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A remote sensing methodology for monitoring lichen cover

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Abstract. Land degradation has been recognised in the mountainous areas of Sweden due to increased land use, particularly the intensive grazing and trampling by reindeer, which causes mechanical damage to the vegetation cover. As these areas are often inaccessible, it is valuable to be able to use satellite data to monitor vegetation changes. The Swedish Environmental Protection Agency has proposed an environmental quality objective for mountainous areas of Sweden, which emphasizes the need for monitoring. The aim of this paper is to investigate a method for such monitoring using satellite data. Of the different heath communities above the tree line, the lichen-dominated heath is among the most sensitive to mechanical damage. Hence lichen cover is used as an indicator of change because of its ecological relevance and its spectral characteristics. Landsat-5 thematic mapping (TM) data, hyperspectral imaging scanner data, and spectral characteristics of relevant mountainous plant communities and lichen species were used to study heath vegetation in the southern part of the Swedish mountain range. For comparison, colour-infrared (CIR) aerial photographs at a scale of 1 : 60 000 and field data were used. The changes in lichen cover have been detected by spectral changes using the normalized difference vegetation index (NDVI) differencing technique and thresholding. The results show that mountainous lichen-dominated heath, above the tree line, can be mapped with good accuracy using Landsat TM data, and this heath is proposed for change detection, as it is possible to differentiate lichen cover in the following classes: low (20–50% cover), moderate (51–80% cover), and high (>80% cover). A lichen cover <20% cannot be separated from other types of dry heath. The class boundaries have been determined using field observations and CIR aerial photographs. The method indicates that a change in lichen cover can be classified and mapped in three classes: unchanged, moderate decrease, and high decrease. The classes can be regarded as three risk-assessment classes for vegetation degradation and ensuing soil erosion. The major conclusion from this study is that a change in lichen cover, differentiated in three classes, can be used as a tool for monitoring disturbed ecosystems in the Swedish mountain range.

Résumé. Le phénomène de dégradation des terres a été observé dans la chaîne montagneuse de Suède suite à des pressions exercées sur l’utilisation du sol, en particulier le broutage intensif et le tassement des sols par les rennes, ce qui a pour effet d’entraîner des dommages mécaniques au couvert de végétation. Étant donné que ces endroits sont souvent inaccessibles, il est utile de pouvoir utiliser les données satellitales pour réaliser le suivi des changements dans la végétation. L’Agence de protection de l’environnement de Suède a défini un objectif au plan de la qualité de l’environnement pour les régions montagneuses de Suède mettant l’accent sur la nécessité de réaliser un suivi. L’objectif de cet article est de développer une méthode pour un tel suivi basé sur l’utilisation des données satellitales. Parmi les différentes communautés de landes situées au-dessus de la limite forestière, la lande dominée par les lichens est parmi la plus sensible aux changements mécaniques. Ainsi, le couvert de lichens est utilisé en tant qu’indicateur de changement à cause de sa pertinence écologique et de ses caractéristiques spectrales. Des données TM de Landsat-5, des données hyperspectrales de capteur imageur et les caractéristiques spectrales des communautés pertinentes de plantes de montagne et d’espèces de lichens ont été utilisées pour étudier la végétation de lande dans la partie sud de la chaîne montagneuse de Suède. Pour fin de comparaison, des photographies aériennes couleur infrarouge à l’échelle du 1 : 60 000 et des données de terrain ont été utilisées. Les changements dans le couvert de lichens ont été détectés par le biais des changements spectraux dérivés à l’aide d’une méthode de différenciation du NDVI et d’un seuillage. Les résultats montrent que la lande de montagne dominée par les lichens, située au-dessus de la limite forestière, peut être cartographiée avec une bonne précision à l’aide des données Landsat TM et nous proposons d’utiliser cette lande comme outil pour la détection des changements étant donné qu’il est possible de différencier le couvert de lichens en fonction des classes : faible (20–50%), modéré (51–80%) et élevé (>80%). Un couvert de lichens <20% ne peut être distingué des autres types de landes sèches. Les limites de classe ont été déterminées à l’aide des observations sur le terrain et des photographies aériennes. La méthode montre qu’un changement dans le couvert de lichens peut être classifié et cartographié en fonction de trois classes : inchangé, diminution modéré et diminution importante. Ces classes peuvent donc être considérées comme constituant trois classes d’évaluation du risque pour la dégradation de la végétation et l’érosion subséquente des sols. La principale conclusion de cette étude est à l’effet

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qu'un changement dans le couvert de lichens, différencié en fonction de trois classes, peut être utilisé comme outil pour le suivi des écosystèmes perturbés dans la chaîne montagneuse de Suède.
[Traduit par la Rédaction]

Introduction

During the last 15–20 years vegetation changes and degradation have been reported in several places in the Swedish mountain range. Studies have shown decreased lichen cover, decreased vegetation cover, and increased number, size, and intensity of patches with bare mineral soil (Ihse and Allard, 1995; Allard et al., 1998). A lichen study is particularly relevant at this time because the Swedish Environmental Protection Agency (Swedish EPA) intends to establish a system for monitoring environmental quality where "A magnificent mountain landscape" is one of the objectives (Swedish EPA, 1999). To obtain this objective there is a need to determine a strategy for monitoring changes in the vegetation cover. The alpine and arctic areas are sensitive because of factors linked to both the high altitudes and the high latitudes (Rafstedt, 1984; Andersson et al., 1985). The summer seasons in the Swedish mountainous areas are short and cool, and the short vegetation season makes the soil-forming processes very slow. Regeneration of a damaged vegetation cover takes up to several decades (Pegau, 1970; Oksanen, 1978; Leader-Williams et al., 1987; Väre et al., 1995). Damage to the vegetation cover reduces the primary production and is the first step towards soil erosion. Soil erosion can be seen in an increase in the number of patches of exposed mineral soils in drier vegetation types. Such patches have been observed above the tree line in the Swedish mountain range (Allard et al., 1998). Extremely dry and dry mountainous heaths and lichen-dominated dry heath are vulnerable to mechanical damage, such as that resulting from trampling by animals and humans or from the tire friction of off-road vehicles (Renman, 1989). Extremely dry heaths are found in locations that are often swept free of snow in winter. Frost-hardy cushion plants such as trailing azalea (*Diapensia lapponica* L.) and crowberry (*Empetrum heramaphroditum* (Hagerup) Böcher) dominate these dry heaths. The vegetation cover is often about 25%. Dry heath occurs where the snow cover is better and is dominated by crowberry (*E. heramaphroditum*) and, where calcareous soils are rare, heather (*Calluna vulgaris* (L.) Hull.). The vegetation usually covers the ground completely (100%) and is low, with a height of about 8–10 cm. In areas with a continental-type climate, lichens often dominate the dry heath. These dry heath types can thus be regarded as potential risk areas for erosion by air pollution and climate change. The issues regarding climate change are beyond the scope of this study but should be kept in mind when proposing methods to monitor land cover change. Damage can also occur from the combined effects of climate change and (or) atmospheric pollution and increased land use intensity. In cold mountain climates with frequent storms, the snow cover will be removed partially and the vegetation cover will be exposed to frost damage and then be more sensitive to damage by trampling. In general, demands on the mountain areas have increased during the last few decades. Tourism continues to increase, off-road vehicles have become common, and reindeer management methods have, since the mid-1970s, changed to more rationalised and motorised schemes (Müller-Wille, 1975). The combined effect of climate change and continued high human impact could have a severe negative effect on the long-term sustainable development of the mountain area in Sweden.

To facilitate future studies using satellite data, changes in mountainous heath communities have been interpreted, in detail, for five test sites using colour-infrared (CIR) aerial photographs, photographed with a time span of 15 years (from 1979 and 1994). Changes in the heath communities during this period have been determined using lichen as one of the test indicators of ecosystem disturbance. The results have been verified by thorough field checks during the summers of 1994, 1996, and 1997 (Ihse and Allard, 1995; Allard et al., 1998).

The aim of this study was to detect and quantify vegetation change in heath communities and map the distribution of change using satellite remote-sensing techniques with the view to their use as a future tool in monitoring systems for the whole Swedish mountain range. Tömmervik and Lauknes (1987) have shown using Landsat thematic mapper (TM) data that one of the main vegetation changes observed in land cover in northern Norway was the decrease of lichen in lichen-dominated heaths. In that study the cover was differentiated in two classes, a dense lichen mat (close to 100% cover) or no lichen coverage (0% cover). For Swedish conditions, these classes are less significant because there are very few areas with a full, dense lichen mat. We therefore need a methodology with the ability to detect a change from moderate to low or to no lichen cover.

Monitoring all changes associated with vegetation is impossible. In this study, lichens have been used as an indicator of ecosystem disturbance. A mature lichen mat works ecologically as an insulator to hold moisture and buffer ground temperature (Larson and Kershaw, 1976; Kershaw, 1985). Lichens also have an effect on the nutritional dynamics by acting as a filter and may reduce the release of nutrition from the ground (Brown and Mikkola, 1974). Some authors have organised lichen dominance of mountainous heath communities into three stages of retrogression under grazing pressure from reindeer, the main herbivore in the Scandinavian mountain range (Pegau, 1970; Tömmervik and Johansen, 1992; Väre et al., 1995). Reindeer feed mainly on herbs and leaves during summer, when they forage in the mountains. In dry conditions the lichens are brittle and vulnerable to trampling (Pegau, 1970; Leader-Williams et al., 1987). The succession of lichens occurs in different stages towards a largely stable climax. The climax stage is dominated by *Cladina stellaris* (Opiz) Brodo in full height (around 10 cm). It is only slightly grazed, or grazed at long intervals. Grazing pressure can be recognised by the height of the lichens. The first stage of retrogression, with moderate grazing pressure, is dominated by *Cladina arbuscula* (Wallr.) Hale and Culb. and *Cladina rangiferina* (L.) Nyl., and the height of the lichens is reduced at least in patches. The second stage of retrogression, with heavy grazing pressure, is dominated by *Stereocaulon paschale* (L.) Hoffm., which is a low-growing resilient species. As the grazing becomes heavier the height of the lichens diminishes, which marks the third stage (Pegau, 1970; Tömmervik and Johansen, 1992; Väre et al., 1995). Tömmervik and Johansen (1992) state that these three stages can be detected using Landsat TM data.

Pale lichens can be used as a remote-sensing indicator of change because their spectral characteristics differ clearly from those of green vegetation (by reflecting high in the visual and infrared wavelength bands). Käykhö and Pellikka (1994) found that separation of lichen-covered ground and green vegetation using Système pour l'Observation de la Terre (SPOT) XS was optimal in the red band (wavelength 610–680 nm).

Previous studies have reported the use of Landsat TM data for mapping Scandinavian mountainous heath communities (Tömmervik et al., 1997; Nordberg, 1998; Johansen et al., 1999; Boresjö-Bronge and Wester, 1999). The potential to map heath community types for the Swedish mountain range using Landsat TM data, with results equivalent to those from the interpretation of aerial photographs, have been reported by Boresjö-Bronge and Thulin (1995). SPOT XS data, lacking information from the mid-infrared (MIR) part of the spectrum, is less suitable according to a report by Käyhkö and Pellikka (1994). A number of Norwegian and Finnish studies, with special focus on habitats for reindeer grazing, have shown good results when using Landsat TM data for change detection (Johansen and Tömmervik, 1990; Tömmervik et al., 1990; Tömmervik and Johansen, 1992; Käyhkö and Pellikka, 1994).

The basis of digital change detection is the comparison of remotely sensed data taken from the same area at two or more different time periods. The comparison on a pixel-by-pixel basis requires accurate geometric transformation. Consideration must also be given to variations in illumination conditions, atmospheric differences, sensor aberrations, and plant phenology (Mouat et al., 1993). Differences in data sets can be enhanced by utilizing several types of image-processing techniques. Reviews of remote sensing change detection techniques are presented by Singh (1989), Mouat et al. (1993), and Muchoney and Haack (1994), among others. Some of the techniques presented and used are post-classification change detection differencing (Estes et al., 1982), vegetation index differencing (Nelson, 1983), change vector analysis describing the direction and magnitude of change between dated images (Lambin and Strahler, 1994), and principal component analysis (Bryne et al., 1980; Fung and LeDrew, 1987). Lyon et al. (1998) compared seven vegetation indices for their value in vegetation and land cover change detection, as vegetation indices have long been used in remote sensing for monitoring temporal changes associated with vegetation. The normalized difference vegetation index (NDVI) was least affected by topographic factors and the NDVI differencing technique demonstrated the best vegetation change detection method. By integrating the mean NDVI values derived from SPOT high resolution visible (HRV) with census and land-cover data, Fung and Siu (2000) were able to provide valuable information for the assessment of environmental quality and its changes. Lambin (1996) argues that seasonal changes in the landscape spatial pattern may be much greater than patterns caused by long-term changes and suggests that multiple temporal satellite images at different scales must be used to quantify the spatial dynamics of landscapes. Mas (1999) also studied an area with large seasonal changes and found post-classification comparison to be the most accurate procedure.

Study area

The study area consists of two mountains, Mount Långfjället and Mount Fulufjället (**Figure 1**), situated around latitude 62°N in the southern part of the Swedish mountain range. These areas were chosen to be representative of the common mountainous heath vegetation types for the southern low and mid-alpine zones. These consist mainly of lichen-dominated dry and extremely dry heaths (Andersson et al., 1985). As the study areas represent important summer grazing habitats for reindeer, Sami people and the county authorities responsible for environmental protection and monitoring helped in their selection.

The climate in the study areas is continental, with annual precipitation around 600 mm/year, cold winters, and cool and dry summers. The diurnal average temperature varies between a minimum of approximately –12°C in January and a maximum of +13°C in July (Wedin, 1995). The average date for the start of the 150 day long growing season (when the average temperature exceeds +5°C) is around 10 May, and the first autumn frost is around 1 August (Wedin, 1995). Mount Fulufjället is formed as a plateau reaching around 900 m above sea level and consists of Jotnian sandstone, with patches of till interspersed with areas of frost-shattered boulders. Mount Långfjället, 30 km northeast of Mount Fulufjället, has bedrock of Eocambrian quartzites and sparagmites and reaches a height of approximately 800–1100 m above sea level. The layer of till is somewhat thicker and covers larger areas than on Mount Fulufjället (Soyez, 1971). The bedrock types on both mountains are resistant to weathering and produce poor topsoil with low nutrient content, and the vegetation comprises relatively few species (Soyez, 1971).

The dry heath at both sites is rich in heather (*Calluna vulgaris*) and, to a lesser extent, crowberry (*E. hermaphroditum*) and dwarf birch (*Betula nana* (L.)). Large parts of the dry heath on both mountains are lichen-dominated. On Mount Fulufjället, the lichen growth is dense and with a height of 5–12 cm; on Mount Långfjället the lichens are fragmented and a few millimetres to about 3 cm in height. The lichens present are mainly *Cladina stellaris*, *Cladina rangiferina*, *Cladina arbuscula*, *Cetraria islandica* (L.), *Cetraria nivalis* (L.) Ach., and *Cladonia* spp. The two mountains have similar physical

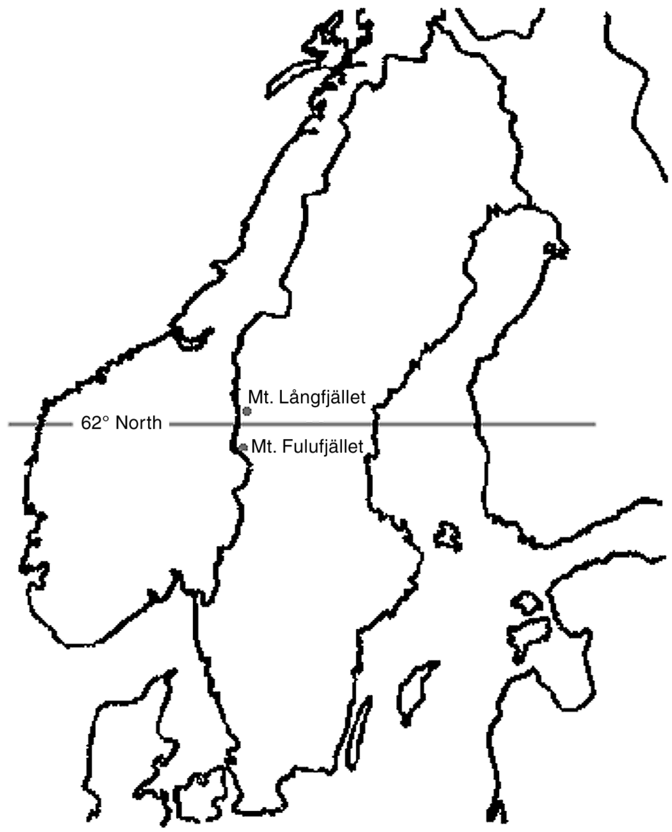

Figure 1. Location of the study areas, Mount Långfjället and Mount Fulufjället, in the southern part of the Swedish mountain range (around latitude 62°N).

conditions and the vegetation could look the same, and did so until 1945 (Allard et al., 1998). Today Mount Fulufjället still looks the same but Mount Långfjället has a degraded vegetation cover. According to Ahti (1977) and Väre et al. (1995), the large areas of lichen heath on Mount Fulufjället can be described as being in the climax stage, with a dominance of *Cladina stellaris* and a height of about 10 cm. On Mount Långfjället, the lichens occur in patches and the areas with a higher percentage of lichen cover are dominated by *Cladina stellaris* with a height of a few millimetres up to 3 cm. Other areas have a dominance of either *Cladina rangiferina* or *Cetraria islandica*, with heights of about 1–3 cm. The bottom layer is rich in bryophytes, mainly *Dicranum* spp., and could be used as an indicator of first-stage regression as defined by Ahti and Väre et al. When using the definition of Tömmervik and Johansen (1992), the height of lichens at Mount Långfjället would fit the categories of heavily grazed (few millimetres in height) and moderately grazed (few centimetres in height), respectively.

Method

The methods in this study include a characterization of vegetation using spectral signature measurements, the development of a classification system as a baseline for change detection, and the development of methods for change detection and accuracy assessment. Landsat-5 TM images collected on 18 June 1986 and 27 June 1995, digital terrain models and digital maps, hyperspectral imaging scanner data from 26 July 1996, and spectral measurements from the laboratory and field were used to study mountain heath communities in two sub-areas (approximately 100 km^2 per sub-area), one located on each of the two mountains. CIR aerial photographs were used to select training areas for the classification and for the evaluation of the resulting map. The classes closely follow those used in the Swedish vegetation maps for mountainous areas (Andersson et al., 1985), but all vegetation types do not exist in the test areas. The knowledge gained in a parallel study, using CIR aerial photographs from 1981 and 1984 and field data collected during the summer of 1996 (Allard et al., 1998), was used for comparison and ground truth. Ihse and Allard (1995) found that 7% of the area at Mount Fulufjället had a maximum change of lichen cover of approximately ±10%, which may be the result of natural changes. Since no reindeer grazing occurs in this area, it was used as the reference area. At Mount Långfjället, 40% of the area had a decrease of 20% or more (up to 60%).

To detect small changes and separate different vegetation types, improved knowledge about spectral characteristics of vegetation types and their variation during the growing season is needed. In the laboratory, the natural environment of lichens was simulated and their spectral signatures were measured with a GER 2600 spectroradiometer with a spectral range of 400–2400 nm. The GER 2600 has two linear detector arrays. The first array with Si-detectors has a spectral bandwidth of 1.5 nm and a range from 300 to 1050 nm. The second array consists of PbS-detectors with a spectral bandwidth of 11.5 nm and a range from 1050 to 2500 nm. This technical arrangement results in the signal detection being weak in the area of 1050 nm, where the change in detectors occurs. This is evident in output curves as a slight blurring in this part of the spectrum. During the measurements, light conditions and distance from the spectroradiometer to the target were kept constant. The mean of three measurements was used in all calculations. Reflectance spectra were corrected by using spectral measurements of a reference plate painted with barium sulfate to simulate Lambertian characteristics. The reference plate was measured immediately before and after each target measurement, and a mean of the two was calculated. To further control the light, measurements were only taken in cloud-free conditions and during approximately 2 h before and after noon, since the angle of the sun is too low outside these hours and shadowing between lichen branches increases (Pearson et al., 1976; Ihse and Graneli, 1985). Due to bad weather conditions, only about 30 measurements were collected.

To test whether the lichen-domination of the three stages of retrogression under grazing pressure, as mentioned in the Introduction, could be differentiated spectrally, five species of air-dry lichen were placed on a layer of humus and measured at four grazing classes. These classes were as follows: lichens in full height (ranging from 10 cm for *Cladina stellaris* (Opiz)

Brodo to 2 cm for *Stereocaulon saxatile* (L.)), half-height, quarter-height, and as fragments on the humus layer, simulating the various conditions of the natural environment. This was accomplished by crushing the dry lichens and blowing away the fragments, thus simulating trampling during a dry summer. Water was sprayed in equal amounts over all five lichen species to simulate the wet condition of full-height lichens. A time lapse of 15 min was allowed before measuring to avoid water droplets interfering with the measurements.

During the first days of August 1997 different types of mountainous heath communities were measured spectrally in situ at Mount Långfjället with a hand-held Tectronics J-16 spectroradiometer (Photodyne). The instrument has four sensors equipped with filters corresponding to Landsat-5 TM bands 1 (blue, 450–520 nm), 3 (red, 630–690 nm), 4 (NIR, 760–900 nm), and 5 (MIR, 1550–1750 nm). Again, the mean of triplicate measurements was used and corrected using the reference plate mentioned earlier. The degree of lichen cover was estimated in the field on both mountains during August 1996. Mount Fulufjället with its dense lichen mats was used as a reference area. The selection of measurement plots was made using CIR aerial photographs from 1994, where polygons were classified according to degree of lichen cover (Ihse and Allard, 1995). The polygons were located and strategic points were measured with a differential global positioning system (DGPS) for correlation to maps and satellite data. Within the classified polygons with different degrees of lichen cover, a number of test plots were chosen. In each measurement plot (0.5 m^2), the cover of dwarf-shrub (e.g., *E. hermaphroditum* and *Calluna vulgaris*), graminids (grass species), lichen, and substrate was determined in 10% classes. At Mount Långfjället, 20–40 measurement plots were analysed per polygon (10 polygons in all), and at Mount Fulufjället 6–12 measurement plots were analysed for each of the six polygons.

If spectral differences exist, spatial resolution is the parameter that will set the limits for possible separation. The potential to distinguish between different plant communities is also highly dependent on the phenological stage of the vegetation, a fact that often seems to be underestimated in literature dealing with satellite data (Holben and Justice, 1981). Lichens can be considered as phenologically stable objects, as it is assumed that they do not react to seasonal variations within one growing season (Kershaw, 1985). To examine the significance of improved spatial and spectral resolution for the detection of small changes in vegetation using remote sensing methods, hyperspectral data were obtained from a geophysical and environmental research (GER) airborne imaging scanner registered on 26 July 1996 at Mount Långfjället and analysed. The spatial resolution was 5 m, and the scanner registered 31 wavelength bands over a range of 0.410–10.983 µm. Due to a low signal-to-noise ratio, the instrument response was too low in the MIR part of the spectrum and could not be used for analysis. On the basis of signal-to-noise ratio and visual appearance, 14 wavelength bands were used. Test areas were selected based on knowledge from the CIR aerial study and analysed spectrally.

The Landsat TM satellite data were corrected for topography-induced illumination effects, namely slope, aspect, and effects of varying sun–target–sensor geometries. Such a process has been shown to improve the classification results in regions with high relative relief (Parlow, 1996). The topographic influence on satellite data has been discussed by several authors such as Teillet et al. (1982), Fiorella and Ripple (1993), Meyer et al. (1993), and Parlow (1996). The method used here for correction of the topography-induced illumination effects is the semi-empirical C-correction method described by Meyer et al. (1993) and is a modification of the cosine correction. The digital elevation model needed for the C-correction was generated from the scanned CIR aerial photographs at a scale of 1 : 30 000 with a precision of 2 m. The relative relief within the test areas is at most 300 m.

Maximum-likelihood classification was performed to obtain spatial distribution for the class lichen-dominated heath. To separate lichen-dominated heath from other mountainous plant communities, training areas for the classes grass heath, dry – extremely dry heath, lichen-dominated heath, mesic and wet heaths, mire, meadow, deciduous and coniferous forest, blocky areas and bedrock outcrops, snow beds, and water were selected and analysed. For the classification, Landsat TM data from 18 June 1986 and digital terrain data were used in a stratified approach based on the altitudinal zonation of vegetation in the Swedish mountain range. Stratified supervised classification was used, a method where information from other data sources is used to create masks for classification in steps where only a limited number of classes are allowed (Boresjö-Bronge and Rud, 1995). The altitudinal zonation of vegetation in the study area is described in Rafstedt (1984).

Evaluation of the classification result was carried out using randomly selected points, which were checked using the CIR aerial photographs and in the field. Thirty points in each class were selected from the classification result. The class lichen heath was used to create a lichen mask for extraction of the spatial distribution of the class lichen-dominated heath in Landsat TM images from 1986 and 1995.

The difficulties in using multitemporal satellite image data for change detection include the following: (1) position, as precise geometric transformation of the images is critical to minimize misregistrations that might provide false changes; (2) the influence of the atmosphere; and (3) differences due to varying phenological states between different dates, though images of multiple dates should be taken from approximately the same time of year (Collins and Woodcock, 1994). The Landsat images from 1986 and 1995 were registered to the Swedish national grid using a plane affine transformation with a root mean square error of less than 0.5 pixels and a nearest neighbour resampling method. The image from 1995 is a precision-corrected product from the Swedish Space Company (Metria). The influence of the atmosphere was reduced using temporal image normalization (Schott et al., 1988). The method is based on the assumption that differences in reflectance for spectrally stable objects between different recording dates reflect the effect of atmospheric conditions. Water areas have been used as reference objects because the mean reflectance of water is assumed to be stable over time. Differences due to seasonal variations, such as phenology, have not been considered because lichen heaths are not assumed to be sensitive to such variations (Kershaw, 1985). The Landsat TM images were recorded on 18 June 1986 and 27 June 1995, at approximately the same period of the growing season. The dates were chosen at a time when the mountain vegetation should have reached its optimum in biomass for the growing season (Jacobsen and Amlien, 1998), i.e., during a period of maximum signal from the vegetation, allowing optimal calculation of NDVI.

The vegetation index differencing technique is a method in which differences of vegetation indices are used to decide whether or not a vegetation canopy has been altered (Nelson, 1983). The vegetation index for satellite imageries, namely the NDVI (TM4–TM3/TM4+TM3), was calculated based on the reflectance values for the two dates, and a difference image was created showing a change variable (NDVI differences) where each value represents a particular change. Linear regression was used to calculate the relationship between the NDVI differences and the CIR aerial photograph interpreted decrease of lichen. By thresholding, three change classes were extracted: unchanged (<20% decrease of lichen), moderate (20–50% decrease of lichen), and high (>50% decrease of lichen). The class boundaries were based on knowledge from the CIR aerial photograph study. For comparison, normalized difference indices based on the calculated reflectance values for Landsat TM5–TM2/TM5+TM2, TM5–TM3/TM5+TM3, and TM4–TM2/TM4+TM2 were analysed as well as differences between the reflectance-calibrated red spectral bands (TM3) for the two Landsat scenes.

Results

The laboratory measurements show that different grazing classes of *Cladina stellaris* can be separated using this method. The results are best with NIR wavelengths (**Figure 2a**). Dry *Cladina stellaris* of full height reflects very high, with a lower curve for the wet lichen, especially in the MIR part of the spectrum (above 1400 nm). When half of the height is taken away, the reflectance is considerably lower; and when only fragments remain on the humus layer, the curve approaches darker reflectance, close to the curve for bare humus (**Figure 2f**). However, this is not the case for *Cladina rangiferina* and *Cladina arbuscula*, except for the fragment stage (**Figures 2b** and **2c**). Wet lichens can be separated from the dry lichens in the MIR area, but all the species of lichen analysed reflect in a similar way in this region and can hardly be separated from each other. The two pale lichens, *Cladina stellaris* and *Cladina arbuscula* (**Figures 2a** and **2c**), have the highest reflectance when measured in full height and air dry. The three darker lichens, *Cladina rangiferina*, *Cetraria islandica*, and *S. saxatile* (**Figures 2b**, **2d**, and **2e**), all have a curve for air dry and full height lower or the same as those for other stages (Allard and Nordberg, 1998).

The field measurements indicate that there are spectral differences between some of the different lichen species (**Figures 3a**). The pale species (*Cladina stellaris*, *Cladina arbuscula*, and *Cetraria nivalis*) reflect higher in all channels. The lowest reflector was *Cladina rangiferina*, with *Cetraria islandica* as an intermediary. Most of the lichens have lower values than green vegetation in the NIR region (**Figure 3b**).

The analysis of hyperspectral data from the airborne imaging scanner shows the potential to separate lichen cover into three classes using bands 4–7 (521.3–665.8 nm) (**Figure 4**). Using separate bands, the best result is gained by using band 4 (521.3 nm). It is possible to distinguish a highest percentage of lichen coverage (81–100%) in all the bands. The low lichen coverage (31–40%) and very low lichen coverage (<20%) can hardly be separated in band 4, but band 9 (768.6 nm, NIR) offers some potential. Classes where lichen coverage is very small reflect higher in NIR than dry heath dominated by *Calluna vulgaris* (**Figure 4**). However, both the difference and the number of observations are small (**Figure 4**).

The results using Landsat TM data show that mountain vegetation above the tree line (grass heath, extremely dry – dry heath, lichen-dominated heath, mesic and wet heaths, mire, meadow, blocky areas and bedrock outcrops, snow bed, and water) can be mapped with a mean overall accuracy of 85% and a kappa value of 0.78. The accuracy for mountainous lichen dominated heath is 90% and the kappa value is 0.89. Boresjö-Bronge and Wester (1999) state an overall weighted accuracy (excluding water, blocky areas and bedrock) of 88% for a "knowledge-based classification" approach of the Swedish mountain range using a similar classification system. The mountainous lichen dominated heath was, however, not evaluated (Boresjö-Bronge and Wester, 1999). The analysis of Landsat TM data confirms the results obtained from the hyperspectral data. Lichen has characteristically high values in the visible part of the spectra (TM2 and TM3) compared with green plants (**Figure 5a**). The spectral difference technique, especially for TM2 and TM3, shows a good possibility to classify the status of the lichen cover in four classes: high (>80% cover), moderate (51–80% cover), low (20–50% cover) (**Figure 5b**), and very low (<20% cover). However, the latter cannot be separated from dry heath. The class boundaries have been determined using field observations of the amount of lichen within test sites interpreted in CIR aerial photographs from 1994. Mount Fulufjället has ground sites with a lichen cover of >80%. At Mount Långfjället the maximum lichen cover is 70%

The correlation between the CIR aerial photograph interpreted decrease in lichen and the calculated NDVI difference is high (r^2 = 0.74) (**Figure 6**). The indices based on different combinations of TM2, TM3, TM4, and TM5 all gave lower correlation coefficients. Vegetation-index differencing as a means of change detection, using Landsat TM data, shows promising results to map a decrease in lichen cover in at least three classes: unchanged (<20% decrease), moderate (20–50%

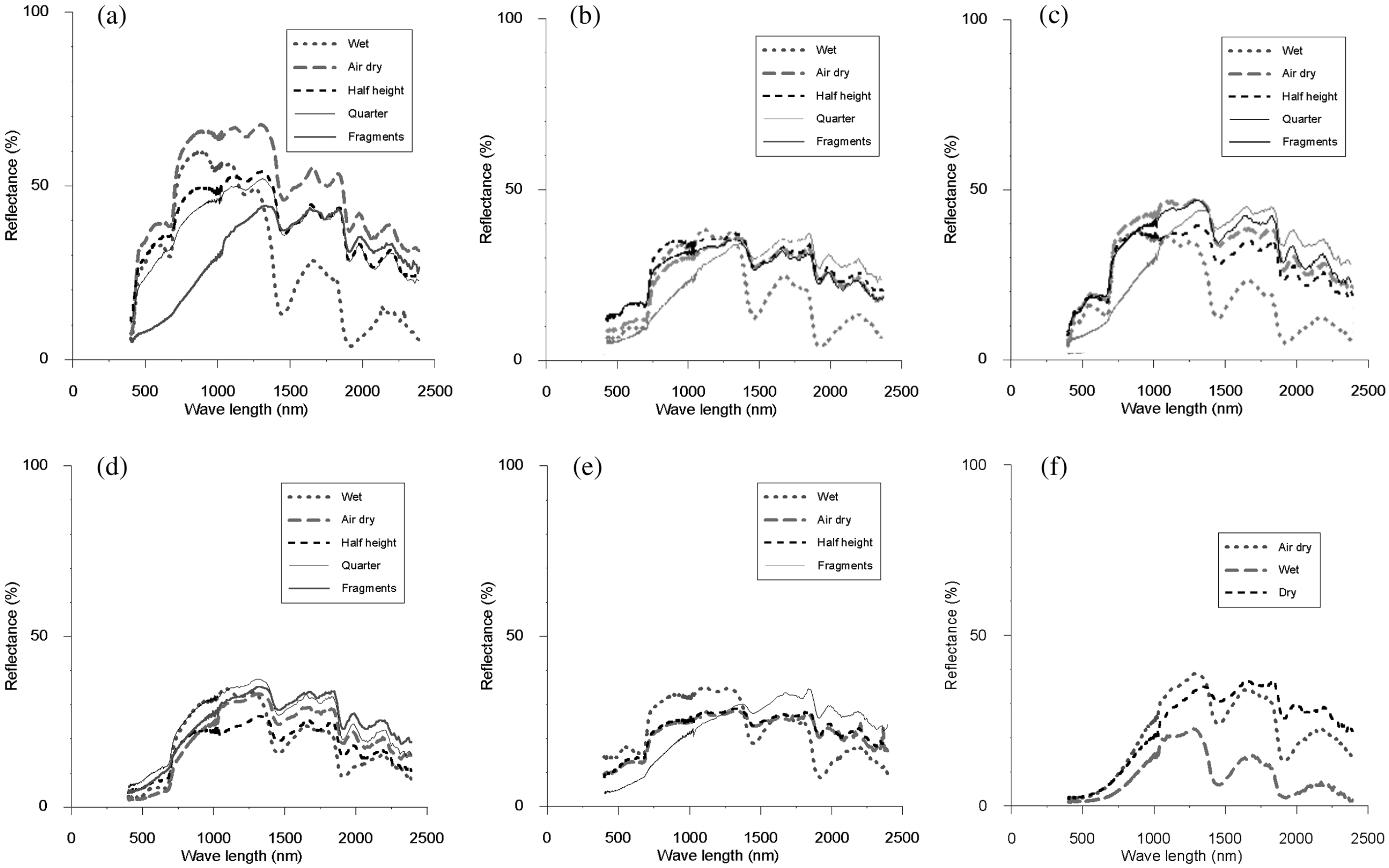

Figure 2. (a–e) Laboratory comparison of spectral measurements of *Cladina stellaris* (a), *Cladina rangiferina* (b), *Cladina arbuscula* (c), *Cetraria islandica* (d), and *Stereocaulon saxatile* (e). The spectra were run on *Cladina stellaris*, *Cladina rangiferina*, *Cladina arbuscula*, and *Cetraria islandica* under five different conditions: lichens at full height, saturated with water (Wet); lichens at full height, air dried (Air dry); lichens at 50% of full height, air dried (Half height); lichens at 25% of full height, air dried (Quarter); and humus mixed with lichen fragments (Fragments). The spectra were run on *S. saxatile* under four different conditions: lichens at full height, saturated with water (Wet); lichens at full height, air dried (Air dry); lichens at 50% of full height, air dried (half height); humus mixed with lichen fragments (Fragments). (f) Comparison of spectral measurements of humus air dry – moist (Air dry), wet (Wet), and dried in an oven for 24 h (Dry).

decrease), and high (> 50% decrease). The lichen coverage is nowhere larger than 70% for Mount Långfjället, therefore further class separation was not possible. On Mount Fulufjället the lichen cover reaches >90% but there was almost no change between the investigated years. The differencing technique, described in the Methods section, is based on the assumptions that lichen heaths can be classified with high accuracy using Landsat TM data (in this study 90%) and that the amount of lichen can be differentiated into classes.

In the study area of Mount Långfjället (approximately 100 km^2), 46% of the Landsat TM pixels classified as lichen heath have >20% decrease in lichen cover between 1986 and 1995 (**Figure 7**). Comparatively, about 40% of the approximately 300 ha test plot used in an aerial photograph based study on Mount Långfjället showed a >20% decrease in the coverage of lichens between 1981 and 1994 (Ihse and Allard, 1995). The evaluation of the Landsat TM based result was done using the same carefully analysed test plot. The accuracy assessment shows an overall accuracy of 77%, which is acceptable (**Table 1**). Both the producer and the user accuracies for the class unchanged lichen coverage (<20%) are good, 82% and 90%, respectively. For the class high decrease in lichen cover (>50%), the user accuracy is low (63%), and for the class moderate decrease in lichen cover (20–50%) the producer accuracy is low. This indicates a certain confusion between the two classes.

Discussion

The aim of the study has been to assess the applicability of satellite data to the detection of small changes in lichen cover within the study area. Evaluation of the causes of such changes is difficult and will need further research. However, of the different heath communities above the tree line, the lichen-dominated heath is among the most sensitive to intensive reindeer grazing and trampling, which causes mechanical damage to the vegetation cover. Decreased lichen cover, independent of the causes, acts as an “early indicator” of a disturbed ecosystem (Allard et al., 1998). In general, the lichen cover has decreased on Mount Långfjället (Ihse and Allard,

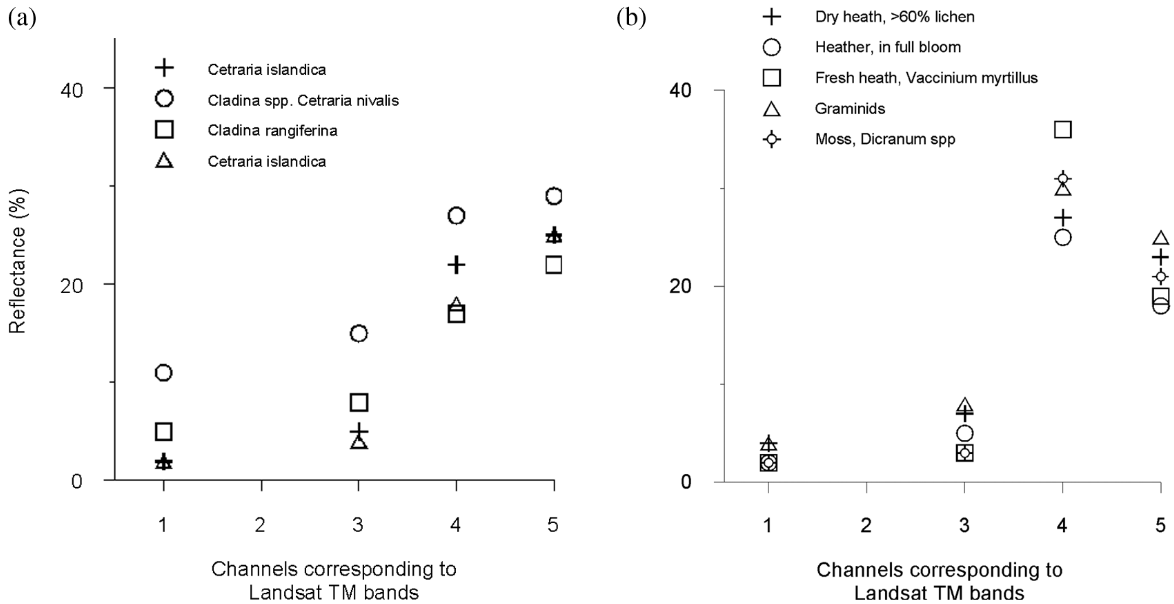

Figure 3. Reflectance of lichens (a) and heath vegetation (b) measured with a hand-held spectroradiometer in the field during the summer of 1997 at Mount Långfjället. Note that two different strands of *Cetraria islandica* were measured in (a). Sensors were equipped with filters corresponding to Landsat TM bands 1 (blue), 3 (red), 4 (NIR), and 5 (MIR). The graminids in (b) refer to grass species common in the area.

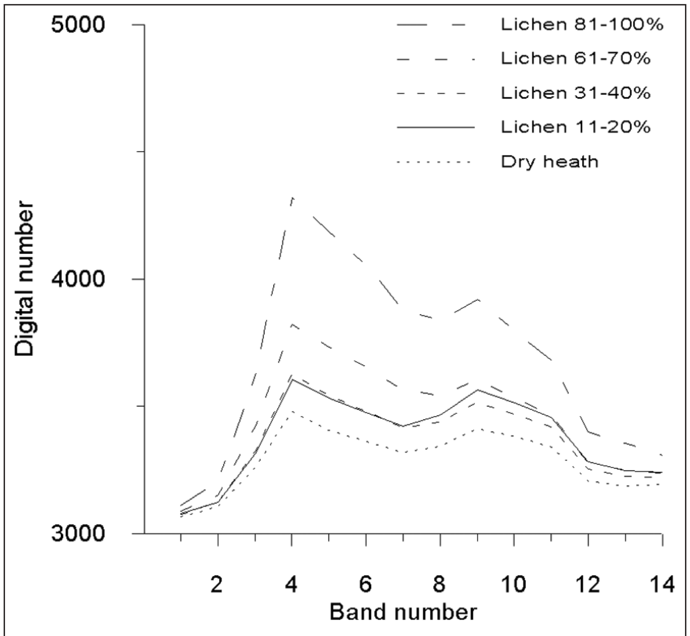

Figure 4. Comparison between dry heath and differing percentages of lichen cover on dry heath measured at Mount Långfjället. Data derived from airborne hyperspectral imaging scanner (410.0–1048.3 nm, bandwidth 10–30 nm, band numbers 1–14). Spatial resolution 5 m. The lowest curve shows, for comparison, the spectral properties of dry heath without lichen. Band 4 (521.3 nm, green) shows the best potential for separating different lichen cover into three classes. Band 9 (768.6 nm, NIR) shows the theoretical possibility for separating lichen cover into four classes.

1995). A major change can be seen when studying photographs from the 1940s, when the lichen cover on Mount Långfjället was thick and dense, much in the same way as that found on Mount Fulufjället today (Allard et al., 1998; Allard, 2001).

For changes in the lichen cover to be detected from satellite data, a change in the spectral reflectance characteristics of the lichen-dominated heath is necessary. Hence improved knowledge about spectral characteristics of different lichen species is needed. The numbers of samples used in the laboratory and field measurements of spectra are unfortunately too few to make an accurate statistical analysis; however, since spectral measurements of lichen species are rare, the results of this study constitute a useful and needed contribution to this topic.

Spectral characteristics of lichens

Johansen and Tömmervik (1992), among others, state that different grazing pressure in lichen heath vegetation can be reflected in a satellite image and can be classified into three groups. These groups are as follows: (1) *Cladina stellaris* dominated areas, which implies slight grazing; (2) *Cladina rangiferina*, *Cladina arbuscula*, and *Cladina mitis* dominated areas, which imply moderate grazing; and (3) *Stereocaulon alpinum* Laur. and *Stereocaulon paschale* (L.) Hoffm. dominated areas as the group showing heavily grazed heaths. The laboratory measurements support a slightly different classification. During the field studies on Mount Långfjället and Mount Fulufjället it was found that none of the *Cladina* or *Stereocaulon* species present were dominant over such a large area as would match a whole pixel (i.e., 30 m from Landsat TM), and therefore this classification cannot be used, even if spectral differences exist.

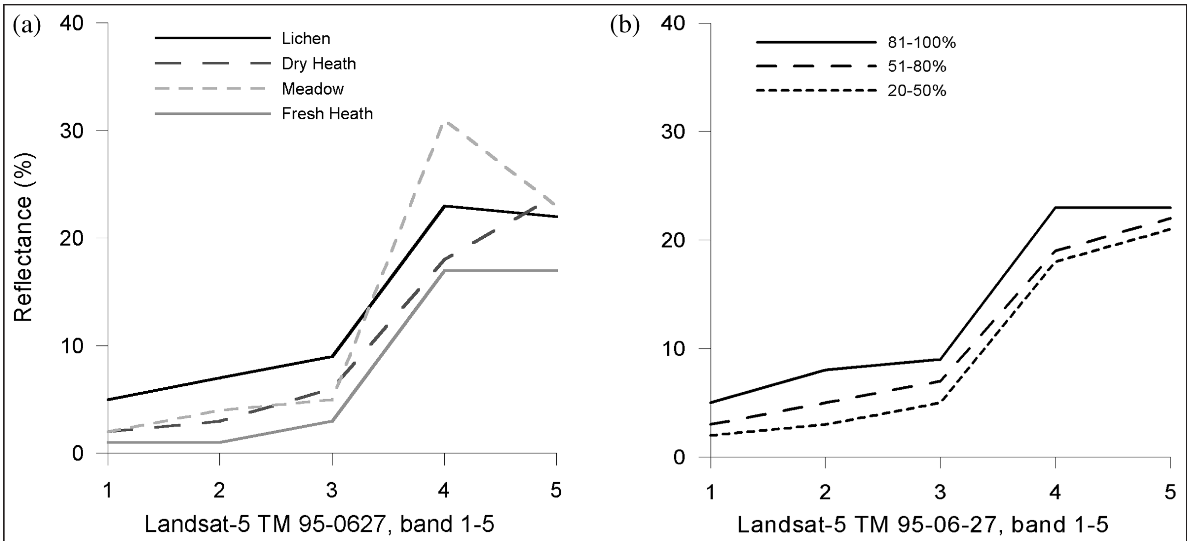

Figure 5. (a) Lichens poor in chlorophyll have high values in the visible part of the spectra (TM2 and TM3) compared with meadow, dry heath, and fresh heath. (b) Test sites with different lichen cover show spectral differences, especially in spectra TM2 and TM3. The degree of lichen cover is estimated in the field.

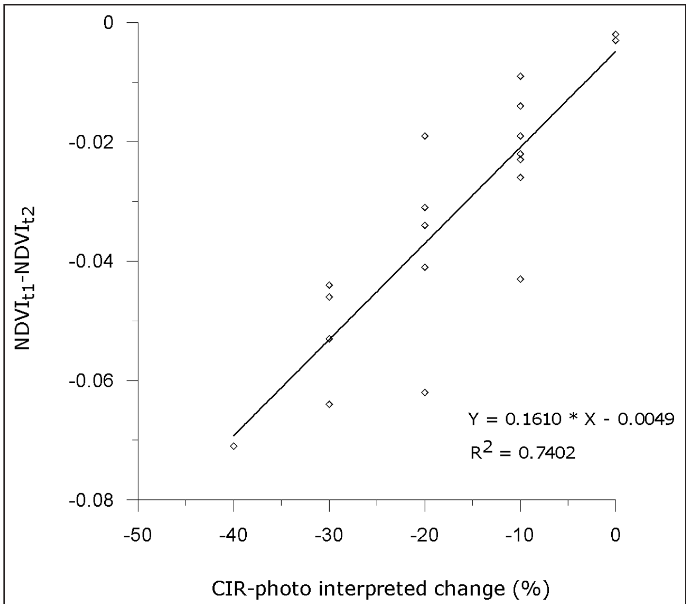

Figure 6. Normalized difference vegetation index (NDVI) change between Landsat TM images from 1986 (t1) and 1995 (t2) versus changes in lichen cover interpreted from CIR aerial photographs. A decrease in lichen cover results in an increase in NDVI.

The reflectance measurements in the field show that the pale species *Cladina stellaris*, *Cladina arbuscula*, and *Cetraria nivalis* represented by a circle in **Figure 3a** have a relatively higher reflectance in all bands compared with the other species. There is a clear difference between those pale species and the darker *Cetraria islandica*, which was much lower in reflectance.

The results from measurements in the laboratory for *Cladina stellaris*, *Cladina rangiferina*, and *Cladina arbuscula* show that the red wavelength has the highest reflectance in the visible spectra. This is supported by the findings of Käykhö and Pellikka (1994). The main difference in the spectral shape is not caused by the difference in species, but by the difference in moisture content and lichen height and the presence of humus (**Figures 2a–2f**).

Cladina rangiferina reflects higher in the NIR when at half and quarter height compared to full height (**Figure 2b**). An explanation for this could be that when the top half gets crushed, there are fewer shadows between the branches, and crushed fragments have accumulated, which should give a higher reflectance. The lichen is also darkest at the top, so when these parts are removed the reflectance rises. *Cetraria islandica* has the lowest reflectance as dry and in full height, even lower than the fragments. This can be explained by the colour of the lichen itself when dry (dark brown), whereas the oven-dried humus is relatively light brown. When the lichen is wet, it takes on a more brown–green colour, which could explain the higher reflectance in the NIR. This lichen is also darker at the top when dry and has shadows between the branches. The shadows could be the explanation for the difference in NIR reflectance between the two stands of *Cetraria islandica* from the field measurements (**Figure 3a**). *Stereocaulon saxatile* has gray phyllocladia, which gives a low reflectance curve. When crushed, the white branches of the pseudopodetia become visible and the reflectance increases.

The laboratory measurements do not show obvious differences in the spectral shape of each individual species when compared to one another. However, the curves demonstrate a different percentage in reflectance for different species (**Figures 2a–2e**). The lichens can be placed in two groups: (1) *Cladina stellaris*, with a reflectance of about 65% in the NIR; and *(2) Cladina rangiferina*, *Cladina arbuscula*, *Cetraria islandica*, and *S. saxatile*, with an average reflectance of about 30% in the NIR.

Table 1. Error matrix for classification of changes in percent lichen cover.

	Reference data				Accuracy (%)	
Classified data	Unchanged (<20% cover)	Moderate (20–50% cover)	High (>50% cover)	Total	Producer	User
Unchanged (<20% cover)	27	3	0	30	82	90
Moderate (20–50% cover)	6	27	3	36	69	75
High (>50% cover)	0	9	15	24	83	63
Total	33	39	18	90		

Note: Overall accuracy is 77%.

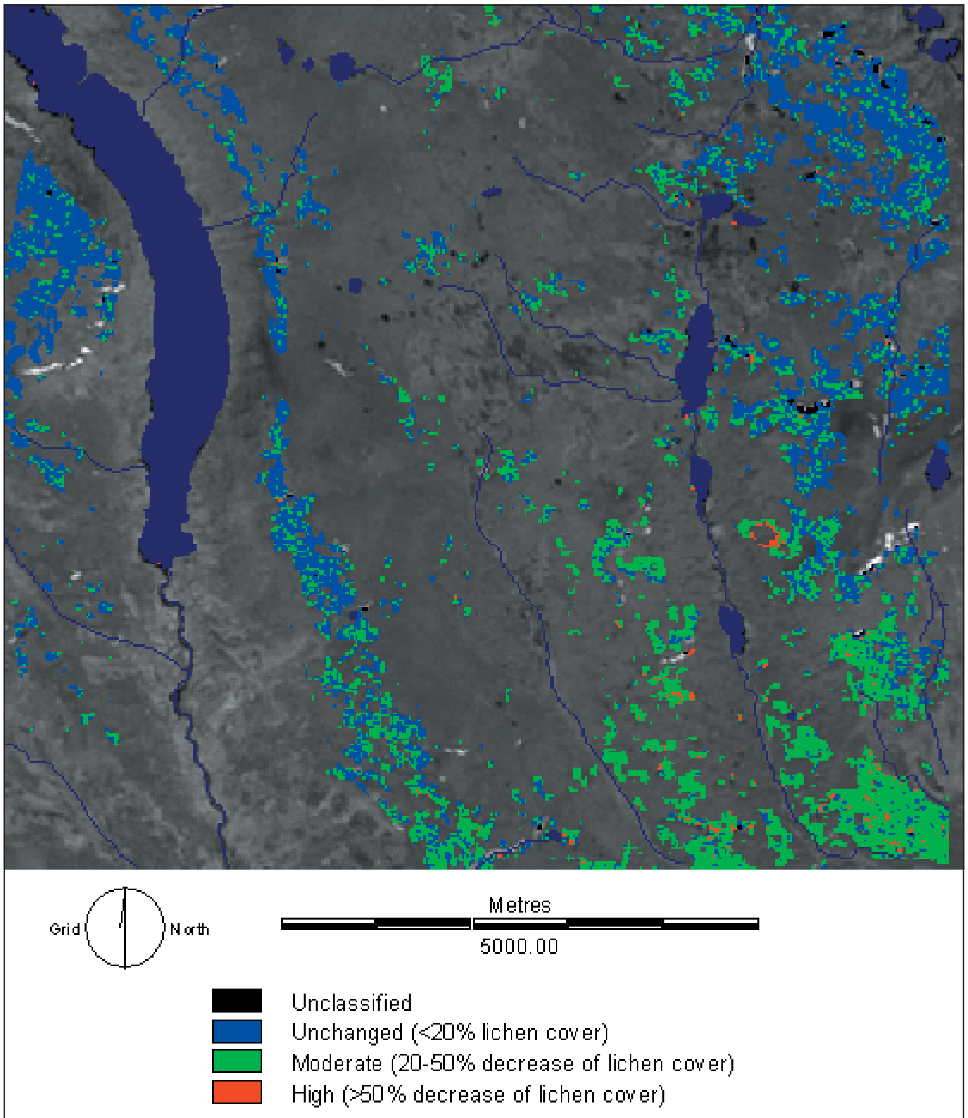

Figure 7. Map of the distribution of differences in the state of lichen heaths in the Mount Långfjället area in the southern part of the Swedish mountain range. The result is indicative of an area that has been subjected to intensive reindeer grazing and trampling.

High- and low-light adaptation may explain the difference in the reflectance of *Cetraria islandica* measured in the field and in the laboratory. The *Cetraria islandica* measured in the laboratory, which was brown–green in colour, was collected in a forest in the Stockholm area and therefore adapted to low-light conditions, whereas the lichens in the mountains are adapted to high-light conditions and are brown in colour.

Digital change detection

In this study, the NDVI calculated from Landsat TM images was used for detecting vegetation changes in mountainous lichen-dominated heath communities. The NDVI differencing technique is based on the assumptions that lichen heaths can be classified with high accuracy using Landsat TM data and that the lichen cover can be differentiated into classes. For the regression and thresholding, reference data corresponding to higher resolution CIR aerial photographs and field data were used to interpret lichen cover at the time of each photograph.

The choice of NDVI for change detection is based on the consideration that lichen-dominated heath shows a significantly lower NDVI value than other heath communities. When the lichen cover decreases, the NDVI value increases. Based on the spectral characteristics for test sites with different percentages of lichen cover according to reference data, the NDVI values were grouped in four classes. The hyperspectral data, with a spectral resolution of about 20 nm and spatial resolution of 5 m, gave no spectral improvement concerning the number of classes. With a higher spatial resolution than that of Landsat TM data, the hyperspectral data from the airborne imaging scanner identified smaller patches with severe degradation, and this may give an earlier signal that the area as a whole is subjected to mechanical disturbance (from animals or humans). However, a higher spatial resolution does not necessarily produce higher classification accuracy, as the increased spatial resolution leads to greater spectral variability and an increased number of boundary pixels (Martin and Howart, 1989). The vegetation density in mountainous plant communities in Sweden varies a lot depending on soil moisture, soil depth, altitude, and aspect. In areas of low and medium vegetation densities, the red wavelength band has been found to give the best result for vegetation mapping and for detecting vegetation changes (Käyhkö and Pellikka, 1994; Chavez and MacKinnon, 1994). The lichen-dominated heaths in the test sites of the present study have medium to high vegetation density, and this is perhaps one reason why the NDVI gives a better result than the individual red spectral band (TM3). Lyon et al. (1998) have shown that the NDVI was least affected by topographic factors and that the NDVI differencing technique demonstrated the best vegetation change detection method. The NDVI differencing method used in this study gives a change product showing three classes: unchanged, moderate decrease in lichen cover, and high decrease in lichen cover. The error matrix shows an overall accuracy of 77% (**Table 1**). Although an accuracy of 77% is acceptable, but not very good, it is adequate for detection and location of areas subjected to degradation of the lichen cover. However, there is a certain confusion between the two classes high decrease in lichen cover (>50%) and moderate decrease in lichen cover (20–50%). The reliability of the reference data and the small area of the class high decrease in lichen cover (>50%) within the test plot used as reference data may explain some of the misclassifications.

A binary change-detection product (change – no change) may place the threshold such that it misses slight changes, or it may include slight changes but label them simply as changed and thus not allow the user to distinguish the slight from the more extreme changes. A lichen cover decrease, differentiated in three classes in steps of approximately 30%, is coarse when compared with that from the CIR aerial photograph interpretation, where steps of 10% can be perceived (Allard et al., 1998). The promise of the method presented lies in its monitoring applications. In monitoring it has to be decided at what level the study should be performed. Aerial photographs, rich in information, are more useful for studying specific degraded areas and monitoring changes in those areas. If the primary interest is to monitor a whole region, then Landsat TM imageries offer opportunities for information collection in areas undergoing moderate or high decreases in lichen cover, i.e., indicating areas of disturbed ecosystems.

Conclusions

For monitoring Swedish mountainous vegetation in areas with a continental climate and dominated by lichen-rich heaths, the chosen indicator (lichen cover) can be used for the detection of disturbances in the ecosystem. The spectral differences of the mountainous plant communities make it possible to classify them with an overall accuracy of 85% and a kappa value of 0.78 using Landsat TM data. Mountainous lichen-dominated heath, above the tree line, can be classified with an accuracy of 90% and a kappa value of 0.89. The laboratory and field measurements demonstrate that different lichens can be separated spectrally if homogeneous spots are measured.

The changes in lichen cover can be detected in Landsat TM data using a NDVI differencing technique. Based on the results it is possible to map a decrease in lichen cover in three classes with an overall accuracy of 77%: unchanged, moderate decrease in lichen cover, and high decrease in lichen cover. In the whole study area, 46% of the pixels classified as lichen heath have a >20% decrease in lichen cover. The differencing technique is based on the assumptions that lichen heaths can be classified with a high accuracy using Landsat TM data and the amount of lichen can be differentiated in the following classes: (1) very low (<20% cover), (2) low (20–50% cover), (3) moderate (51–80% cover), and (4) high (>80% cover). The classes can be regarded as risk-assessment classes for vegetation degradation and ensuing soil erosion. The major conclusion from this study is that a change in lichen cover, differentiated in three change-classes, can be used as a tool for monitoring disturbed ecosystems in the Swedish mountain range.

Acknowledgments

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