OBJECT BASED CHANGE DETECTION OF HISTORICAL AERIAL PHOTOGRAPHS REVEALS ALTITUDINAL FOREST EXPANSION

M. Middleton [a, *], P. Närhi [a], M-L. Sutinen [b], R. Sutinen [a]

[a] Geological Survey of Finland, P.O.Box 77, 96101 Rovaniemi, Finland – (maarit.middleton, paavo.narhi, raimo.sutinen)@gtk.fi
[b] Finnish Forest Research Institute, Eteläranta 55, 96300 Rovaniemi, Finland – marja-liisa.sutinen@metla.fi

KEY WORDS: High Resolution, Forest, Temporal, Change Detection, Soil

ABSTRACT:

Object based image classification is applied to assess the upward advance of tree species in Finnish Lapland caused by the current global warming. An automated Feature Extraction Module (Fx) implemented in ENVI is used to extract the tree crowns from a digitized panchromatic aerial photograph acquired in 1947 and a false colour aerial photograph from 2003 of an altitudinal forest-tundra ecotone on Lommoltunturi fell (a mountain shaped by Pleistocene glaciations). The two step Fx process included segmentation and feature classification with support vector machines with textural, spatial and spectral channels as inputs. The change in the resulted relative crown areas of Norway spruce (*Picea abies*) and downy birch (*Betula pubenscens*) were then assessed in GIS analysis, and compared to forest inventory and age data of saplings and trees. Within the last 56 years, Norway spruce has expanded uphill, in terms of distance, approximately 100 m and birch 40 to 60 m. In accordance with the birch-pine-spruce succession concept, the downy birch dominated forest-tundra ecotone stands are now replaced by Norway spruce. The treeline of Scots pine (*Pinus sylvestris*) reach the fell top (557 m a.sl.). The spruce and birch treelines reach 510 m. We did not find water availability, soil temperature nor N to be limiting factors in expansion of spruce-birch forest but a surplus of Al relative to base cations may disfavour spruce on some sites in the tundra. Primarily, the harsh winter wind-climate and spatial variability in thickness of snow cover are presently restricting the regeneration of trees on the open tundra.

1. INTRODUCTION

The alpine forest-tundra ecotone, considered here as a transition from closed forest to the treeless top of a subarctic fell, is dynamic in nature and sensitive to fluctuations in climate. The current global warming is thought to contribute to more favourable conditions for tree establishment and survival and therefore expansion of open and closed forests to higher elevations by natural regeneration. Recent observations in Eurasia and North America demonstrate an upward pattern of conifer treeline advance (Luckman and Kavanagh, 2000; Shiyatov et al., 2007). In the northern hemisphere, the present position of the alpine treeline is primarily attributed to climatic conditions, air and soil temperatures (Körner and Paulsen, 2004; Wieser and Tausz, 2007). However, the climatic boundaries often deviate from the actual treelines. This is due to spatial variability of solar, soil, microclimatological, wind and snowpack factors that contribute to the treeline position locally (Grace et al. 2004; Wieser and Tausz, 2007; Sutinen et al., 2007).

The remote sensing community has given substantial attention to the ongoing changes in the boreal taiga-tundra transition, and polar treelines. Previously, the potential of satellite remote sensing data has been proven in regional investigations (e.g. Rees et al., 2002; Ranson et al., 2004). Myneni et al. (1997) showed significant spring greening of the circumpolar vegetation over a period from 1981 to 1991. Spatial analyses of the alpine treeline advance are less common. An elevation shift of 26-35 m has been interpreted through GIS comparison of past (1910) and present (2000) ecological maps of the Russian Ural mountains (Shiyatov et al., 2007). Furthermore, historical photographs have provided evidence of treeline advance e.g. in Russia (Moiseev and Shiyatov, 2003) and Sweden (Kullman, 1993; 2002).

The aim of this paper is to study the pattern and dynamics of the treeline advance to higher elevations on Lommoltunturi fell (Fig. 1) in Finnish Lapland. We utilized object oriented image analysis of present and past aerial photographs and age data obtained from trees and saplings in an alpine tundra-forest transition. The panchromatic imagery is widely available and most often the oldest remotely sensed data which can be processed into information of landscape change over the past century. The object oriented image analysis which incorporates image texture and spatial statistics into the classification is expected to result in an advance in classification of the high resolution aerial imagery, especially with the single channel panchromatic photographs. To explain the spatial heterogeneity of the ecotone an extensive set of soil variables were collected along the altitudinal fell gradient (to be published elsewhere).

2. MATERIALS AND METHODS

2.1 Lommoltunturi Fell Study Site

The Lommoltunturi fell (68°00’N, 24°09’E) is located 30 km south of the spruce forest line and 55 km of the pine forest line (Fig. 1). Lommoltunturi fell is composed of Mg-tholeitic metavolcanite rocks (bedrock database by the Geological Survey of Finland), and covered with a thin veneer of glacial till. The top of the fell (A in Fig. 1; 2) reaches 557 m a.s.l. whereas the base is approximately at 378 m (B in Fig. 1; 2). The pristine forest at our study site (960 m by 1640 m, Fig.

---

* Corresponding author.

2) is part of the Ounas-Pallastunturi National Park. No signs of recent fires or logging were observed, but the fell is subjected to reindeer grazing.

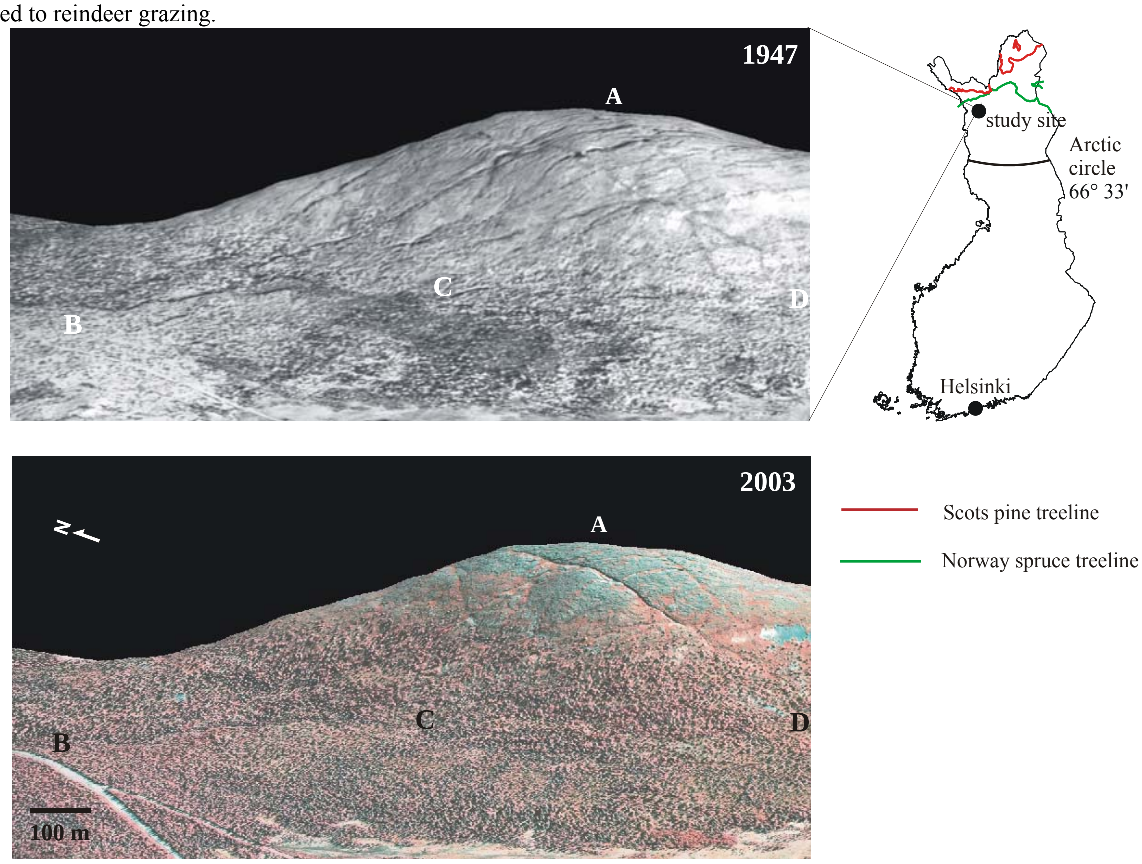

Figure 1. Panchromatic (year 1947, upper) and false colour (year 2003, lower) aerial photographs of Lommoltunturi fell's west slope draped over digital elevation model. Field data was acquired along A-B, A-C and A-D transects. Aerial photographs from the Finnish Defence Forces Topographic Service © and Blom-Kartta Oy ©.

2.2 Imagery, Feature Extraction and Change Detection

The 2003 aerial false colour imagery, with a scale of 1:30000, was acquired with a Leica RC30 camera using colour infrared film from an altitude of 4600 m. The imagery was then digitized with drumscanning and ortorectified to 0.5 m pixel size. The 1947 panchromatic imagery was acquired at 1:60000 scale. The black and white prints were digitized with a planar scanner and georeferenced to match with the 2003 imagery also to 0.5 m pixel size. The RMS error was high, up to 20 m on the fell top.

The imagery was classified with ENVI Fx version 4.4 (ITT Visual Information Solutions, Boulder, U.S.). The Fx is based on a two step automated processing where the objects are first delineated with segmentation and then the obtained features are classified with a supervised or rule based approach. The kernel size was determined for both images with semivariogram analysis (1947: 4.5 m; 2003: 2.5 m). In the segmentation process, a scale level of 24 was used with the 2003 and 30 with the 1947 imagery. Merging and thresholding were not applied. An automated attribute selection was used to determine the best of the spectral, textural (occurrence measures) and spatial attributes, and in the case of the 2003 imagery, NDVI. We applied support vector machines (SVM, Chang and Lin, 2001; Wu, Lin and Weng, 2004) in the supervised classification process. Choosing the training sites for SVM was merely based on visual interpretation of the imagery, GPS located objects of interest (tree tops etc.) and inventory data of our sampling plots. Classes 'understorey', 'shadow', 'mineral' and 'deciduous canopy' were obtained from both the 1947 and 2003 imagery. Conifers in the 2003 imagery were separated into 'pine' and 'spruce' but in the 1947 data pine crowns could not be distinguished. Therefore, the amount of spruce is overestimated in the 1947 classification since the 'spruce' class also included most of the pine crowns. Radial basis function with parameters: 1.0/3.0 (1947/2003) gamma, 300/100 penalty parameter and 0.30/0.30 probability threshold were determined based on viewing the classification result in the preview window.

The classification rasters were exported to ArcMap (ESRI, Redlands, U.S.) and the crowns were exported to vector format. A vector mesh with 20 m square size was created, and the area of deciduous crowns (birch) and conifer crowns (spruce) were calculated within each cell for both years. The area interpreted from the 1947 imagery was then subtracted from the area in 2003 to create the change maps in figure 2.

2.3 Field Data

We established 46, 10 m by 10 m, sampling plots along 3 transects (Fig. 1; Fig. 2; A-B, A-C, A-D) on the west slope (16-26% slope) of Lommoltunturi fell. The east side is steeper (50% slope) and therefore considered too challenging for image interpretation and field work. The plot centres were spaced 50 m apart along the transects. The starting point was placed at the top of the fell (A in Fig.1). Field data were collected from the 7th to the 10th of August, 2007.

At each plot, soil dielectric permittivity (DP, dependent on soil volumetric water content, Topp et al., 1980) was measured with an electrical capacitance probe (Adek Ltd., Tallin, Estonia) at a depth of 10 cm. Simultaneously, soil temperature was also measured with a Prima Long thermometer (Amarel). Mineral soil was sampled (0-10 cm depth) with a cylindrical sampler, 10.6 cm in diameter. In the laboratory, concentrations of major and trace elements, extractable with 1 M ammonium acetate (NH_4OAc) in pH 4.5, were measured in the soil samples, sieved in <2 mm fraction, and using inductively coupled plasma atomic emission spectrometry (ICP-AES) on a Thermo Electron iCAP 6500 Duo ICP Emission Spectrophotometer. Concentrations of total C and N were analyzed on a Vario MAX CN Elemental Analyzer.

For each plot, coverages of plant species were estimated from shrub/tree, field, and bottom layers separately. Stand inventory included i) counting of tree species individuals, and measurements of ii) height and iii) breast height (1.3 m) diameter. The ages of conifer trees, Scots pine and Norway spruce, were determined from drilled bore samples at 1.3 m height. The tree-ring counts were made in the laboratory using a stereomicroscope with a magnification of 15-25 X. The age of trees too small for core sampling (saplings, seedlings) was determined by counting the number of branch whorls and scars. The thickness of snow pack was measured with a ground penetrating radar on the 2nd of April, 2008, along the sampling transects. Statistical analysis included comparison of the field variables between forest, transition and tundra with a non-parametric Mann-Whitney U test.

3. RESULTS

Based on the field data, the present species specific treelines (an individual tree with height >1.3 m) are as follows: birch at 510 m a.s.l., spruce at 510 m, and pine at 550 m. The forest line was assessed at 490 m adapting the EUNIS (Davies and Moss, 1999) and FAO (Nyyssönen and Ahti, 1996) classifications (10% canopy cover). Sites ranging ≤15 meters in elevation from the forest line were defined as forest-tundra transition sites (*n*=9 sampling plots). This classification was used in the further statistics (Table 1, plot *n*=17 in the tundra; *n*=20 in the forest).

At present, the forest is dominated by birch-spruce stands with pine as a principal associate (see Table 1). The average field measured canopy covers in the forest are low: 13.4% for birch, 7.3% for spruce and 1.5% for pine. Stem counts of trees (>1.3 m in height) are consequently low (50–485 stems/ha). *Empetrum nigrum* and *Digranum sp.* dominate the understorey at the upper part of the gradient. In the transition zone, the coverage of *Pleurozium schreberi*, *Vaccinium myrtillus* and *Dicranum sp.* increase as compared to tundra. Further on in the forest, *Pleurozium schreberi* and *Vaccinium myrtillus* become the most common species (see Table 1).

Variable	Tundra	Transition	Forest
Pleurozium schreberi (%)	3.3	31.7	47.0
Vaccinium myrtillus	3.6	12.9	24.3
Empetrum nigrum	39.1	41.1	20.4
Hyloconium spledens	0.7	0.9	13.9
Dicranum sp.	25.9	27.2	13.8
Scots pine (stems/ ha)	11.8	55.6	50.0
Norway spruce	5.9	155.6	305.0
Downy birch		166.7	485.0
Scots pine (saplings/ha)	58.8	35.0	82.4
Norway spruce	82.4	777.8	1430.0
Downy birch	117.7	1577.8	265.0
Scots pine tree age	24.0	36.2	59.6
Scots pine sapling age	7.2		5.4
Norway spruce tree age		19.8	45.6
Norway spruce sapling age	8.4	10.5	12.6

Table 1. Mean values of understorey coverage, forest inventory parameters, and tree and sapling ages at 46 field plots calculated on tundra, transition and forest.

Change detection analysis of the tree species specific crown coverages revealed over 100 m shift of spruce trees (460 m – 530 m a.s.l.) and a 40 to 60 m shift of birch (480 m – 510 m a.s.l., red in Fig. 2). The forest structure and pattern of the tree species advance is spatially variable (Fig. 2). Overlaying the field data of tree counts (Fig 2.) indicates that these transitional stands are still sparse. Overall, the greatest change in the forest- tundra ecotone is the invasion of spruce trees and decrease in birch population. In figure 2a, the shades of blue are dominant indicating loss in birch canopy coverage, whereas in figure 2b the yellow-orange overwhelms suggesting an increase in spruce canopy.

The average ages calculated from the field data reveal that birch is the most efficiently regenerating species in the transition zone, whereas spruce gradually replaces birch in the forest (Fig. 2b). In the transition zone spruce often forms krummholz islands (Fig. 3) and it also appears as ribbons, in association with pine (Fig.4). These ‘safe sites’ in bedrock fractures and troughs were found to be snowdrift sites in winter. The age structure of conifers, the youngest individuals being located at the transition zone and tundra, also demonstrates the advance of species lines and treelines to higher elevations (Table 1). The oldest spruce was 165 years of age at 462 m and pine 86 years at 478 m.

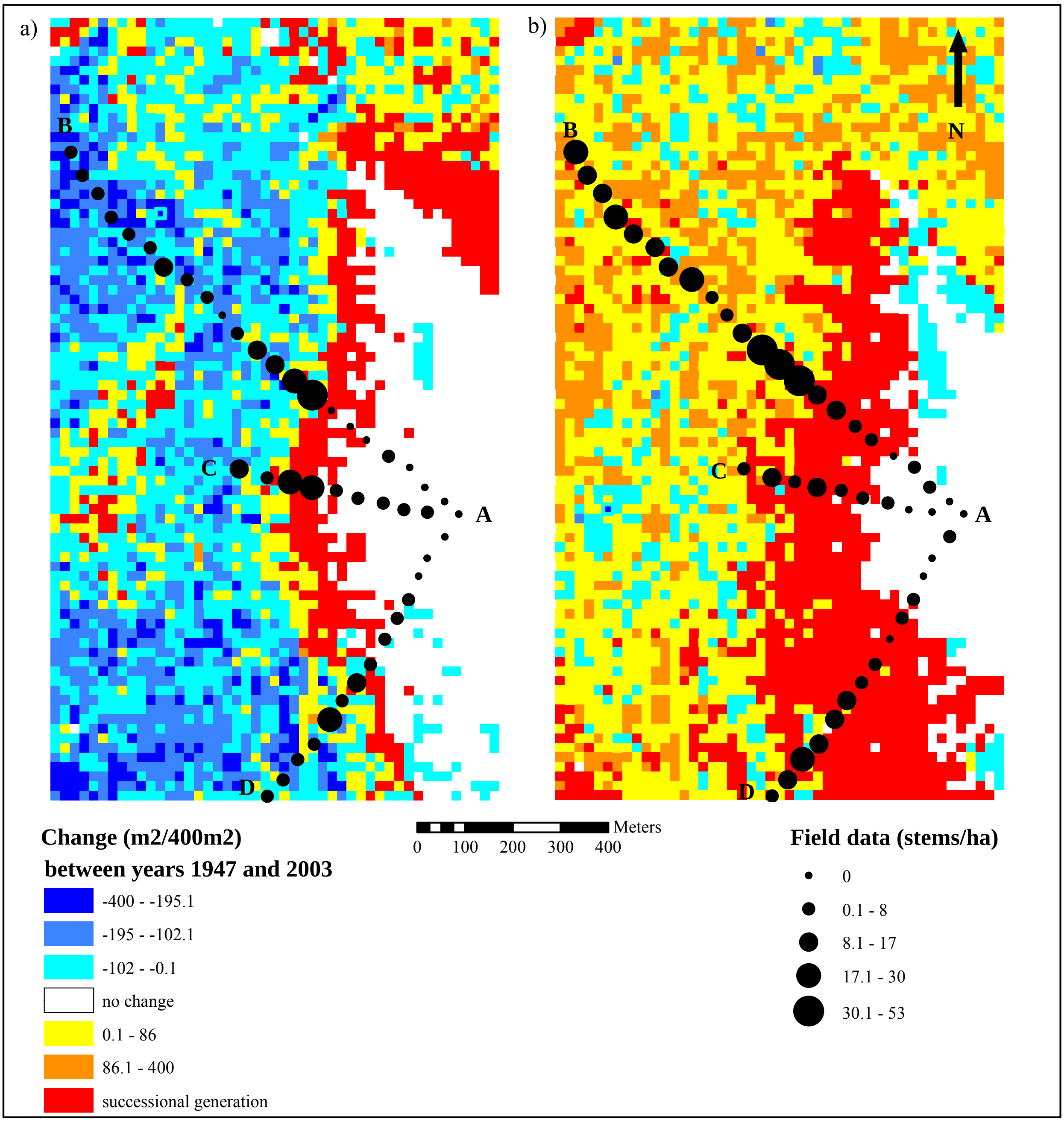

Figure 2. Change in area (m^2) per 20 m by 20 m pixels (400m^2) of a) downy birch and b) Norway spruce between years 1947 and 2003. The 2007 field data is overlaid as symbols.

The soil Ca-to-Al ratio and concentrations of Mg were significantly higher ($p<0.001$) in the forest, whereas concentrations of Al, total-N and total-C ($p<0.001$) were higher in the tundra. Soil temperature, measured in August, was not dependent ($p=0.66$) on elevation: mean temperature of 14.2 ^{o}C was measured in the tundra, 13.3 ^{o}C in the transition and 13.4 ^{o}C in the forest. The thickness of snowpack (mean 73.4 cm, std. 32) was 20 cm at its thinnest and 137 cm at its maximum in the open tundra. In contrast, the thickness of snow in the forest (mean 105.9 cm, std. 8 cm) was 90 cm at its thinnest and 114 cm at its maximum. Due to surface water ponding in bedrock fractures the highest soil water contents were measured in the tundra.

4. DISCUSSION

4.1 Object Based Forest Assessment of Forest-Tundra

In comparison with numerous studies done on texture and object based classification of high resolution multichannel optical imagery in economical forests (eg. Lang et al., 2006), low canopy cover and lush green understorey of the forest-tundra ecotone bring about a challenge of separating the objects of interest based on historical panchromatic photographs. For example, conifers with low reflectance can easily be confused with understorey. In our dataset, the albedo of deciduous trees had saturated the film which caused the crowns to be merged and appear relatively larger compared to spruce crowns. The success of the classification seems merely to be based on the image quality. High classification uncertainties can also be expected because of the changing camera viewing angle (looking at trees from the side). Thus the calculated changes in canopy coverage (Fig. 2) cannot be viewed as absolute values but rather a representation of relative change in compositional stand structure. In addition, it must be noted that in the object based change detection analysis, only trees which are 'visible' in both images can be taken into account. The newly regenerated forest zone was probably not treeless when the 1947 data was acquired but already occupied by individuals which produce minimal shadow and possibly even saplings less than 2 m in height.

Figure 3. Krummholz island of Norway spruce.

Figure 4. Western winds and snow abrasion challenge 'ribbon trees' on the fell.

The sparse canopy and low sun elevation angle at the high latitudes is also an asset in tree species identification. The narrow cone shaped spruce crowns can be identified by the dark shadow compared to the round fuzzier shadow of birch. In comparison to spruce and birch, pine crowns are more difficult to recognize. As the change in stand structure and invasion of the forest to higher elevations can be well visualized (compare Fig. 1 year 1947 to 2003), and referenced with extensive ground data our interpretation of change can be considered realistic. In our experience, the Fx process is a fast and efficient classification tool yet more work with classification validation must be accomplished to assess its performance.

4.2 Altitudinal Advance of Trees

The recruitment of Norway spruce was consistent within the forest-tundra ecotone signifying the upward advance pattern (Fig. 2b). The estimated shift of 100 m (Fig. 2b) within less than 60 years may be more intensive as has been reported earlier in Russia (Moiseev and Shiyatov, 2003) and Sweden (Kullman 1993; 2002). In accordance with the birch-pine-spruce succession concept (see Pastor et al., 1999), we found the replacement of birch by spruce in the forest (Fig. 2). Even though spruce is shade tolerant and a climax species in the forest succession sequence, it thrives best on nutrient-rich soil regimes (Sutinen et al., 2007). We found that the Ca-to-Al ratio and concentration of Mg were significantly higher in the forest, whereas concentration of Al was highest on the tundra. Since the soil Mg and Ca are important elements for the growth of Norway spruce, an inhibitory effect of Al on the uptake of Mg (van Praag et al., 1997) may disfavour spruce on some sites in the tundra. In general, variability in soil chemical properties has been linked to different weathering and decomposition rates, and down-slope transport of the soluble elements. However, on the studied gradients soil total-N and total-C were found to increase with elevation.

In comparison to the forest, high spatial variability in the snowpack thickness was found on the open tundra. Survival of newly recruited seedlings is known to be restricted by low soil temperatures and water availability (Smith et al., 2003), hence snow accumulation in fractures and troughs creates 'safe sites' for advance of tree species to higher elevations. Increasing shrub cover, in terms of high rate of birch regeneration at the transition zone, can also result in greater snow accumulation, higher soil temperature and microbial activity in winter, which may then promote tree establishment (Sturm et al., 2005). Snow drift in bedrock fractures of the tundra implies that soil water availability does not restrict survival of seedlings (Smith et al., 2003). Even though on a global scale, low soil temperature determines treeline position (Körner and Paulsen, 2004) we found the highest soil temperatures (not statistically significant) in the tundra near the top of the fell. We contend that the patchy pattern of krummholz islands and 'ribbon trees' in the transition zone (figs. 3-4) are due to winter wind-climate and spatial variability in snow cover.

5. CONCLUSIONS

Change detection and object based image analysis of present false colour and past panchromatic aerial photographs at an altitudinal forest-tundra ecotone in Finnish Lapland demonstrated a spatial expansion pattern of Norway spruce and downy birch. Validated with field data of tree and sapling ages the Norway spruce and downy birch were found to expand higher in elevation on the Lommoltunturi fell within the past 60 years which is attributed to the current global warming. The amount of spruce increased in the forest tundra ecotone whereas birch had decreased following the birch-pine-spruce successional concept. Future work will involve improvement in the georectification, quantitative accuracy assessment of the object based classification and improvement of the change detection technique.

6. REFERENCES

Chang, C.-C. and C.-J. Lin, 2001. LIBSVM: a library for support vector machines (computer software). http://www.csie.ntu.edu.tw/~cjlin /libsvm (accessed 30 Apr. 2008)

Davies, C.E. and Moss, D., 1999. EUNIS habitat classification. *European Topic Centre on Nature Conservation*, European Environment Agency.

Grace, J., Berninger, F. and Nagy, L., 2004. Impacts of Climate Change on the Tree Line. *Annals of Botany* 90, pp. 537-544.

Kullman, L., 1993. Pine (*Pinus sylvestris L.*) tree-limit surveillance during recent decades, Central Sweden. *Arctic and Alpine Research* 25(1), pp. 24-31.

Kullman, L., 2002. Rapid recent range-margin rise of tree and shrub species in the Swedish Scandes. *Journal of Ecology* 90, pp. 68-76.

Körner, C. and Paulsen, J., 2004. A world-wide study of high elevation treeline temperatures. *Journal of Biogeography* 31, pp. 713-732.

Lang, S., Blaschke, T. and Schöpfer, E. (eds.), 2006. Workshop proceedings, 1st International Conference on Object-based Image Analysis (OBIA 2006), Saltzburg, Austria, http://www.commission4.isprs.org/obia06/papers.htm (accessed 30 Apr. 2008)

Luckman, B. H. and Kavanagh, T., 2000. Impact of climate fluctuations on mountain environments in the Canadian Rockies. *Ambio* 29(7), pp. 371–380.

Moiseev, P.A. and Shiyatov, S.G., 2003. The use of old landscape photographs for studying vegetation dynamics at the treeline ecotone in the Ural Highlands, Russia. In: Nagy, L., Grabherr, G., Körner, C. and Thompson, D.B.A. (eds.), *Alpine biodiversity in Europe*, Springer-Verlag, Heidelberg-Berlin, Germany.

Myneni, R.B., Keeling, C.D., Tucker, C.J., Ascar, G., and Nemani, R.R., 1997. Increased plant growth in northern high latitudes from 1981 to 1991. *Nature* 386, pp. 697-702.

Nyyssönen, A. and Ahti, A. (eds.). 1996. Proceedings of FAO expert consultation on global forest resources assessment 2000 in cooperation with ECE and UNEP with the support of the goverment of Finland. *Metsäntutkimuslaitoksen tiedonantoja 620*, Finnish Forest Research Institute, Vantaa, Finland.

Pastor, J., Cohen, Y., and Moen, R. 1999. Generation of spatial patterns in boreal forest landscapes. *Ecosystems* 2, pp. 439-450.

Ranson, K.J., Sun, G., Kharuk, V.I. and Kovacs, K., 2004. Assessing tundra-taiga boundary with multi-sensor satellite data. *Remote Sensing of Environment* 93(3), pp. 283-295.

Rees, G., Brown, I., Mikkola, K., Virtanen, T. and Werkman, B., 2002. How can the dynamics of the tundra-taiga boundary be remotely monitored? *Ambio special report* 12, pp. 56-62.

Shiyatov, S.G., Terent'ev, M.M., Fomin V.V. and Zimmermann, N.E., 2007. Altitudinal and horizontal shifts of the upper boundaries of open and closed forests in the Polar Urals in the 20th century. *Russian Journal of Ecology* 38(4), pp. 223-227.

Smith, W.K., Germino, M.J., Hancock, T.E. and Johnson, D.M., 2003. Another perspective on altudinal limits of alpine forest lines. *Tree Physiology* 23, pp. 1101-1112.

Sturm, M., Schimel, J., Michaelson, G., Welker, J.M., Oberbauer, S.F., Liston, G.E., Fahnestock, J. and Romanowsky, V.E., 2005. Winter biological processes could help convert Arctic tundra to shrubland. *BioScience* 55, pp. 17-26.

Sutinen, R., Kuoppamaa, M., Hyvönen, E., Hänninen, P., Middleton, M., Pänttäjä, M., Teirilä, A. and Sutinen, M.-L., 2007. Geological controls on conifer distributions and their implications for forest management in Finnish Lapland. *Scandinavian Journal of Forest Research* 22, pp.476-487

Topp, G.C., Davis, J.L. and Annan, A.P., 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. *Water Resources Research* 16, pp. 574-582.

Van Praag, H.J., Dreze, P., and Cogneau, M., 1997. Effects of aluminium on calcium and magnesium uptake and translocation by root segments of whole seedlings of Norway spruce (*Picea abies* Karst.). *Plant and Soil* 189, pp. 267-273.

Weiser, G. and Tausz, M. (eds.), 2007. *Treelines at their Upper Limit.* Springer, Netherlands.

Wu, T.-F., Lin, C.-J. and Weng, R.C., 2004. Probability estimates for multi-class classification by pairwise coupling. *Journal of Machine Learning Research* 5, pp. 975-1005.

7. ACKNOWLEDGEMENTS

We acknowledge Yrjö Norokorpi from the Finnish Forest and Park Service for allowing us to make the research in the Ounas-Pallastunturi National Park. Finnish Defence Forces Topographic Service and Blom-Kartta Oy are acknowledged for providing the aerial photography. We thank Hannu Herva at the Finnish Firest Research Institute Kolari Station, for tree-ring sampling and analyses, and Juha Davidila, Ilkka Keskitalo, Matti Piekkari and Aleksi Sutinen for field measurements. The expertise of Ilkka Aro, Pekka Hänninen and Juha Majaniemi in snow measurements is greatly appreciated. Kent Middleton revised the language.