Polar Record 48 (244): 94–106 (2012). © *Cambridge University Press 2011.* *doi:10.1017/S0032247411000556*

Analysis of human impact on boreal vegetation around Monchegorsk, Kola peninsula, using automated remote sensing technique

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ABSTRACT. The boreal vegetation of the sub-Arctic comprises more than 30% of the Earth's forest area and plays a major role in controlling the global environment. In the 20th century the boreal vegetation of Fennoscandia was significantly changed by heavy industrialisation leaving many forest areas damaged or dying. Due to severe climate conditions of the sub-Arctic such vegetation changes are traceable over long periods of time. This provides an opportunity to study all types of human impact on vegetation in time and to develop methods to monitor geographical and structural changes in the vegetation cover. Here we present the first part of a larger study in which we use the remote sensing technique to investigate the dynamics of the boreal vegetation in Fennoscandia in context of human impact. We have developed a novel method for an automated analysis and mapping of vegetation and of all types of human impact based on a single support-vector-machines classifier (for the whole area). Implemented with free and open source software the method uses Landsat TM and ETM+ band data (for which it automatically performs atmospheric correction) and a number of indices like NDVI, NBR, etc. The accuracy of the 16-class classification has been assessed using field data and literature sources and determined to be 74.1%. The method has been successfully applied to a study area around Monchegorsk, Kola peninsula, Russia, the most industrialised part of northern Europe. We have characterised all major types of human impact on the boreal forest and tundra vegetation performing the change detection analysis in an area of 1750 km^2 between 1986 and 2005. The analysis has confirmed industrial atmospheric pollutions as the primary type of human impact here. We have discussed the role of forest fires and uncovered temporal trends in the vegetation cover. We have found that during the 19 years covered by the study more than one third of all coniferous forest in the area was transformed primarily to wetland, deciduous forest and typical tundra vegetation. The success of the method in this area allows us to extend the study to the rest of Fennoscandia and look at large scale changes in the boreal vegetation cover.

Introduction

There are many factors that define the dynamics of the global environment (Svetlosanov 2009). To a large extent these factors have natural causes, such as varying levels of solar radiation (Strahler and Strahler 2005; Panin and others 2008) or volcanic activity (Smithson and others 2002). The natural transformation of the environment is a slow process that takes years, decades or often centuries. This allows the environment to stay stable and in balance (Ives and Carpenter 2007). At the same time, with the rise of man, human activity has become another substantial factor impacting the environment, often over much shorter time intervals. Farmland development and forest logging (often related to the former) had dominated human impact on the environment for centuries (Marsh and Grossa 2002). However, the rapid industrial development of the 19th–20th centuries and the fast growth of the world's population have changed the way man transforms the environment. Greenhouse gas emissions, toxic air pollutions, industrial clear cutting, toxic landfill and water waste are among those activities that define human impact today. Even though the extent of the global human impact on the environment is currently undergoing the scrutiny of the scientific community and the public in many developed countries, little is known about how local and measurable human impacts are linked to changes in the global environment. Understanding those provides the possibility of differentiating between changes caused by man and those occurring naturally, and in turn, developing effective methods of reducing the impact of man.

Bonan and others (1992a), ACIA (2005), Smithson (2002), AMAP (2006) and others show that the boreal vegetation plays one of the primary roles in controlling the global heat and radiation balance, hydrological cycle, ocean currents etc. This is not surprising as the coniferous boreal forest comprises 30.5% of the Earth's forest area (FAO 2002), whilst the boreal region covers more than 17% of the Earth's terrestrial area (ACIA 2005). Tundra and the boreal forest together hold about 40% of all soil carbon (Melillo and others 1993). Furthermore, Kruchkov (1991) and Tømmervik and others (2003) show that the position and structure of the boreal vegetation depend primarily on climatic conditions and human activity. This defines the boreal vegetation as a feedback system, which is both controlled through the environment and external impact, and itself controls the environment. Severe weather conditions with long winters, late snowmelt and short vegetation seasons make any natural transformation and restoration of the northern environment even slower than elsewhere (Shugart and others 1992; Hofgaard 2004). Changes are conserved and accumulated over a very long period of time and the restoration takes years. Any human induced changes are, therefore, highly visible. The factors described above make the boreal vegetation an ideal target to study all types of human impact on vegetation in time and to develop methods to monitor geographical and structural changes in the vegetation cover.

The richness and variety of natural resources have attracted people to sub-Arctic and Arctic for more than a century. The northern parts of Fennoscandia, and in particular the Kola peninsula, have become the most industrialised and economically developed regions of the north. The vegetation in Fennoscandia is, therefore, greatly affected by various types of human activity, for example reindeer grazing, logging, forest fires as well as industrial and residential development. Unfortunately, available publications tend to deal with just one prevailing type of impact for each respective study area. For example, Tømmervik and others (2004) as well as Johansen and Karlsen (2005) have researched reindeer grazing in Finnmark, Rees and Williams (1997) as well as Tømmervik, Johansen and Pedersen (1995) have studied industrial atmospheric pollutions around Monchegorsk and Nikel in Russia, and the UNEP (2005) report addresses forest logging in Lapland, Finland, and so on. In the whole of Fennoscandia one observes the following five major types of human impact on the boreal vegetation: (a) industrial atmospheric emissions, (b) forest fires, (c) forest logging, (d) reindeer grazing and (e) industrial and residential infrastructure development. We believe that in order to quantify the dynamics (changes in position, structure and regeneration capacity) of the boreal vegetation (separating natural contributions from those caused by human impact), one needs to produce comprehensive mappings of forest and tundra along with all the types of human impact characteristic for the region. Otherwise, it is impossible to account for fluctuations in the vegetation cover that are due to natural causes. Therefore, we have systematised all the types of human impact and integrated them all into our method.

This paper is a part of a larger study, in which we investigate the dynamics of the boreal vegetation in Fennoscandia in time and in the context of human activity. Any detailed data for an area of the size of Fennoscandia would be massive, and comprehensive field data would be tedious to collect. The element of temporal analysis adds further complexity to the problem. Rees and others (2003) and Jensen (2007) demonstrate how remote sensing methods and satellite imagery provide an effective way to monitor the environment and human activity on a large scale, in particular over the areas that are difficult to reach, such as those in the north. High resolution satellite imagery has been widely used by a number of research teams to study the northern vegetation and the impact of human activity on it (Toutoubalina and Rees 1999; Virtanen and others 2004; Tømmervik and others 2004; Johansen and Karlsen 2005; Rees and Danks 2007; Hofgaard and others 2010). The wide range of spectral reflectance in multispectral satellite imagery provides a means for differentiating between many types of land cover like coniferous and deciduous forests, tundra, water, eroded soil or industrial development. Therefore, we use the remote sensing approach in our study. It allows us to perform both qualitative and quantitate assessment of land cover and of environmental changes caused by both natural factors and human activity.

The scope of this paper is limited to developing the technical approach and applying it to a test area around Monchegorsk, Kola peninsula, Russia. Here we describe the very first successful results in analysing the dynamics of the boreal vegetation: we have performed a comprehensive automated analysis of all changes to the boreal vegetation over 19 years around Monchegorsk mapping all types of human impact in time. In order to achieve a high throughput (required in future to process information for all of Fennoscandia) we have used publicly available archives of satellite imagery (Earth Explorer, earthexplorer.gov; Global Land Cover Facility, www.landcover.org) and our own field data (both described in detail later), and have developed a novel method that can perform image analysis, normalization (atmospheric correction), land cover classification and mapping in a fully automated manner. Automating the workflow has opened the possibility of using high resolution multispectral Landsat TM and ETM+ imagery without compromising the general nature of the study. Having such a method at hand opens a real opportunity to map human impact on vegetation over the vast territory of Fennoscandia within days rather than years and to monitor and study its structural and geographical dynamics.

Study area

In this paper we perform an automated analysis of human impact on the boreal vegetation for the area around Monchegorsk, Kola Peninsula, Russia. This area has seen high levels of industrial development since the early 1930s when the copper-nickel smelter Severonikel started to operate using local nickel-copper ore (Kola GMK 2005). The area is situated in the boreal forest zone beyond the Arctic Circle, centred around 67°56′22″N, 32°54′56″E (Fig. 1) and generally suffers from toxic air pollution, fires and occasional logging. The terrain height varies between 100 m and 1250 m above sea level. The forest zone extends up to 350–400 m. The forest is primarily coniferous (*Picea* spp., *Pinus* spp.) with occasional deciduous species (*Betula* spp., *Salix* spp.). At higher altitudes the forest is followed by birch shrub and mountain tundra, which features dwarf shrubs, lichen and moss.

The vegetation around the smelter is suffering from highly toxic atmospheric emissions of sulphur dioxide, carbon monoxide and heavy metals (Glazovskaya and Kasimov 1987; AMAP 1997; Zhirov and others 2007; Lukina and others 2005). Local topography plays an essential role in the spread of air pollutants. The mountains of Monchetundra effectively block their spread southwards. Affected by the long term wind pattern (Yakovlev

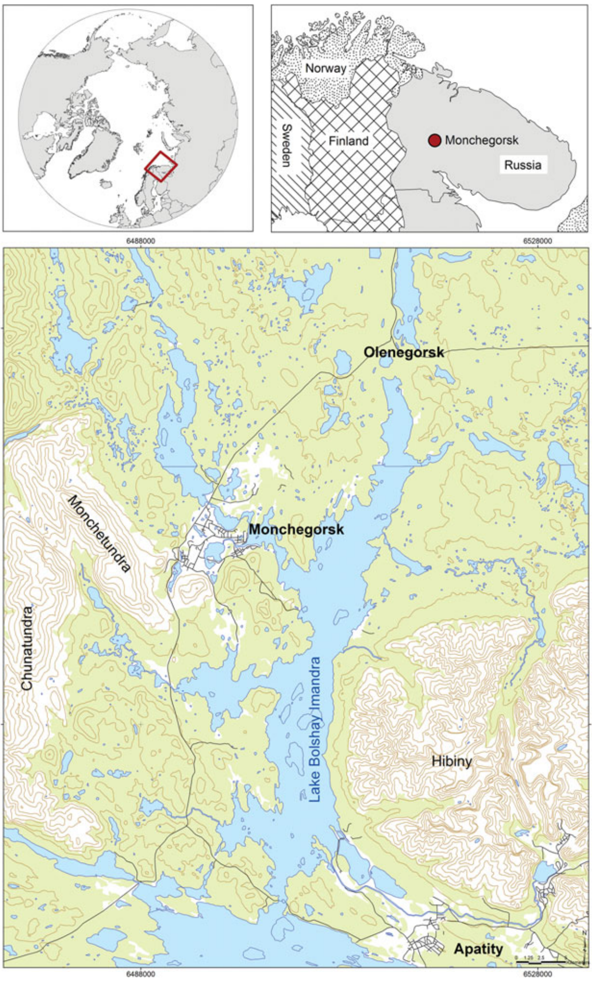

Fig. 1. Geographical location of the study area around Monchegorsk in Kola peninsula, Russia, as shown on Russian topographic maps. The study area is located beyond the Arctic Circle in the boreal forest zone.

Table 1. Landsat imagery used for change detection and generation of land cover maps for the area of Monchegorsk

Satellite	Sensor	Path/Row	Date
Landsat 5	TM	188/012	28 July 1986
Landsat 4	TM	186/012	11 July 1988
Landsat 4	TM	186/013	11 July 1988
Landsat 7	ETM+	188/012	26 July 2000
Landsat 5	TM	187/012	09 July 2005

1961) the area of the highest air pollution stretches northwest from the smelter.

Already in the early years of operation the adverse effect of the smelter activity on the ecosystem became obvious. By 1946 the surrounding forest looked fully dry within 6 km around the smelter (Karpenko 1994). By 1970s this same area was fully covered by the destroyed forest (Doncheva 1978), with similar situations reported for other smelters of Kola peninsula. The scale of the impact increased substantially along with the capacity of the smelter and after it was moved to operate using sulphur rich ore from Talnah in 1968 (Kruchkov and Syroid 1984; Lukina and Nikonov 1993). At that point the level of sulphur in the ore rose from 3.5% to 25%. According to Kruchkov and Syroid (1984), and Doncheva (1978) by the 1980s the ecosystems around the smelter had turned into those at different stages of industrial damage, from slightly damaged (up to 20% of dead shrubs and 40–60% of dead trees) to technogenic barrens (areas free of vegetation). By 1980s the Severonikel industrial area had spread to 728 km^2 including 8 km^2 of technogenic barren (Yarnishko 2005). At present, the total area of dead forest stretches 4–5 km south and 6–8 km north of Severonikel (Golubeva and others 2003). Fires are wide spread around the smelter. Many present aged burnt areas are 30 to 40 years old and are located in the industrially damaged dry forest. Thereby the state of vegetation around Monchegorsk is controlled by two main factors: the quantities of atmospheric pollution and the frequency of fires in places of destroyed vegetation.

Logging in this area is mostly dated about 70–80 years and goes back to 1940s and 1950s when the cities of Monchegorsk and Olenegorsk (to the north of Monchegorsk) were under development. Some new logging areas are linked to building of new roads or other types of communications (Nikonov and others 2005) and to clearing of land for agricultural use, but those are fairly rare.

The implicit industrial impact from the smelter spreads over even larger distances: chlorosis and necrosis of vegetation stretch as far as 55–60 km north, while the geochemical analysis of samples of plants and soils shows some impact even at distances of 80–90 km (Kruchkov 1993). Metal dust from Kola smelters was detected as far as North America (Kruchkov and Makarova 1989).

Among the mentioned five types of impact, grazing is not typical for this area and has not been detected in any measurable quantity. Similarly, no snow can be detected in the study area, as it does not include any high mountains.

Data

We have used Landsat TM and ETM+ imagery to perform the change detection in the study area (Table 1). Landsat TM and ETM+ each have 7 bands in the visible and infrared electromagnetic spectra (as compared to just 4 in MSS sensors) and each additional band adds further information to the classifier generally improving its accuracy (unless fully correlated). The bands of TM and ETM+ sensors are comparable.

The growing season in northern Fennoscandia peaks between the middle of July and the beginning of August (Golubeva and others 2003; Shutova and others 2006). Therefore, all the imagery was acquired in this period (but for different years, see Table 1). Landsat data can only be used if the sun elevation is greater than 30° (USGS 2010), otherwise the radiance reflected from the Earth's surface in the visible and infrared bands is too low for the sensors (Marshall and others 1993). Whenever possible we have also tried to pick images with low cloudiness. Summer cloudiness is very characteristic for the region and, therefore, it was impossible to avoid it completely.

One of the main differences that our method demonstrates against those currently in use is in the following. Usually a separate classification problem is solved for every image whereas we use one and the same classifier trained on a large amount of field data and expert knowledge from a very large area (both in time and space). This improves the robustness of the results, their comparability and reproducibility. This further ensures that our method can be applied to a larger area than just the immediate study area (like that of Fennoscandia) producing accurate land cover maps.

During the initial stage of classification an overall area of 272800 km^2 comprising parts of northern Norway, Sweden, Finland and Russia was selected based on the same principles as used for change detection described above. For training the classifier (see the Methods section below), we also used an extensive archive of field data collected in Fennoscandia during the summer seasons of 1994, 1996, 2001–2004, 2007 and 2008 as well as a variety of maps and literature sources including statistical air pollution and meteorological data.

Methods

Image processing principles

As a part of a larger study, which investigates the dynamics of the boreal vegetation in Fennoscandia, we have developed a novel method for performing the change detection and generating land cover maps. A detailed description of the method is a topic for a separate publication; here we provide only a high level overview essential to understand the approach and concentrate on the change detection results. The method is based around a supervised multi-class classification of multispectral remote sensing data. This general principle is widely used in remote sensing and environmental studies (Lillesand and Kiefer 2000; Jensen 2007).

The novelty of our method lies in the following three principles:

1) Applying a single classifier to the entire dataset. We train a single classifier for the whole area (like Fennoscandia). Typically researchers perform independent classification for individual images. This makes the results subjective, often not reproducible and difficult to compare (in time, between regions, or between research teams). Having a single classifier addresses all these issues. However, it introduces further complexity for image preprocessing and defines extra requirements described below.
2) Using automation scripts to speed up map creation. We incorporate the preprocessing, classification and post-processing (mapping) into a single automation script. This allows us to minimise the time needed for defining a high quality classifier and for obtaining classification results. This also enables the processing of data for large areas (like Fennoscandia). Typically, all these stages are manual and require much time and expert knowledge. From experience, manual classification of a single satellite image takes up to a few days, while with our method we can do the same in minutes depending on the computational resource available (and it is easily to parallelise on a high performance cluster).
3) Using open source software. We have developed our method around free and open source libraries and software packages. This allows other researchers to reuse our method easily in studying other areas of interest without a licensing barrier yielding more accessible and open science.

In order to train a single classifier that would be valid for a large area of Fennoscandia, and in order to automate the process, the following basic requirements need to be satisfied:

1) Field data, expert knowledge and satellite imagery are required to span far beyond the immediate study area, covering all types of human impact we want to address and spanning over a number of years;
2) All satellite data need to be comparable (in particular when acquired at different locations or time points), which can be achieved with normalisation using, for example, atmospheric correction;
3) Satellite metadata need to be incorporated in the analysis workflow to aid normalisation; the metadata need to be processed automatically to extract relevant information about sun elevations, data ranges, etc;
4) The classifier needs to be validated using field data and expert knowledge in the larger area of Fennoscandia;
5) A language suitable for scripting needs to be used to glue all elements of the workflow together.

The software and the analysis workflow

The analysis workflow chart is given in Fig. 2. The analysis begins with a manual process of picking satellite images for collecting training data. These images are automatically normalised using the atmospheric correction protocol described below. Another manual process is selecting training areas for each class. This can be done using any image analysis application that can process TIFF images.

Images are normalised by performing atmospheric correction using information from image metadata. This eliminates differences caused by variations in the sensitivity of detectors, solar illumination, satellite gains, atmospheric aerosol, etc. The dark pixel value is estimated from the 2nd percentile in each band separately.

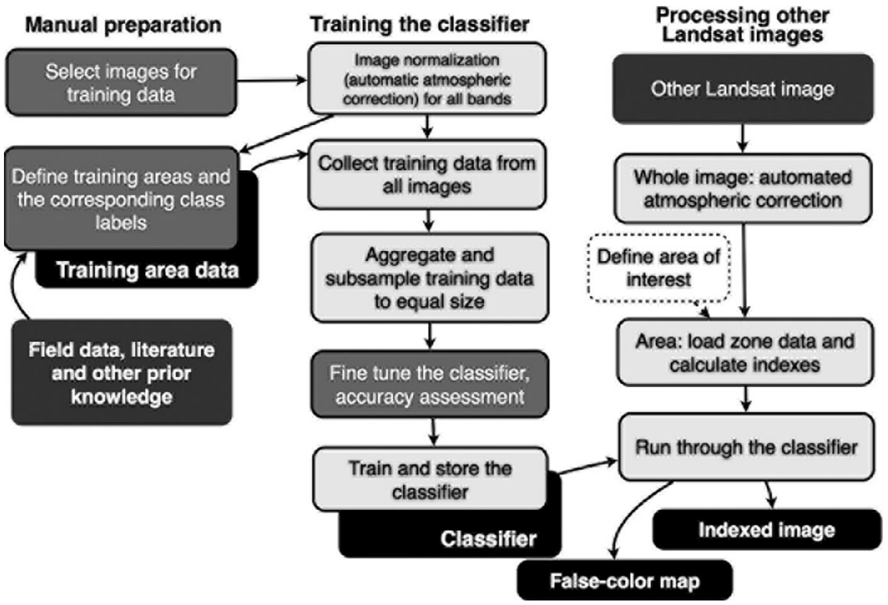

Fig. 2. The workflow chart of the automated processing and classification of Landsat data. Shades of grey indicate different types of user interaction with the system: light grey – fully automated processes, medium grey – manual processes, dark grey – input data and black – intermediate or final results.

This value was obtained empirically by processing a large number of images manually and minimising the difference between the manual and automated dark pixel value selection. The value is driven largely by the noise level in each of the bands. A manual mask is composed for each raw image and only pixels within the mask are considered for the dark pixel computation. This is done to eliminate noise at the edges of the sensor. The atmospheric correction protocol was proposed by Markham and Barker (1986) using parameters for calculating the Sun-Earth relationship by Iqbal (1983) and the dark pixel subtraction method by Chavez (1996). The atmospheric correction has been fully automated in this study with all the reference information extracted from image metadata.

Next, the training data are collected from all the normalised images and the following information is retrieved for all points in the training set: the reflectance values of bands 1–5 and 7, the value of the normalised burn ratio (NBR; Key and Benson 2006; Miller and Yool 2002; Brewer and others 2005), normalised difference vegetation index (NDVI; Singh 1989), snow index (Dozier 1984, 1989) and water index (Gao 1996). These data constitute a 10 dimensional data set used in the classifier.

We have originally defined 22 classes relevant to change detection in Fennoscandia and the Monchegorsk area in particular. The training data are collected from a large area based on our own field data and expert knowledge from Soviet digital military topographic maps of scale of 200,000, 100,000 and 50,000, GoogleEarth, vegetation maps, papers and project reports. The frequency of all the classes was equalised by randomly subsampling large classes to contain the same number of data points (500) and to have an equal probability to be predicted by chance.

We use support vector machines (SVM) classification provided by the R library e1071 (cran.r-project.org/web/packages/e1071), which is implemented using the libsvm library (Chang and Lin 2001). In a recent comparison of the SVM to 16 other methods, it was the only one that consistently scored within the top 3 on all test problems (Meyer and others 2003). The trained classifier is stored in the R library. From this moment on any number of images can be classified and mapped in a fully automated manner either in full or sliced to the area of interest.

The overall functionality has been implemented as two R libraries (‘gdal’ for image analysis, and ‘geo’ for atmospheric correction, classification and mapping) and a standalone R script that allows users to execute the overall analysis workflow.

Classifier accuracy assessment

The classifier accuracy was assessed in two complementary ways. Firstly, we have used the cross validation (McLachlan and others 2004) to fine tune the SVM and assess its overall accuracy. Any machine learning method needs to be fine tuned for the problem domain and the training set. In fine tuning one makes a decision on the optimal set of parameters that maximise the classification accuracy in cross validation. For the SVM, those parameters are the kernel function itself, the cost factor and the value of gamma (shared by all kernel functions considered in e1071). We have used the 10 fold cross validation in which random 10% of the training data are

Table 2. Class definitions and their abbreviations used to represent statistical information hereafter

Class	Class name
BG	background
I.1 Human impact or non-vegetated in forest zone	
I.1.1	Fire impact, severely and moderately burnt areas
I.1.2	Grazing impact, severely damaged areas with lichen cover <25% and stereocaulon domination and moderately damaged with cladonia domination
I.1.3	Air polluted with 40–60% of damaged trees and old burnt areas
I.1.4	Air polluted with 80–100% of damaged trees
I.1.5	Air polluted technogenic barren with 100% of dead trees
I.1.6	Non-vegetated: quarry, spoil heap, asphalt, residential and industrial areas
I.1.7	Industrial water
I.2 Human impact and non-vegetated in the tundra zone	
I.2.1	Air polluted, technogenic barren, no living tundra vegetation
II.1 Natural forest	
II.1.1	Coniferous forest
II.1.2	Deciduous forest
II.1.3	Wetland
II.2 Natural tundra	
II.2.1	Tundra vegetation
II.2.2	Stone tundra
III. Other	
III.1	Clouds
III.2	Snow
III.3	Clean water

left out to perform the validation (repeated a number of times). The optimal set for our training data was to use the Gaussian radial kernel (Buhmann 2003), the cost factor of 750 (default was 1) and gamma of 0.20 (default was 1 over the number of classes that is 0.05). This yielded the accuracy of 69% in the 10-fold cross validation over 22 classes. In the final results we have merged some of the classes so that the final set used in the analysis hereafter consisted of 16 classes. The full list of classes and their abbreviations are given in Table 2.

Secondly, we then used the land cover map generated for Landsat 5 TM (2005) sampling at least 30–50 points per class and using the majority of pixels in 3×3 window to assess the accuracy. This image was selected for two reasons. First, only a small fraction of the training data was obtained from this image and we could use other field data (not used in training the classifier) for validation. This allowed us to assess the accuracy of predicting data in images other than those used to train the classifier. Second, the forest valuation map of 2001 from the Monchegorsk Forestry Department has allowed us to collect control points for making a comparison.

Results and discussion

Environmental monitoring of land cover changes for 1986–2005

We have analysed the area of about 30×60 km^2 around the copper-nickel smelter Severonikel in Monchegorsk. For the period between 1986 and 2005 we have constructed a set of vegetation cover maps (Figures 3–6) using the classification method described and the data described in Table 1. A summary of land covers by the types of vegetation (natural and suffering from human impact) is given in Table 3.

Edges of clouds are often confused with non-vegetated areas. Nevertheless, thick clouds are detected correctly: for example, in Fig. 3 (year 1986) the level of cloudiness is 1.8%, in Fig. 4 (1988) - 1.2%, in Fig. 5 (2000) - 0.3% and Fig. 6 (2005) is cloud free. Clouds and misclassification of edge pixels due to sub-pixel alignment contribute further errors in the area under clean water, which is expected to be nearly constant over the study period. The corresponding variations of 1–2% are indicative of these further errors (on top of the detected classification errors) due to cloudiness, sub-pixel alignment etc.

Land cover changes: forest fires and the spread of technogenic barrens

Prior to the 1990s the smelter was using sulphur-rich ore, which led to a high level of sulphur dioxide pollution. Under their toxicity large areas of the boreal forest were turning dry. Later the smelter changed to local ore with a lower sulphur content and reduced its operational volumes. As discussed earlier, drying forest leads to fires, which we observe decreasing gradually from 2.2% in 1986 to 0.5% in 2005 due to a negative trend in the availability of flammable substance. Literature analysis confirms many dry forest fires in summer periods prior to 1986 (Rees and Williams 1997). Even though the change that we observe is small, a consistent monotonous reduction is not expected purely by chance. By 2005 many of these burnt areas had been partially restored by tundra vegetation, mostly grass and dwarf shrubs. For example, in Fig. 3 one can clearly see forest fires on the western side of Viteguba bay (area A), which turn into tundra vegetation by 2005 (area A in Fig. 6). Recent fires are likely to be caused by tourists and trespassers: more and more fresh burnt areas occur in easy-to-reach, undamaged coniferous forests next to roads, along the coastline and on the islands of lake Imandra (areas B in Figs. 5 and 6).

Similarly to the expansion of dry forest that contributed to fires in the 1990s, a sharp transition of moderately damaged forest (40–60% damaged) to technogenic barren can be attributed to the high volumes of toxic air pollution and the peak of the industrialisation in the 1980s that ended shortly after the collapse of the Soviet Union in 1991. During the period covered by the study the area of technogenic barren in the forest zone increased monotonously from 2.6% in 1986 to 5.4% in 2005. The

Table 3. Predicted land cover as percentage of the whole area analyzed for years 1986, 1988, 2000 and 2005

Class	Class Name	28 July 1986 area, %	11 July 1988 area, %	28 July 2000 area, %	9 July 2005 area, %
	I.1 Human impact or non-vegetated in the forest zone				
I.1.1	Fire impact, severely and moderately burnt areas	2.2	1.5	1.1	0.5
I.1.2	Grazing impact, severely damaged areas with lichen cover <25% and Stereocaulon domination and moderately damaged with Cladonia domination	0.0 (0.01)	0.1 (0.05)	0.0 (0.02)	0.0
I.1.3	Air polluted with 40–60% of damaged trees and old burnt areas	7.9	11.8	3.9	6.2
I.1.4	Air polluted with 80–100% of damaged trees	0.0	0.1	0.8	0.3
I.1.5	Air polluted technogenic barren with 100% of dead trees	2.6	3.5	3.6	5.4
I.1.6	Non-vegetated: quarry, spoil heap, asphalt, residential and industrial areas	4.7	3.8	3.5	3.1
I.1.7	Industrial water	0.2	0.3	0.4	0.1
	I.2 Human impact or non-vegetated in tundra				
I.2.1	Air polluted, technogenic barren, no living tundra vegetation	0.4	0.5	0.0 (0.01)	0.8
	II.1 Natural forest				
II.1.1	Coniferous forest	37.0	26.1	24.2	23.1
II.1.2	Deciduous forest	1.1	1.6	9.5	5.2
II.1.3	Wetland	10.9	14.9	17.7	17.9
	II.2 Natural tundra				
II.2.1	Tundra vegetation	1.8	5.1	6.1	7.9
II.2.2	Stone tundra	1.4	2.3	3.0	1.4
	III. Other				
III.1	Clouds	1.8	1.2	0.3	0.0
III.2	Snow	0.0	0.0	0.0	0.0
III.3	Clean water (lake, rivers)	28.1	27.4	26.1	27.9

area of technogenic barren in the mountain tundra zone increased in the same period from 0.4% to 0.8%. There is a fall in the detected technogenic barren area of the tundra zone for the year 2000, which is probably due to the class ambiguity with stone tundra. As seen in areas D of Figs. 5 and 6, the spread of technogenic barren since the end of the 1990s (after the peak of the industrialisation) is caused primarily by earlier fires, which had not yet recovered.

Using unsupervised classification of ISODATA from Landsat MSS and TM images acquired between 1978 and 1994, Solheim and others (1995) analysed an area of 6574 km^2 around Monchegorsk and detected a significant enlargement of areas of damaged vegetation. Their calculations suggest that the area of partly damaged vegetation increased from 6.3% in 1978 to 17.5% in 1994, the area of technogenic barren increased respectively from 4.0% to 11.5%. In order to allow some degree of quantitative comparison, the area under clean water needs to be normalised out of the results. The class of clean water constituted 15.0% of land cover in the work by Solheim and others (1995), which results in an increase of normalised values from 7.3% to 20.7% for the partly damaged vegetation and from 4.7% to 13.7% for technogenic barren (of the overall terrestrial area). After performing the same normalisation on our data, we see fluctuations of the partly damaged vegetation at the level of 17.1±3.4% and an increase in technogenic barren from 4.1% to 8.2% (of the overall terrestrial area). These values agree well with the results by Solheim and others (1995) both qualitatively and quantitatively.

Land cover changes: forest logging and the spread of wetland

We know from field data that there were large areas affected by forest logging prior to 1986 in the area of Monchegorsk. In the climate conditions of the Kola peninsula, fresh logging often leads to a spread of wetland. These can be clearly seen in the area C1 of Fig. 3. In the following years this area was restored by deciduous forest. This is a common restoration pattern in the areas affected by logging: the first stage is wetland that potentially transforms to deciduous forest later. The old logging areas can only be detected as deciduous

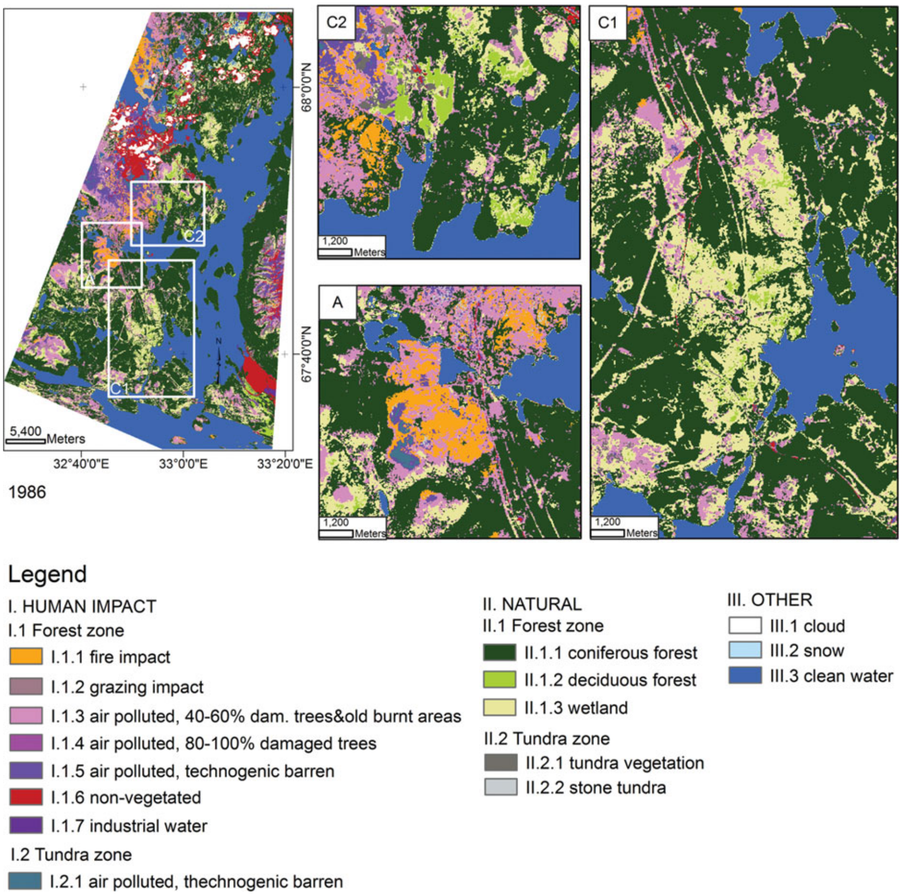

Fig. 3. Generated land cover map for the area of Monchegorsk in 1986.

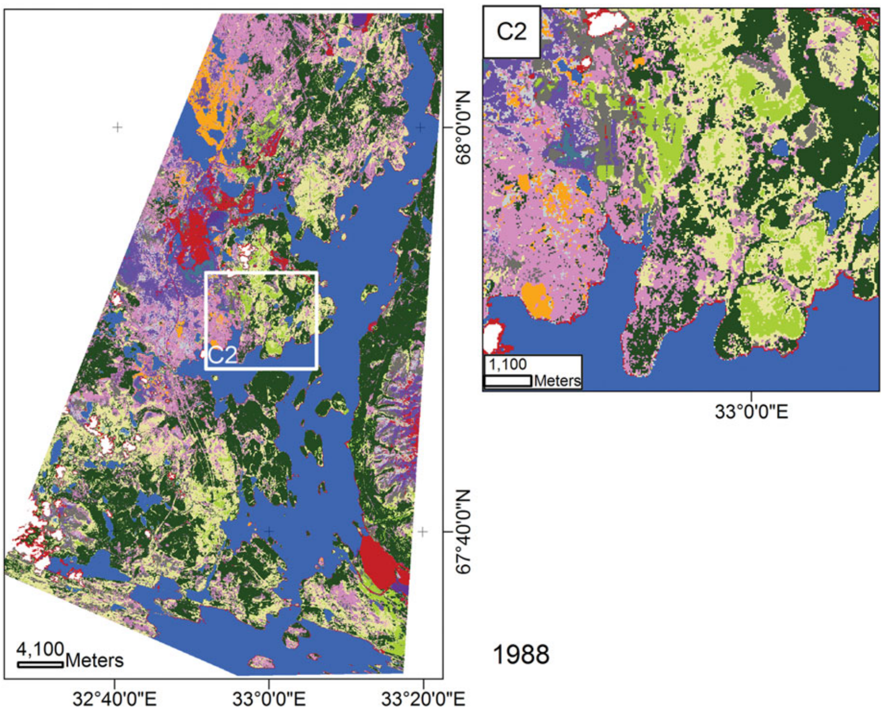

Fig. 4. Generated land cover map for the area of Monchegorsk in 1988.

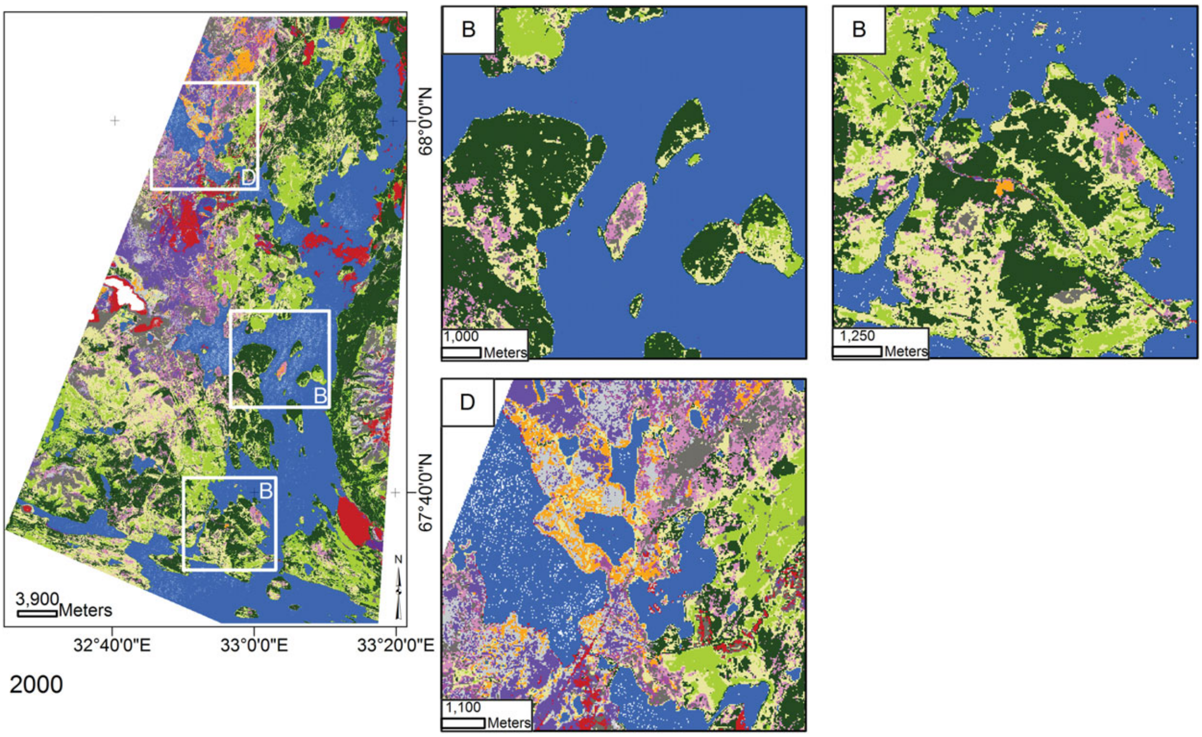

Fig. 5. Generated land cover map for the area of Monchegorsk in 2000.

forests, mostly birch and willow, which are not typical for the area. The only indicator of logging in the past are the straight lines of the edges of deciduous forests. Further areas covered in grass, birch and willow can be seen in the areas C2 of Figs. 3 and 4. Here it is known that the cutting was carried out in Soviet times to open areas for agricultural use by Collective Farm Verhniy Nued. Currently, logging is used primarily to clear off areas for residential development southeast of Monchegorsk. Primarily due to logging, the overall wetland area had increased from 10.9% in 1986 to 17.9% in 2005.

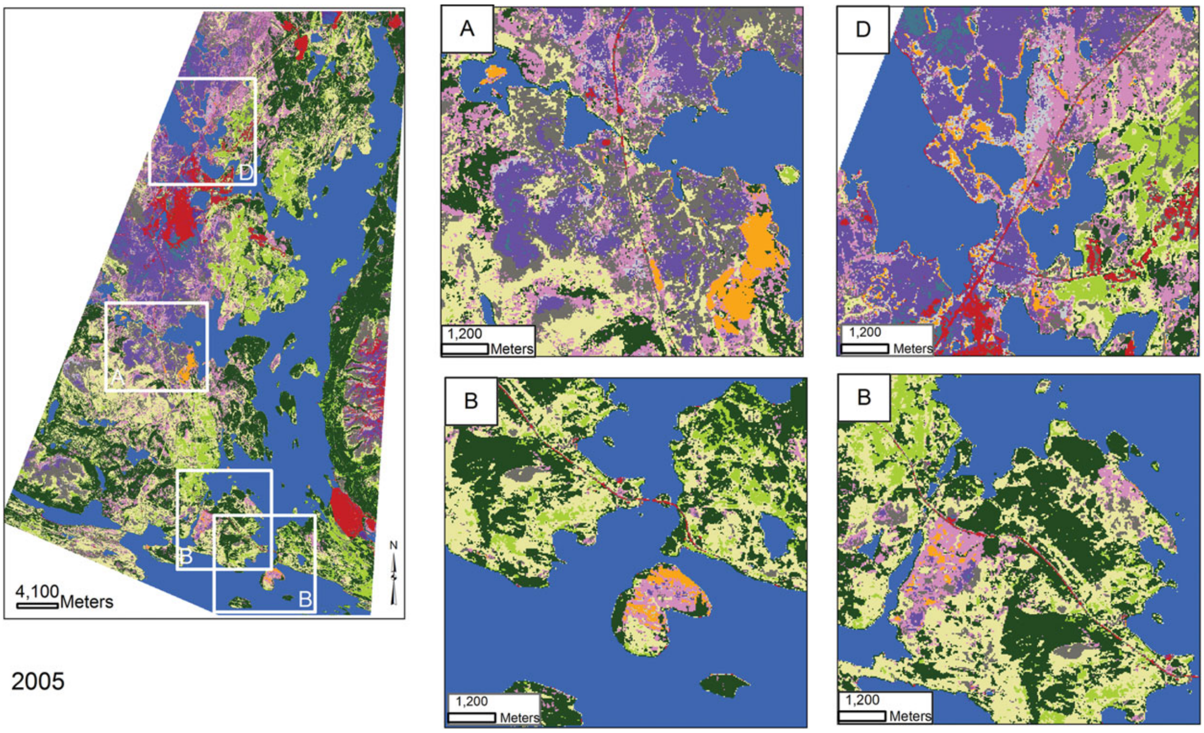

Fig. 6. Generated land cover map for the area of Monchegorsk in 2005.

Table 4. The trend in the total vegetated area

Class	Class name	28 July 1986 area, %	11 July 1988 area, %	28 July 2000 area, %	9 July 2005 area, %
II.1.1	Coniferous forest	37.0	26.1	24.2	23.1
II.1.2	Deciduous forest	1.1	1.6	9.5	5.2
II.1.3	Wetland	10.9	14.9	17.7	17.9
II.2.1	Tundra vegetation	1.8	5.1	6.1	7.9
Total	Total vegetated	50.8	47.7	57.5	54.1

Land cover changes: vegetation restoration and the decay of coniferous forest

The restoration of the boreal forest damaged by air pollution occurred between 1986 and 2005 primarily by typical tundra species. These are less sensitive to changes in air conditions, but are more sensitive to changes in soil (moisture, nutrition components and other). This is why the tundra had spread from 1.8% in 1986 to 8.0% in 2005. As indicated above, areas affected by logging restore to wetland first followed by deciduous forest. At the same time as the area of wetland increased to 17.9%, the area of deciduous forest increased from 1.1% in 1986 to 5.2% in 2005. Even though both processes are effectively restoring the vegetation, the vegetation had never restored to its initial state, coniferous forest, pine and spruce. Naturally, deciduous trees grow along rivers or in mountain regions between the typical tundra and forest zones. However, due to human impact more and more coniferous forest is converted to deciduous forest. In line with the change in the wetland, tundra and deciduous forest cover by a total of 17.0% (of the land cover), the cover for coniferous forest had decreased by a total of 14.0% (of the land cover), namely, from 37.0% in 1986 to 23.1% in 2005. This means that more than a third of all boreal forest had been destroyed in the area during the 19 years covered by this study as a result of human activity.

At the same time, our results are in places more optimistic then the previous study of the same area by Rees and Williams (1997). The authors have used hybrid (unsupervised/supervised) classification of Landsat MSS images from 1978–1992 and have detected an increase in damaged vegetation on the total area of 22225 km^2. Their data suggest that the area under severely damaged forest (71–97% damaged) stayed around 4.4 ± 0.4% and the area under partly damaged forest (31–71% damaged in the authors' definition) increased from 19.2% in 1980 to 38.0% in 1992, both contributing to the decrease of the healthy and lightly damaged forest (11–30% damaged) from 51.2% in 1980 to 36% in 1992. Our results have been obtained for a smaller territory, in a close proximity of the smelter and with a greater part covered by water, yet they indicate that by 1988 healthy forest (both coniferous and deciduous) had constituted at least 27% of the land cover around Monchegorsk while the three classes of damaged forest and technogenic barren together did not exceeded 15% of the land cover. Further 20% were covered with tundra vegetation and wetland. Areas farther from the smelter should show even better ratios of healthy to damaged vegetation.

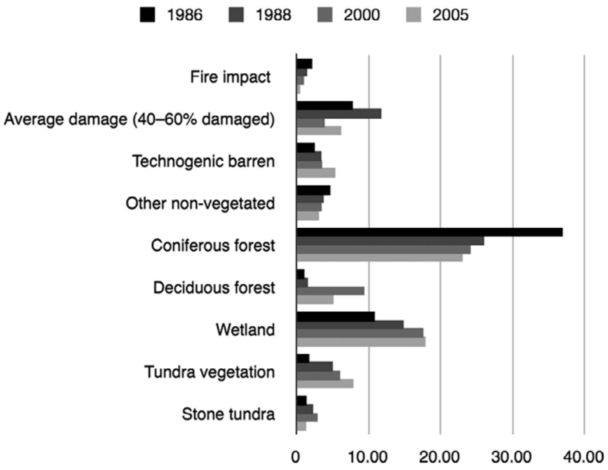

Fig. 7. Diagram of trends in land cover changes between 1986 and 2005 (classes with small and relatively constant land cover omitted)

Table 4 sums up the trend in the total area covered by vegetation from 1986 to 2005. There is a positive change of 5% in vegetation cover restored in a decade between the end of 1980s and the beginning of 2000s. Furthermore, Fig. 7 displays the trends discussed above in a single bar plot. There are visible trends across most of the classes. These support the transformation of coniferous forest to deciduous forest, tundra vegetation and wetland discussed above.

In contrast to many previous studies, our method allows to study the damage to vegetation both, by type and severity of the damage: each class describing any type of damage can be further separated into subclasses by levels. Applying this extended set of classes is beyond the scope of this publication.

Assessment of the method and the maps

The overall accuracy of the 16-class land-cover map was estimated at 74.1% and the overall Kappa statistics at 70.6%. This is a good result for the number of classes and considering that the majority of training data was coming from other images. It proves that, firstly, the atmospheric correction provides a good normalisation of data and, secondly, a single classifier approach is viable. As discussed earlier grazing is not characteristic for the study area: we neither identified it in the data nor obtained any false positives in the classification results.

Table 5. Confusion matrix between reference (columns) and predicted (rows) classes along with producer's and user's accuracies

	BG	I.1.1	I.1.2	I.1.3	I.1.4	I.1.5	I.1.6	I.1.7	I.2.1	II.1.1	II.1.2	II.1.3	II.2.1	II.2.2	III.1	III.2	III.3	Total	prod, %	user, %
BG	9																	**9**	100.0	100.0
I.1.1		126		20	2	17	1					8	5	2				**181**	98.4	69.6
I.1.2			0															**0**		
I.1.3		2		199	2	8			3	8	1	28	14					**265**	84.3	75.1
I.1.4				3	23	4												**30**	82.1	76.7
I.1.5				1		33			4					5				**43**	29.7	76.7
I.1.6				1		4	45		8			1	2	10				**71**	72.6	63.4
I.1.7								47									3	**50**	100.0	94.0
I.2.1						16	1		14				1					**32**	48.3	43.8
II.1.1										53		1						**54**	84.1	98.2
II.1.2											37							**37**	92.5	100.0
II.1.3				1						2	2	52	3					**60**	54.7	86.7
II.2.1						2	9					4	25					**40**	50.0	62.5
II.2.2				11	1	27	6					1		17				**63**	50.0	27.0
III.1															0			**0**		
III.2																0		**0**		
III.3																	50	**50**	100.0	100.0
Total	**9**	**128**	**0**	**236**	**28**	**111**	**62**	**47**	**29**	**63**	**40**	**95**	**50**	**34**	**0**	**0**	**53**	**935**		

Equally, the image used for accuracy assessment was snow and cloud free, which is reflected by zeros next to the corresponding classes (Table 5). In spite of the overall good accuracy, accuracy of individual classes varies. The producer's accuracies for individual classes vary from 29.7% for I.1.5 to 100.0% for I.1.7 (Table 5). The user's accuracies show generally the same level of variation. Most confusion arises between II.2.2 (natural stone tundra) and I.1.5 (technogenic barren) in which nearly half of technogenic barren is classified as natural stone tundra. This is not surprising as there is little difference in the spectral reflectance (and appearance) of these two classes. Another example worth mentioning is the I.1.3 class (area of a moderate impact). It is a dominating class in the area and contains very few false negatives (objects of this class identified as something else), however, it has a high false positive rate: about one third of II.1.3 (wetland) is identified as area under a moderate damage. This is primarily because this class is an aggregator class, which puts together different elements of human impact each yielding a moderate damage. Other classes show relatively little confusion between them.

The accuracy assessment shows that the current advanced method is reasonably accurate overall and demonstrates good accuracy for the majority of individual classes. However, in some cases, in which the training data are spectrally inseparable or not homogeneous, improving accuracy requires extra data. Going ahead we will consider introducing the digital elevation model (DEM) into the classifier for a better separation of tundra and forest zones, and minimizing the confusion between technogenic barren and stone tundra.

Conclusions

We have examined all major types of human impact on the boreal vegetation characteristic for the highly industrial area of Monchegorsk in Kola peninsula, Russia. The change detection analysis has been performed for the period of 1986–2005 by applying a novel method of automated classification and mapping of human impact on the vegetation. We have developed a novel method for an automated analysis and mapping of vegetation and of all types of human impact based on a single support-vector-machines classifier. We used Landsat TM and ETM+ band data (for which the method automatically performs atmospheric correction) and a number of indices like NDVI, NBR to generate land cover maps for 1986, 1988, 2000 and 2005. We then performed both qualitative and quantitative assessments of the land cover over the region of 1750 km^2.

The spatial distribution of the damaged areas shows a clear dependence on the local topographical and meteorological conditions. The pronounced spread of industrial atmospheric pollution towards northwest from the Severonikel smelter lies along the dominant wind directions and is blocked on the southern side by mountain barriers. The extent of the damage sees to pass the peak of industrialisation in the 1980s. Old fires are primarily found in dry forests caused by industrial atmospheric pollution and their frequency has been declining over the years. New fires can be related to tourism and can be found along roads and in areas popular among tourists. The restoration of areas damaged by fires of by industrial atmospheric pollutions directly occurs frequently through a creation of wetlands or tundra vegetation depending on the area. Old logging areas of coniferous forest regenerate primarily to birch and willow which are not characteristic for this boreal forest area. Our results indicate that the land cover of coniferous forest decreased from 37% in 1986 to 23.1% in 2005 in the study area. This means that more than one third of all coniferous forest was destroyed (or partially converted to deciduous forest) within the 19 years that this study covers.

The success of the method in the area of Monchegorsk opens the possibility of follow up studies using the same technique on the whole of Fennoscandia. This will allow us to investigate the relation between local human impact on vegetation and global changes in the environment.

Acknowledgements

The Landsat images are courtesy to Earth Explorer at the U. S. Geological Survey. The research was performed as a part of the first author's dissertation financially supported by Trinity College, Cambridge and the Overseas Trust, Cambridge. Extra field data for the area were collected with support of the Moscow State University and personally Professor Elena Golubeva and Dr Olga Tutubalina (both at the Faculty of Geography) and Mr Sergey Konyaev at the Hibiny Field Station on Kola peninsula, Russia. The authors are most grateful to Bernt Johansen from the Northern Research Institute in Tromsø for his time reviewing this paper and making extremely useful suggestions, comments and corrections.

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