extensive frost formation also on the fells of Lapland when the air cools down (Solantie 1974). The open-water season on the Bothnian Bay is predicted to become longer (Kauppi & Kämäri 1996) and hence, the snow load formation on trees may increase. These would mean an increased risk of heavy snow load damage to trees on the fells of Lapland (see Jalkanen & Konôpka 1998).

On the fells examined here, it is likely that as a result of climate warming, the actual timberline will advance in the coming decades on gentle slopes where ground-related factors resemble those of a closed forest (see Fig. 8). This process requires, however, that there are no extreme weather conditions, and that the competition between conifer seedlings and dwarf shrubs and mosses for light and nutrients is not too intense, at least not during the first growing seasons (Kallio & Lehtonen 1973; Holtmeier 2003). Thus the altitudinal position of the actual timberline can ascend through a process in which the seedling stocks currently standing at or above the actual timberline develop into forests, and many of the birches, spruces and pines growing above the altitudinal timberline reach a height of 2 metres, which is considered the minimum for trees (Fig. 13) (see Holtmeier 2003). The vertical ascend of the actual timberline from the present maximum elevations (ca. 440–460 m a.s.l.), mainly at climatic timberlines, will be some tens of metres at best. In felltop areas, it is most uncertain whether trees can grow there successfully at all. Orographic timberlines at steep slopes and abundant block fields can hardly be expected to advance as a result of climate warming – not even after long periods of time (see Holtmeier 2003). The potential advance of actual timberline will vary substantially from place to place due to variations in topography, edaphic factors and microclimates.

Conclusions

The key conclusions of the research can be summarised as follows:

- The average actual timberline elevation varies from ca. 370 metres to 400 metres a.s.l., depending on slope aspect. On Aakenustunturi and Yllästunturi, the timberline reaches the average and maximum elevations on the west-facing and south-facing slopes, whereas the limit for continuous forest is lowest on the steep southern slope of Pyhätunturi. The lowest vertical forest limit in the study area lies at approximately

270 m a.s.l., and the highest continuous forest reaches almost 460 m a.s.l. The actual timberline is hardly ever composed of a single tree species but rather featuring alternating occurrences of spruce, pine and mountain birch.

- The proportion of block fields and the slope gradient are the most significant and visible factors controlling the altitudinal position of the actual timberline. Timberlines dictated by block fields make up at ca. 10% of the total length of the actual timberline on Aakenustunturi, ca. 50% at Peurakero on Pyhätunturi and ca. 30% on Yllästunturi. North-facing slopes with inclination 30°–44° are susceptible to avalanches, which are a substantial agent affecting the actual timberline position. On slopes with a gentle inclination and no block fields, the actual timberline reaches its highest elevation. Here the limit of continuous forest is controlled by climate.
- Delayed snow deposits effectively block the advance of the actual timberline mainly on the north-facing and east-facing slopes. On Aakenustunturi, for instance, the actual timberlines bordered by delayed snow deposits constituted ca. 5% of the length of the entire actual timberline.
- The amount of snow load damage depends on tree species, slope aspect, to some extent on slope inclination and most importantly on terrain elevation. The average snow load damages at the actual timberline on Aakenustunturi and on Yllästunturi, respectively, are 66% and 48% to pine, as compared with 21% and 40% for spruce, respectively. Snow load damage evidently debilitates the trees at and above the actual timberline and therefore hampers the potential advance of the actual timberline and treeline.
- Recent successful regeneration, seedling establishment and young growth just above the actual timberline and in the treeline ecotone on gentle southern and western slopes with no block fields suggest that forests are in the process of ascend due the climate warming. This will take place more slowly on slopes with northern and eastern aspect. It is, however, unlikely that timberlines determined by steep slopes and the presence of block fields would make any major advance. Results suggest that natural regeneration is most uncertain at the treeline near the felltops. The projected climate change may bring along negative phenomena such as increasing snow loads on trees and greater occurrence of strong winds, which may slow down or even prevent the advance of timberline.

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