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Classification of Current Vegetation Cover and Alpine Treeline Ecotone in the Praděd Reserve (Czech Republic), Using Remote Sensing

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The goal of the study was to derive up-to-date and complex information on the current vegetation cover of the Praděd Reserve (Hrubý Jeseník Mountains, Czech Republic), with special regard to the unique alpine treeline ecotone formed by krummholz of Norway spruce. We argue that the data of remote sensing and automated techniques of image processing should be preferably used. Accordingly, a color-infrared orthophoto map was classified in a land cover map employing maximum likelihood spectral classifier, ancillary data, texture analysis, and a knowledge base classification technique. The overall classification accuracy was about 78%, distinguishing 7 land cover classes. Using a reclassified land cover map and the moving window mean filter, a spruce canopy closure map was calculated. The continuous map of the canopy closure was subsequently reclassified in predefined intervals that were used for an automated delimitation and mapping of complex transitional borders of the alpine treeline ecotone. The proposed method can serve for objectified mapping of gradual transitions between any land cover or vegetation classes.

Keywords: *Alpine treeline ecotone; boundary detection; canopy mapping; classification; remote sensing; timberline; Czech Republic.*

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Introduction

The Praděd National Nature Reserve (further referred to as "the reserve") is one of the few localities in the Czech Republic that reach the alpine treeline ecotone (ATE). The ATE in the Hrubý Jeseník Mountains is naturally formed by open dissolving stands of dwarf Norway spruce (krummholz zone), without natural occurrence of dwarf pine (Jeník 1973). However, this unique site suffers from both historical and current human impact. The intensive historical use of the summit part of the reserve—mainly through overgrazing in the 18th and 19th centuries (Hošek 1973)—led to degradation and water erosion (Kirchner 2004). At the end of the 19th and beginning of the 20th centuries the area was afforested with allochthonous dwarf pine. Today, the allochthonous stands of dwarf pine are propagating into valuable alpine grasslands and into the unique Norway spruce krummholz zone. Therefore, the dwarf pine stands are at present mostly regarded as undesirable.

Nowadays the reserve is endangered by massive recreational activity both in summer and in winter, in particular by alpine skiing (Buček and Maděra 2004). Apart from the direct anthropogenic formations developing during the construction of various objects (residential and recreational facilities, landfills, dumps, impact of heavy machines on ski pistes), human impact also shows in disturbed vegetation along tourist trails and in accelerated water erosion (Kirchner 2004).

The goal of the whole study was to derive up-to-date and complex information on the current vegetation cover of the reserve, including determination of allochthonous dwarf pine stands and anthropogenic formations within the ATE. With regard to its limited extent, this article focuses in particular on the delimitation of alpine grasslands and treeline ecotone.

Studies of ATE have become very popular recently in connection with the ongoing debate on climate change. The ATE is believed to be a sensitive indicator of climate change and the response of vegetation to climate change (eg Baker et al 1995; Kupfer and Cairns 1996; Kimball and Weihrauch 2000). The data and techniques of remote sensing (RS) have been widely used to study ATE, due particularly to their major advantages in obtaining a synoptic overview and completeness of data. RS makes it possible to record an entire study area, and thus continuous transitions and transitional borders can be studied with more complexity. Various data sources have been used for mapping mountainous vegetation communities of ATE, including both conventional and digital aerial photography (Baker et al 1995; Butler et al 2003; Walsh et al 2003; Resler et al 2004). With regard to mapping techniques, time-consuming human interpretation in combination with ground-truthing is still one of the basic methods used (eg Kimball and Weihrauch 2000). In the Hrubý Jeseník Mountains the traditional field-mapping approach was recently used by Treml and Banaš (2000). However, boundaries of vegetation communities derived by photo interpretation do contain more human subjectivity than is the case when more objective ecotone identification algorithms are used (Baker et al 1995). A wide range of automated methods to detect and characterize boundaries, including image processing techniques, were presented for example by Fortin et al (2000) and Fagan et al (2003).

On the other hand, the standard automated image classification techniques have proved to have considerable drawbacks with regard to clustering information effectively (Mather 1999). Numerous authors agree that spectral information alone is not sufficient for extracting land cover data (eg Joria and Jorgenson 1996; Shrestha and Zinck 2001). A logical and currently widely used solution is the incorporation of ancillary data in the classification process. Ancillary information layers can be added to the original image as additional bands and can be classified simultaneously with spectral information (Avery and Berlin 1992). A different approach suggests first to carry out the classification of multispectral data and subsequently to use ancillary layers in postclassification sorting in order to reduce misclassifications. This approach is also called expert (system) classifier, rule-based classification, modeled classification, or knowledge base classification (Joria and Jorgenson 1996; Kontoes and Rokos 1996; Král 2003). One of the sources of additional information for correct image classification can be an image texture (Hudak and Wessman 1998; Resler et al 2004).

This study attempted to find a more objective and effective way of ATE mapping, employing automated techniques of image processing including texture analyses, knowledge-base classification, and image filtering and thresholding.

Material and methods

Study area

Forming the central part of the Hrubý Jeseník Mountains, the Praděd reserve, with the highest mountain in Moravia and Silesia (Praděd, 1491 m), occupies areas of highest altitudinal vegetation zones, of which occurrence in the Czech Republic is rare. The geographical coordinates of the approximate center of the study area are 50°04′N and 17°14′E. The summit parts of mountain ridges and hilltops are dominated by alpine grasslands, gradually passing into a unique belt of timberline formed by dwarf Norway spruce (krummholz zone of *Picea abies*), without natural occurrence of dwarf pine (*Pinus mugo*); this species was introduced in the area during afforestations in the late 19th and early 20th centuries (Jeník 1973; Hošek 1973). In the lower parts of the reserve, mountain spruce forests are the predominant forest type.

Data used

A seamless color-infrared (CIR) orthophoto map acquired on 21 August 2000 was used as the source of RS data. The 12 partial scenes of the area in question were merged by mosaicking, and the image spatial resolution was resampled to 0.9 m. The shape file of contour lines was used to develop a digital elevation model (DEM), with a spatial resolution of 8 m for easier automated extraction of data during the assessment of results. For the same purpose the vector layer of the reserve boundary was used.

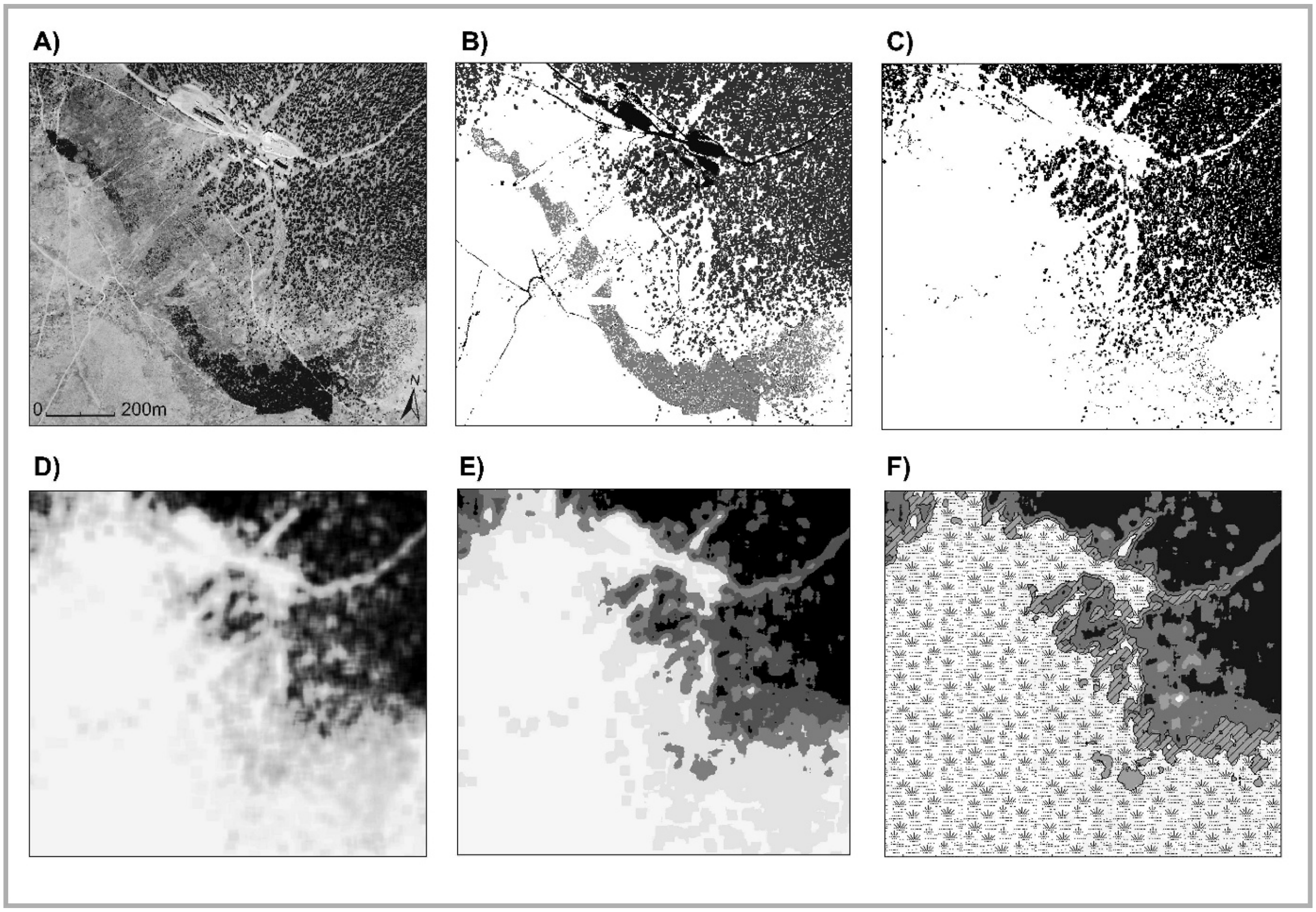
Land cover classification

The basic method to process the CIR orthophoto map (Figure 1A) was that of supervised classification with the maximum likelihood classifier. Due to the high spectral variability of particular real surface classes and rather low spectral resolution of CIR photographs, the land cover classes coming from the maximum likelihood classification often were of a somewhat mixed character; textural analysis was therefore required. A variable used was the standard deviation of digital number (DN) values of pixels inside a square moving window of 7×7 pixels for all 3 (G, R, NIR) digital image bands. The size of the focal filter was determined empirically after examination of various sizes. The goal of this analysis was to discern surfaces 'overgrown with spruce' from surfaces 'without spruce' by means of image texture. Values of the resulting layer were therefore classified into these 2 respective classes.

Even by means of the texture, some surface types could not be distinguished by automated operations from other classes of similar spectral characteristics. The elements of these surface types (more precisely the raw-drawn areas of their occurrence) had to be digitized manually. This applied particularly to the anthropogenic surfaces, where roads and buildings could not be separated from debris and rocks and dry spruce standing trees.

The 3 above-described data layers with 3 different types of information (maximum likelihood classification, carrying the radiometric information; classified standard deviation of the 7×7 pixel moving window, carrying the information on texture; the vector layer, carrying the information on a priori assumed occurrence of objects) were integrated into a thematic map by means of knowledge-base classification. A set of rules was developed for this purpose that combined the above-mentioned input data in a thematic map using conditional ("IF," "THEN") and logical ("AND," "OR")

FIGURE 1 Processing of the image data (viewport). (A) Input CIR orthophoto map; (B) land cover classification; (C) reclassification into 2 classes: spruce canopies and other classes; (D) calculated spruce canopy closure by the focal mean filter; (E) spruce canopy closure reclassified into 5 intervals; (F) delimited patch of alpine grassland (grass symbol) and continuous belt of alpine treeline ecotone (hatch).



operators. The resulting map with 7 thematic classes (Figure 1B) represents one of the results of this study. The layer was also used as input for further processing.

The accuracy of the resulting map was checked by comparison with a set of 900 reference points in which the "true" thematic class was determined by visual photo-interpretation of the CIR orthophoto map. A confusion matrix was constructed, and basic accuracy measures such as overall accuracy as well as user's and producer's accuracy of individual thematic classes were calculated (Congalton 1991; Nilsson 1998).

Spruce crown canopy calculation and mapping

The result of the land cover classification was reclassified into 2 classes as follows: spruce canopy class (assigned pixel value DN = 1) and all other classes (assigned pixel value DN = 0) (Figure 1C). After due consideration, the area for canopy calculation was set up to be about 1000 m^2, which roughly corresponds to a moving window of 35 × 35 pixels of a pixel size of 0.9 m. The moving window (image filter) scans the input raster layer by both lines and columns, shifting by 1 pixel at a time and calculating an arithmetic mean of pixel values contained in the window. The obtained value is assigned to the appropriate central pixel of the window in the new raster layer. The result is a raster (spatial resolution 0.9 m) of real numbers occurring within an interval of $<0.1>$. Multiplied by the value 100, every number directly corresponds to the gross percentage of local canopy closure in a 1000 m^2 surrounding (Figure 1D). For purposes of the study, the values were arranged into 5 classes (Figure 1E).

Delimitation of alpine grasslands and treeline ecotone

The possibility of a simple delimitation of the alpine grasslands and the belts of the treeline ecotone emerged during the conversion of the grid layer of 5 spruce canopy classes into vector form, which gave rise to separate

TABLE 1 Crown canopy closure–based differentiation of spruce growth in the Praděd reserve.

No	Spruce canopy closure class	Canopy (%)	Area (ha)	Area (%)	Altitude (masl) Max	Min	Mean	Range (m)
1	No trees	0–1	331.7	16.0	1491	848	1398	643
2	Emergent trees	1–25	303.1	14.7	1478	842	1348	636
3	Groups of trees	26–50	215.2	10.4	1447	840	1311	607
4	Open-canopy forest	51–75	396.5	19.2	1434	839	1272	595
5	Closed-canopy forest	76–100	820.7	39.7	1430	836	1238	594
	Reserve TOTAL	0–100	2067.2	100.0	1491	836	1290	655

polygons demarcating areas with a certain degree of spruce canopy closure. Alpine grasslands were thus for the purpose of this study defined as the continuous hilltop areas (polygons) of the 2 lowest spruce canopy classes, ie those with a spruce crown coverage of 0–25% (see Table 1). In other words, alpine grasslands refer to a single (the largest) treeless patch above the ATE. The ATE was hence defined as a polygon (continuous belt of variable width) with a spruce canopy closure of 26–50%, neighboring with alpine grassland on one side and with an open-canopy forest on the other side (Figure 1F). This perception differs slightly from the generally accepted definition of treeline ecotone (eg Körner and Paulsen 2004), which is rather broader and would include also the second spruce canopy-closure class (ie 1–25%). Correspondingly, in our approach the timberline would be delineated as the "lower" edge of the ATE situated next to the open-canopy forest.

Results

Current vegetation cover

The actual state of vegetation in the Praděd reserve was presented in the form of a land cover map, illustrated in Figure 1B. Seven land cover classes were distinguished (Table 2). Two of these cover almost 95% of the reserve: grasslands and gaps (870 ha) and spruce canopies (1083 ha).

Reliability of the map was verified by means of a confusion matrix. Data on the actual occurrence of the thematic classes at reference points are presented in columns, while respective data originating from the classification (map) are presented in rows. The main diagonal in Table 2 represents the correctly classified pixels of the digital map. The overall accuracy of the map (78%) was computed as a quotient of the total number of correctly classified points (sum of the diagonal) and the total number of reference points.

From the viewpoint of ATE mapping, the accuracy of discrimination of spruce canopies was of particular interest; misclassifications among the other classes were not so important, as they would be merged in 1 class before the calculation of the spruce canopy closure. Table 2 shows some mixing with grasslands and gaps, indicating a slight overestimation of the spruce canopy area.

Crown canopy–based spruce forest differentiation and mapping

Areas and characteristic altitudes of occurrence of spruce canopy–closure classes are presented in Table 1. Areas considered to be forest are those with a minimum canopy closure of 50% (on an area of 1000 m^2). Most interesting are data on the maximum and mean altitudes of occurrence of individual classes, where all maxima were measured on Praděd Mountain, particularly on its milder western slope. Very low minimum occurrence altitudes in the classes of low spruce canopy closure (up to 50%) are affected by human activities such as deforestation on clear-felled and built-up areas.

Mapping of alpine grasslands and treeline ecotone

Table 3 presents data on the occurrence altitudes of alpine grassland and treeline ecotone including the maximum, minimum, and mean elevation of the occurrence and appropriate area. The belt of the ATE in the Praděd reserve reaches a maximum elevation of about 1440 m asl. The maximum altitude of timberline is then 1434 m asl, relating to the maximum occurrence altitude of open-canopy forest (Table 1). Both maxima were measured on Praděd Mountain, more precisely on its milder western slope.

Discussion

Classification and texture analysis

The achieved overall classification accuracy of 78% can be considered satisfactory taking into account the number of distinguished classes (7) and type of RS data used (CIR aerial photographs). The analysis of texture and

TABLE 2 Confusion matrix confronting the resulting map with the network of random reference points, containing basic indicators of the map accuracy.

Land cover class	Reference data (reality)						
Classification data	Anthro-pogenic surfaces	Grass-lands and gaps	Dwarf pine	Broad-leaves	Spruce canopies	Standing dead spruce trees	Debris and rock outcrops
Anthropogenic surfaces	19	0	0	0	0	0	0
Grasslands and gaps	3	262	12	16	45	2	2
Dwarf pine	0	5	56	0	3	0	0
Broadleaves	0	1	0	25	0	0	0
Spruce canopies	1	94	5	7	321	0	1
Standing dead spruce trees	0	1	0	0	1	9	0
Debris and rock outcrops	0	0	0	0	0	0	8
Reference TOTALS	**23**	**364**	**73**	**48**	**370**	**11**	**11**

TABLE 2 Continued.

Land cover class		Accuracy indicators	
Classification data	Classification TOTALS	User's accuracy	Producer's accuracy
Anthropogenic surfaces	**19**	100.0%	82.6%
Grasslands and gaps	**342**	76.6%	72.0%
Dwarf pine	**64**	87.5%	76.7%
Broadleaves	**26**	96.2%	52.1%
Spruce canopies	**429**	74.8%	86.8%
Standing dead spruce trees	**11**	81.8%	81.8%
Debris and rock outcrops	**8**	100.0%	72.7%
Reference TOTALS	**900**	**Overall accuracy: 77.8%**	

the knowledge-base classification considerably improved the classification accuracy and increased the number of discernible classes.

During texture analysis the alternative window sizes of 21 × 21 and 11 × 11 pixels were tested for separation of the spruce area. Although the surface overgrown with spruce could be very well discerned by using these filter sizes, the level of detail was unsatisfactory. The filter size of 7 × 7 pixels (at a pixel size of 0.9 m) represents a compromise between the level of detail and the resolution capacity of the standard deviation variable for the separation of spruce. However, this texture variable, designed for distinction of small separated spruce crowns, fails to identify spreading and merging crowns of beech; as a consequence, these were mapped with the lowest accuracy. Scale and class sensitivity of

TABLE 3 Comparison of the continuous enclaves of alpine grassland and treeline ecotone and their characteristic altitudes of occurrence.

Vegetation type	Locality (name)	Altitude (masl)				Area (ha)
		Max	Min	Mean	Range (m)	
Alpine grassland (continuous patches)	Malý děd	1364	1267	1337	97	17.6
	Praděd	1491	1248	1417	243	107.5
	Vysoká hole–Jelení hřbet	1462	1111	1373	351	458.5
	Alpine grassland TOTAL	**1491**	**1111**	**1380**	**380**	**583.6**
Treeline ecotone (continuous belts)	Malý děd	1368	1259	1343	109	27.5
	Praděd	1441	1247	1370	194	59.3
	Vysoká hole–Jelení hřbet	1408	1107	1308	301	59.3
	Treeline ecotone TOTAL	**1441**	**1107**	**1339**	**334**	**146.1**

textural information was also found by Resler et al (2004).

Comparing other classification results with those achieved by Resler et al (2004), the overall classification accuracy rates are similar (about 83% distinguishing 4 classes: tundra/bare, alpine meadow, open canopy/krummholz, closed canopy forest). However, it is evident that the classification approaches taken are rather different. While Resler et al (2004) directly distinguished the 2 classes of forest according to the canopy closure, we separated first the class of pure spruce canopies and subsequently calculated actual canopy closure in an extra layer. The accuracy of this layer fully depends on the accuracy of input classification.

Mapping alpine treeline ecotone

According to the above analysis, the timberline in the Praděd reserve reaches a maximum elevation of about 1434 m asl. This finding does not seem to be in good agreement with results presented by Treml and Banaš (2000), who mapped the alpine timberline combining field survey and manual photo interpretation and who claim that the maximum elevation of the alpine timberline in the Praděd reserve is at 1405 m asl on the northwestern slope of Praděd. This disagreement may be explained by nonuniform criteria of mapping. Although both studies use the 50% canopy closure of spruce trees as a threshold between forest and trees outside the forest (above timberline), the new approach neglects the criterion of minimum tree height (5 m) that was employed in the earlier study. On the other hand, subjectivity influencing the placement of the borderline in human identification might also play a role.

Table 3 also shows the mean altitudes of occurrence. The mean values, easily calculated from the DEM, may represent a better variable for future comparisons. In contrast to extreme (minimum/maximum) values, they are based on the total area of the ecotone and therefore should be less sensitive to errors possibly included in treeline or timberline delineation.

The advantage of the new method is the possibility of setting the size of the mapping grain (moving window) individually according to the user's needs, as well as the possibility of producing the map of canopy density with a continuous range of values that can be subsequently classified in arbitrary intervals. The technique based on image filtering advantageously combines the fine spatial resolution and wider context information, ie the spatial resolution of the input layer is preserved while containing information about local surroundings (in our case 1000 m^2). This method, suitable for in-depth investigation of ATE, is not restricted only to canopy-closure calculation, but can also be applied for mapping of various complex transitional borders between 2 land cover or vegetation classes. Therefore, one might call it an "objectified ecotone identification algorithm." This instrument can ensure replicability of results and, consequently, more objective multitemporal analyses and change detection.

The proposed method can complement the boundary detection techniques reviewed by Fortin et al (2000) and Fagan et al (2003). Although they listed several approaches based on moving windows (so-called kernel approaches), this was mostly a question of image enhancement algorithms that use filters (moving windows of typically 2 × 2 or 3 × 3 pixels) to highlight edges by showing the presence of the highest rate of change between adjacent pixels. Our approach, based on a focal mean filter of the binary raster (typically coming from reclassified data of remote sensors), calculates the mean proportion of a certain class in a predefined surrounding area. As it does not compare adjacent pixels but rather evaluates a broader spatial context (in our case the window size was 35 × 35 pixels), the method is particularly convenient for mapping gradual transitions.

Conclusions

A new method of automated ATE identification from RS data was proposed and tested in the Praděd reserve. The method makes use of image processing techniques including knowledge-base classification, image filtering, thresholding, and raster/vector conversion. Based on a broader spatial context compared with other common boundary detection techniques, this approach is particularly suitable for mapping gradual transitions and complex or patchy ecotones.

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