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Use of digital aerial photography for sub-alpine vegetation mapping: A case study from the Krkonoše Mts., Czech Republic

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Abstract

Multispectral aerial photographs from 1986, 1989 and 1997 were used for mapping and assessment of changes in sub-alpine vegetation of the Krkonoše Mts Plateau (1300 to 1400 m a. s. l.), Czech Republic. Scanned aerial photographs were digitally processed by various remote sensing methods, such as histogram equalization, principal component transformation, Normalised Difference Vegetation Index, and classification (both unsupervised, i.e., Iterative Self-Organizing Data Analysis Technique, and supervised, i.e., Parallelepiped and Maximum Likelihood algorithm). The results were geometrically corrected by registration into orthophoto images. Field data from 1991 assisted in class labelling and vegetation description. A detailed vegetation analysis was conducted using 1989 multispectral photographs since the field-verification and comparison to ground-based vegetation map could be done with only two-year difference. The unsupervised classification resulted in six classes (three of them mixed) with a 60.6% overall accuracy of unmixed classes. Some important vegetation types could not be separated. The supervised classification resulted in nine classes with the overall accuracy of 81.1%. The most common vegetation types were: mat-grass communities (40.4% of the total area) and tall grass and herb communities (23.1%). Pine stands, the best separated of vegetation types, were evaluated on the multispectral photographs from 1986 and 1997 and the *P. mugo* stands doubled in area over 10 years. The aerial-photograph based maps were compared with an available vegetation map obtained by a field survey. The correspondence between both ranged from $24 - 75\%$, with the highest values obtained for pine stands and mat-grass communities. In comparison to the field survey, aerial photography provided less detail and vegetation was characterized mostly by dominant species. The approach failed to map small patches of heterogeneous or atypical vegetation and to differentiate vegetation types with dominants of similar appearance. Nevertheless since this method is comparably less time- and labour-consuming, it seems suitable for mapping distinct vegetation types, surveying larger areas and identifying changes over time.

Introduction

Traditional field methods of vegetation mapping (according to the Braun-Blanquet floristic approach, Braun-Blanquet 1965) provide with a possibility to describe vegetation in a large detail but are time/labour intensive and are biased by the subjectivity of the interpreter (Congalton 1991). Remote sensing (RS) can partly eliminate these problems but the nature of resulting information differs (Mosbech and Hansen 1994). Instead of focusing on community structure and floristic composition, RS is based on dominant species, their biomass (i.e., chlorophyll content and leaf area), water content, physiognomy (e.g., height of plants, width of leaves and their position), canopy structure and its character (e.g., canopy closure – a ratio of bare ground visible through the canopy), and soil conditions (Graetz 1989; Franklin et al. 1994).

The relatively high spatial resolution of multispectral aerial photography makes this tool useful for mapping vegetation composed of a mosaic of small units. The digital processing employed in the present study has several advantages and disadvantages compared to the manual one. Manual vegetation mapping is not only time/labour intensive, hence expensive, but also subjective. Although a higher number of classes (some very small and unique) can be achieved, the classification is not reproductive. Labour intensity of manual interpretation usually limits the spatial extent of databases and the manual classification accuracy is not readily assessed (Carmel and Kadmon 1998). Digital RS classification is more homogeneous and consistent. It often distinguishes fewer classes, but their number increases as the operator gets more experienced, the software/classification more sophisticated, and the amount of input data (multitemporal) or quality of input data (from multispectral to hyperspectral) increases. Computer processing must deal with changes in illumination across the scene and other data irregularities. Yet it enables partial correction of geometrical distortions, image enhancement, filtering and other pre-processing techniques, statistical evaluation, visualisation of result etc. (Pope et al. 1996).

The present study examined the application of multispectral aerial data to the mapping of sub-alpine vegetation that is vulnerable to human-induced disturbances and extremely valuable from the conservation point of view. The usefulness of digital interpretation of analogous aerial photography for vegetation cover-type mapping, that would adequately address the needs for conservation purposes in the area, is evaluated. The study was aimed at finding a methodology that could be applied to future aerial data of the area so as to assess and monitor temporal changes in the area (mainly due to human disturbances).

The study was designed to answer the following questions: (1) Can aerial multispectral data be a useful tool in classifying sub-alpine vegetation? (2) To what extent can be different vegetation types separated on this kind of imagery? (3) Are the results of aerial data analysis comparable with those obtained in the field? (4) To what extent it is possible to detect temporal changes in vegetation using time series of aerial data?

Study Area

The Krkonoše Mts (Giant Mts, Riesengebirge) lie in the northeastern part of the Czech Republic. The study site (Figure 1) is located on the western of the two sub-alpine plateaus (1300 to 1400 m a. s. l, 15° 33′ E; 50° 45′ N) belonging to the uppermost area situated above timberline. It represents a particular landscape system, often called arcto-alpine tundra (Soukupová et al. 1995), with affinities to both sub-arctic and high-mountain regions and subjected to extreme climate conditions, such as exposition to strong northwestern winds. Average temperature is 0 to +1 °C, snow cover lasts more than 180 days, annual precipitation is 1400 mm, and there is periodical soil regelation and deflation. The plateaus are formed by crystalline metamorphic rocks, covered by poor acidic soils of the alpine sod podzol type, patches of peat bogs, raised bogs, polygonal and patterned soils. The treeless summits of the Krkonoše Mts harbour some unique physiographic components, such as relic and endemic populations and community types (Soukupová et al. 1995).

The study area is heterogeneous in terms of vegetation and abiotic environmental factors such as geomorphology, texture, soils, microclimate and disturbance regime. Vegetation cover is composed of grassland, scrubland, fens and peat bogs. The most typical plant species include *Pinus mugo* (forming alliance *Pinion mughi* and *Oxycocco-Empetrion hermaphroditi*), creating large dense krummholz; *Nardus stricta*, a typical grass dominant of dense uniform stands of alliance *Nardo-Caricion rigidae* at the localities of high snow cover and deeper humus podzol soils based on granites; *Molinia caerulea* and *Calamagrostis villosa* forming acidophilous communities of tall grasses and flowering herbs (alliance *Calamagrostion villosae*) on wet, wind-protected soils with long-lasting snow cover; *Deschampsia cespitosa* (a dominant of alliance *Poo chaixii-Deschampsion caespitosae*), found on mezotrophic to eutrophic deeper, permanently humid soils; peat mosses; and *Baeothryon cespitosum* subsp. *cespitosum* forming oligotrophic communities of boreoarctic and alpine raised bogs with prevalence of shrub form and peat mosses (alliance *Oxycocco-Empetrion hermaphroditi*). For details see Table 4, where the field botanical survey according to the Braun-Blanquet floristic approach (Fišerová 1991) is summarized and the percentage of the area covered by each vegetation type given.

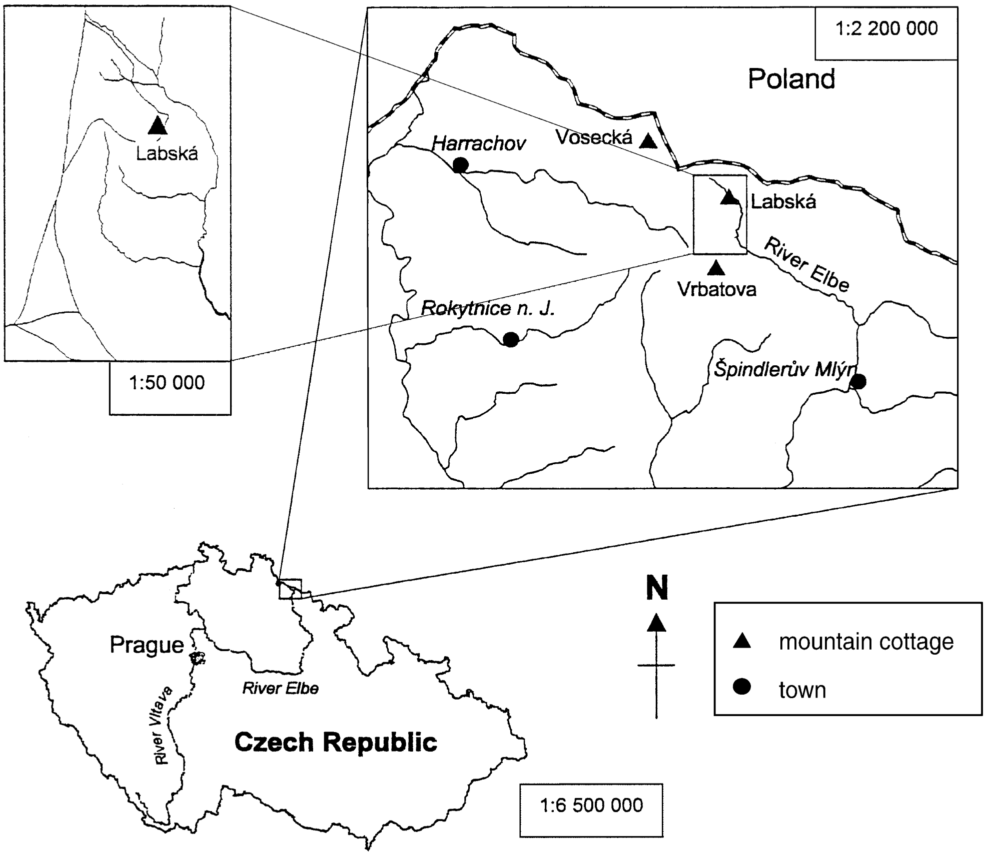

Figure 1. Location of the study site.

The study site situated on the Western Plateau covered an area of ca 2 × 3 km. It was selected according the available field vegetation maps and aerial MS photography. The plateaus themselves are relatively small (Western Plateau: 18.7 km^2; Eastern Plateau: 29 km^2) and the study site therefore covered 30% of the Western Plateau and 8% of the whole sub-alpine region.

Material and methods

The following material was used in the analysis:

- multispectral aerial photography of 1986 (acquired 20.9 1986; scale − 1:22000; channels − 0.48, 0.54, 0.66, 0.84 μm), 1989 (acquired 18.9 1989; scale − 1:22000; channels − 0.54, 0.60, 0.66, 0.84 μm) and 1997 (acquired 12.9 1997; scale 1:15000; channels − 0.54, 0.60, 0.66, 0.84 μm); created and provided by the Agency for Nature Conservation and Landscape Protection in Prague; technical parameters – camera MSK-4, focal length 125 mm, film material – FOMA (visible spectrum, 1986 and 1989), Aviphot Pan 200PE1 (visible spectrum, 1997), I-840 (NIR channel, 1986 and 1989), Kodak Aerographic Infrared Film 2424 (NIR channel, 1997)
- panchromatic orthophotographs (1997; created from scanned aerial panchromatic photographs of scale 1:22500 with overlap of 60%, using a digital terrain model created by vectorization of topographic maps 1:10000, orientation points of images identified by analytical aerotriangulation in system ORIMA; orthorectification performed on digital photogrammetric station Leica-Helava DPW 770, module Mosaic, final pixel resolution 0.5 m), created by Geodézie Krkonoše (private company), provided by the Krkonoše National Park Authority
- field botanical survey (Fišerová 1991; scale 1:5000) – vegetation units drawn into 1989 aerial photographs.

Aerial photography was chosen instead of the more commonly used satellite data although it requires a more complicated rectification then the satellite data and here is a complicated illumination effect across the area combined with the variation in the movement of the aircraft. This approach was adopted since such data at a high spatial resolution (0.5 to 1 m) were available (provided by the Krkonoše National Park conservation authorities). Analogous aerial photographs (i.e., negatives) were transformed to digital form by scanning the negative of each channel separately in resolution 1000 dpi to allow the computer processing. The digital type of processing was selected since digital analyses can easily be repeated on multitemporal data to evaluate changes over time. Scanned image channels were co-registered by image-to-image registration and then geo-referenced using the orthophotographs. Forty to fifty ground control points distributed along whole rectified photograph were collected. The second order of transformation was applied. To minimize the errors caused by mis-registration the final resolution was coarsened to pixel size 1 × 1 m. The effect of atmospheric transmittance and the angular effect, which would require additional data correction, were ignored, as well as the terrain correction, since the area was generally flat.

The detailed vegetation analysis was carried out on the multispectral photographs of 1989. From the four channels available (0.54, 0.60, 0.66, 0.84 μm), Red and Near-Infrared channels proved to be most useful. The digital form provided an opportunity to enhance the visuality of vegetation types by histogram equalization (proved to by particularly useful), principal component transformation (PCA) and Normalized Difference Vegetation Index (NDVI), and to apply unsupervised and supervised classification methods. In the unsupervised approach the Iterative Self-Organizing Data Analysis Technique (ISODATA) was employed with following parameters − 20 clusters, 20 iterations. The number of clusters (20) was selected after the clustering process from 2 to 30 clusters was examined. Higher number of clusters made their interpretation comparatively difficult. Resulting clusters were grouped together according the field verification. In the supervised approach, Parallelepiped classification (non-parametric method defining classes on the basis of the lowest and the highest value in every spectral band) was applied at first to pre-process the data, to ease the training area selection and to define the desired land-cover categories possible to distinguish on the image. The *a priori* probability of the class occurrence determined by the Parallelepiped algorithm was then used in the Maximum Likelihood analysis, resulting in the final classification map. A Minimum-distance classifier was attempted but rejected due to the poor results. Descriptions of the methods can be found in Jensen (1996), Lillesand and Kiefer (1999) or Mather (1999). The digital analyses were carried out using the Chips software (Chips Development Team 1998).

The resulting classes of both supervised and unsupervised approaches were examined using Chips software to produce scattergrams to determine the consistency of reflectance values and spectral difference of the class signatures. The Jeffries-Matusita distance measure of separability (Jensen 1996) was used to assess the separability of pairs of classes (and training sites for supervised classification) on the basis of their signatures.

An accuracy assessment of the 1989 results was carried out using descriptive and analytical statistic techniques as described in Congalton (1991). Evaluation areas used for the final assessment were positioned randomly over the area and were independent of the training sites used for the supervised classification. Stratified random sampling was used to ensure all strata are included in the sample (Congalton and Green 1998). An overall accuracy as well as 'user's accuracy' (the measure of commission error) and 'producer's accuracy' (the measure of omission error) of individual classes were calculated from the confusion matrix. The discrete multivariate technique used in the accuracy assessment was the KAPPA coefficient (Bishop et al. 1975). After the validation the final results were smoothed using a 3 × 3 mode filter. Synoptical maps of the study area were then produced.

The RS results of 1989 were compared with the field survey data (FS) of Fišerová (1991). The FS incorporated field observation and visual interpretation of the same aerial photographs, classifying the vegetation at the level of communities or their transitions according to the Braun-Blanquet floristic approach (Braun-Blanquet 1965). The FS map was digitised using the CartaLinx software (Clark Labs 1998). Information contained in the map was utilized for the training area selection and classification interpretation of the RS analysis. The RS and FS maps were compared in terms of the number of distinguished vegetation types, their distribution, extent, and the mapping accuracy. The level of correlation between ground and aerial-based vegetation maps was evaluated. RS and FS approaches were compared in regard of the area covered by each vegetation type as well as on the cell-by-cell bases in a GIS environment using ArcView GIS (Environmental Research Inst. 1999). The percentages of corresponding cells and the most commonly confused classes were identified in the correspondence matrices and it was possible to deduce likely reasons for the differences. To test the possible distortion of RS/FS comparison caused by registration errors, the pixel dimension was coarsened from 1 × 1 to 2 × 2, 3 × 3 and 4 × 4 m and the new RS/FS correspondence matrices were generated.

Interpretation of multispectral data sets of 1986 and 1997 focused on the best separable vegetation type – *P. mugo*, describing its dynamics during 10 years. The unsupervised classification was applied since in the previous detail analysis this simple and fast method proved to be sufficient for such purpose.

Nomenclature of taxa follows Rothmaler et al. (1991), that of syntaxa Moravec (1995).

Results

Unsupervised classification

The unsupervised (ISODATA) classification (Figure 2) was only moderately successful in determining the main vegetation and land-cover types, with some categories mixed. Fifteen classes were identified. Since many classes included the same vegetation/land-cover types, they were merged into six resulting classes (Table 1): (1.) *pine stands* (*Pinus mugo* dominated stands); (2.) *mat-grass communities* (*Nardus stricta* dominated stands); (3.) *tall grass and herb communities* (dominated by *Calamagrostis villosa* or *Molinia caerulea*); (4.) *road-altered vegetation mixed with tall grass and herb communities*; (5.) *roads or mat-grass*; (6.) *roads or short grasses and herbs* (*Deschampsia cespitosa*). The last three classes were mixed, covering 25% of the area (Figure 3). Some important vegetation types were not separated, such as mat-grass and roads in the mixed class 5.

The resulting classification was verified in the field. As classification accuracies (Table 2) could not be calculated for the mixed classes, the overall accuracy of 63% and KHAT statistics of 45% is only based on classes 1 − 3 (covering 75% of the area). The user's accuracy ranged from 58 to 74% and the producer's accuracy from 55 to 72%. The best results, 74% (user's accuracy) and 72% (producer's accuracy), were obtained for pine stands. The Jeffries-Matusita distance measure of separability (growing from 0 to 1.41) showed the highest separability (above 1.2) for classes 1, 4 and 6, and the value of 0.9 for classes 2/5 and 2/3.

Supervised classification

Minimum distance and Maximum Likelihood algorithms were tested. The former did not show satisfactory results and was therefore rejected (such as in Fuller and Parsell 1990).

Resulting classes of the Maximum Likelihood classification (Table 1):

1. *Pine stands – Pinus mugo*, forming krummholz, i.e., procumbent shrubs, represents dominating wood above the timberline. Constrained polycormons of *P. mugo* (Figure 2), inhabiting sheltered forks and patches of organic and mineral soils expand to surrounding grasslands. Present communities belong to the alliance *Pinion mughi*, association *Myrtillo-Pinetum mughi* and alliance *Oxycocco-Empetrion hermaphroditi* with an endemic association *Chamaemoro-Pinetum mughi*. *P. mugo* is partly natural to the area and partly planted. Plantation resulted in closed-canopy stands with a regular pattern sharply contrasting with jagged boundaries of the natural ecosystems (Soukupová et al. 1995).
2. *Mat-grass communities* are dominated by *Nardus stricta* and belong to the alliance *Nardo-Caricion rigidae* (as. *Carici fyllae-Nardetum*). *N. stricta* represents a prevailing dominant of local grasslands (Figure 2) and has a low stress tolerance and high vulnerability to trampling and eutrophication. It is endangered by expanding *P. mugo* krummholz since these krummholz favour concurrent gramineous species. The class was further subdivided into three categories (A, B and C) expressing the transition to tall grass and herb communities or that between mineral and peat soils (from A to C), from sites dominated by *N. stricta* (pH 4.5) to those with prevailing *Molinia caerulea* and *N. stricta* as a con-dominant (subas. *Carici fyllae-Nardetum molinietosum caeruleae*; pH 3.7–3.9).
3. *Tall grass and herb communities* are acidophilous and occur on granite-based wet, wind-protected soils with a long lasting snow cover; they are dominated by *Calamagrostis villosa*, *Veratrum album* L. subsp. *lobelianum* (Bernh.) Rchb. and

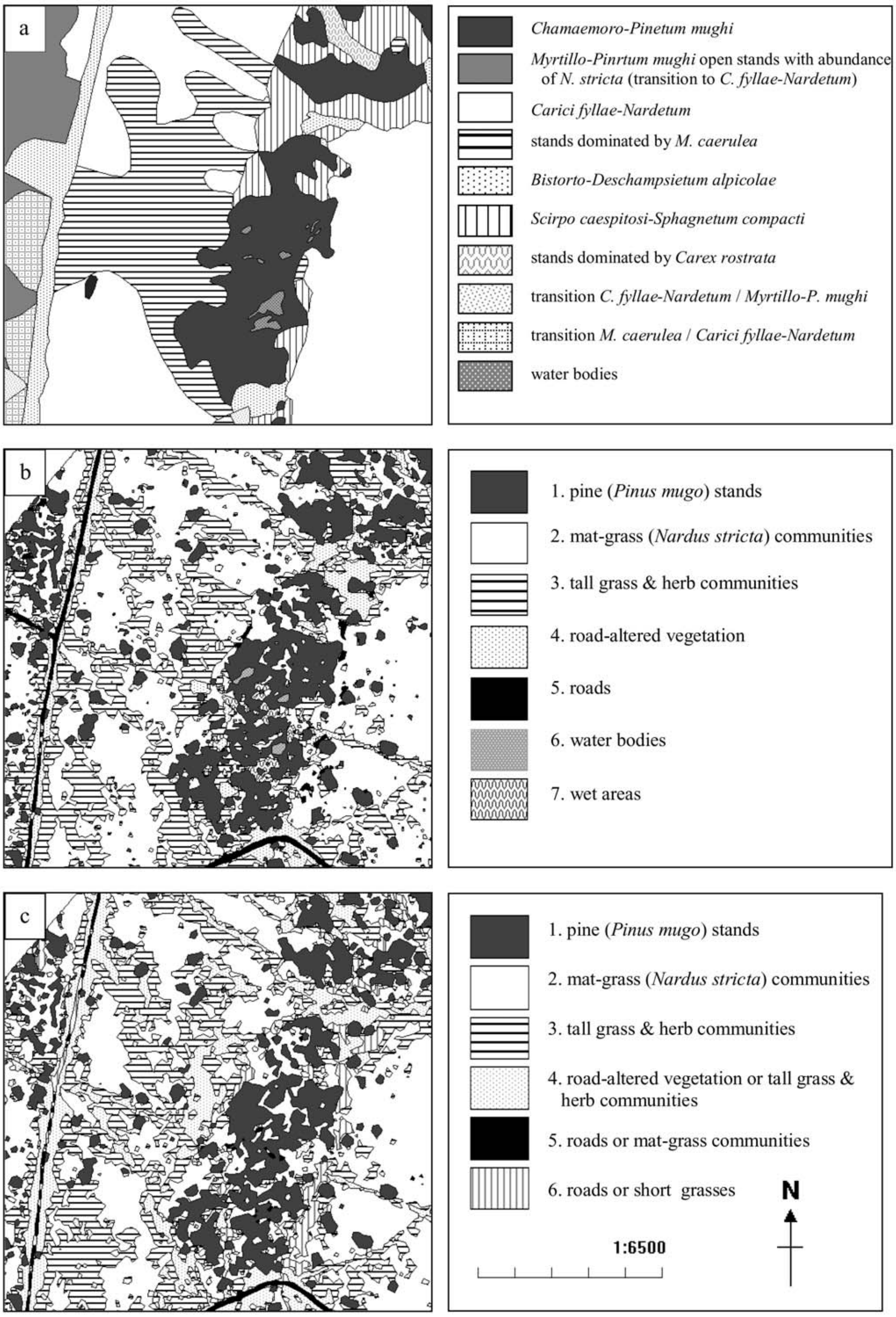

Figure 2. Comparison of the results of three vegetation mapping methods: (a) the field survey (Fišerová 1991); (b) multispectral aerial photo interpretation – supervised classification approach (Maximum Likelihood algorithm); (c) multispectral aerial photo interpretation – unsupervised classification approach (Iterative Self-Organizing Data Analysis Technique – ISODATA).

Table 1. Summary of the aerial photography classification, both unsupervised (ISODATA) and supervised (Maximum Likelihood) classification approaches.

Unsupervised classification (ISODATA algorithm)				Supervised classification (Maximum Likelihood algorithm)			
No	Class Name	Class characteristics	% of area	No	Class Name	Class characteristics	% of area
1	pine stands	Compact stands of *Pinus mugo* procumbent shrubs	17.1%	1	pine stands	see ISODATA class 1.	18.6%
2	mat-grass communities	*Nardus stricta* dominated stands, prevailing grassland type	37.6%	2	mat-grass communities	see ISODATA class 2.	40.4%
				2.1	mat-grass communities A	sites dominated by *N. stricta* (pH 4.5) on mineral soils	14.2%
3	tall grass & herb communities	acidophilous communities of tall grasses and flowering herbs on wet soils dominated by *Calamagrostis villosa*, *Veratrum album* subsp. *lobelianum*, *Senecio hercynicus* and *Molinia caerulea*	20.3%	2.2	mat-grass communities B	transition between A and C	7.9%
				2.3	mat-grass communities C	sites with prevalence of *Molinia caerulea* with *N. stricta* as a con–dominant (pH 3.7–3.9) on peat soils, transition to tall grass & herb communities	18.3%
4	road-altered vegetation and tall grass & herb communities	mixed class of vegetation in the road vicinity altered by leaching ionts from alkaline road-building material, and tall grass & herb communities	15.3%	3	tall grass & herb communities	see ISODATA class 3.	23.1%
				4	road-altered vegetation	see ISODATA class 4.	11.5%
5	road or mat-grass communities	mixed class	3.5%	5	roads	hardened by dolomite and melaphyre gravel, some covered by asphalt	4.8%
6	road or short grasses & herbs	mixed class of roads and communities dominated by *Deschampsia cespitosa*	6.1%	6	water	pools and waterlogged depressions	0.3%
				7	wet areas	peat bogs, stream alluvium, surroundings of *Pinus mugo* shrubs	0.7%
				8	unclassified		0.6%

Overall accuracy of unmixed classes = 63.1%; K_{hat} of unmixed classes = 44.5%; Overall accuracy = 78.8%; K_{hat} = 74.6%

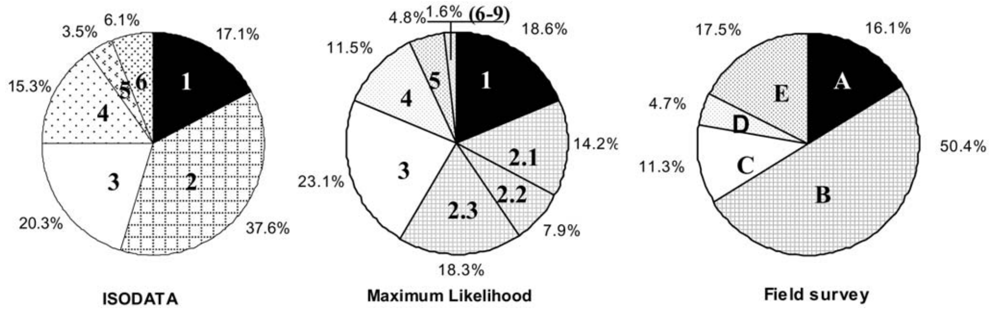

Figure 3. Diagrams showing the distribution of classes in both RS data (ISODATA and Maximum Likelihood) and the field survey (FS). Numbers and letters representing class names are explained in Figure 2 (RS), and in Table 4 (FS).

Table 2. Unsupervised classification accuracy, confussion matrix. Numbers correspond to the number of pixels.

ISO classification	Pine stands	Mat-grass communities	Tall grass & herb communities	User´s accuracy
Pine stands	71	12	13	74%
Mat-grass communities	20	72	32	58.1%
Tall grass & herb communities	8	30	54	58.7%
Producer´s accuracy	71.7%	63.2%	54.5%	63.1%

Senecio hercynicus Herborg (alliance *Calamagrostion villosae*, as. *Crepido-Calamagrostietum villosae*), or *Molinia caerulea* stands of subas. *Carici fyllae-Nardetum molinietosum caeruleae*.

4. *Road-altered vegetation* occurs along roads paved and hardened by allochtonous alkaline building material. Alkaline ions are continuously washed into the originally nutrient poor environment, supporting tall herbs and grasses growing on soils richer in nutrients (this vegetation can be partly classified as *Bistorto-Deschampsietum alpicolae* or *Crepido-Calamagrostietum villosae* associations) with a high amount of ruderal species (*Urtica dioica*, and indigenous *Rumex alpinus*), species of lower altitudes (*Senecio ovatus* (Gaertn., B. Mey. *et* Scherb.) Willd., *Hypericum maculatum* and *Cirsium arvense*) and expansive local species (e.g., *Senecio hercynicus*, *Cirsium helenioides*, *Veratrum album* subsp. *lobelianum*, *Deschampsia cespitosa*, *Calamagrostis villosa*).
5. *Roads* were hardened by dolomite and melaphyre gravel, some covered by asphalt.
6. *Water bodies* are small pools and waterlogged depressions; their size and overgrowth by *Sphagnum sp.* differ according to fluctuating precipitation.
7. *Wet areas* are peat bogs, stream alluvium and surroundings of *Pinus mugo* shrubs.

The separability of supervised classification training classes measured by the Jeffries-Matusita distance (growing from 0 to 1.41) showed values above one for non-vegetation training classes and for the pine class. Tall grass and herb communities training classes showed possible confusion with mat-grass (0.98) and road-altered vegetation (0.74), similar separability was achieved for the resulting classes.

An NDVI analysis was carried out on the 1989 photo only. It was used mainly to enhance the visuality of classes prior the classification and to enable the selection of classes possible to discriminate on the photograph. NDVI values were higher because of radiance used instead of reflectance values since an atmospheric correction of the image was not performed. Vegetation classes of highest mean NDVI were pine stands, tall grass and herb communities and road-altered vegetation, while non-vegetation structures received NDVI values under zero.

The most common classes were mat-grass communities (the most frequent sub-class C), tall grass and herb communities and pine stands (Figure 3). The user's accuracy ranged from 62 to 87% and the producer's accuracy from 70 to 88% with the overall accuracy of 79% and KHAT statistic of 75%. The best accuracy was achieved for pine stands and mat-grass communities (Table 3).

Table 3. Supervised classification accuracy, confussion matrix. Numbers correspond to the number of pixels.

Maximum Likelihood classification	Pine stands	Mat-grass communities	Tall grass & herb communities	Road-altered vegetation	Roads	Water	Wet areas	User´s accuracy
Pine stands	84	2	3	2	1	3	2	86.6%
Mat-grass communities	6	95	8	3	0	0	0	84.8%
Tall grass & herb communities	3	8	79	12	1	0	3	74.5%
Road-altered vegetation	2	6	8	75	4	0	5	75%
Roads	0	2	2	5	45	3	0	78.9%
Water	0	0	0	0	6	24	0	80%
Wet areas	0	4	8	0	0	2	23	62.2%
Producer´s accuracy	88.4%	81.2%	73.1%	77.3%	78.9%	75%	69.7%	78.8%

Comparison of different approaches

The field survey and the RS approach are compared in Table 4. Eleven vegetation types were recognized in the field map (Fišerová 1991, Figure 2). FS vegetation classes were related to the RS classes (see Table 4). Three FS vegetation types dominated by *P. mugo* contributed to the pine category, two FS classes dominated by *Callamagrostis villosa* and *Molinia caerulea* contributed to the category of tall grasses and herbs. A large group of FS classes could not be distinguished by RS means or related directly to the RS classes, i.e., *Scirpo caespitosi-Sphagnetum compacti* (classified predominantly as mat-grass or tall grass and herb communities), *Salicetum lapponum* (mostly classified as tall grass and herb communities or road-altered vegetation), stands dominated by *Carex rostrata* (accordingly classified as tall grass and herb communities), transitions between *M. caerulea* and *Carici fyllae-Nardetum* (classified according to the character of the transition as mat-grass communities or tall grass and herb communities, i.e., *M. caerulea* dominated), transitions between *Carici fyllae-Nardetum* and *Myrtillo-Pinetum mughi* (classified as pine stands, tall grasses and herbs or mat-grass communities. These classes (covering 17.5% of the area) were joined into a residual group.

A similar distribution of categories was obtained by using the three RS approaches (Figure 3), while the FS showed lower values for the tall grasses and the road-altered vegetation in favour of the mat-grass (and the residual group). The classes contributing to the residual group were excluded from the correspondence assessment (Table 5, Table 6). The resulting correspondence values (RS/FS) varied from 24% to 75% with the overall correspondence of 59% for the unsupervised approach and 55% for the supervised one. The highest FS/RS correspondence values were achieved for the pine stands (over 70%).

Enlargement of the cell dimension from 1 × 1 to 2 × 2, 3 × 3 and 4 × 4 m had negligible impact on overall correspondence values and never exceeded 1%.

Change detection

Due to the difficulties arising from the nature of the multispectral data (varying quality and exposure, inaccuracy of the geometric correction etc.) only the best separable vegetation type (pine stands) was selected to assess the changes over the time covered by available data (1986-1997). Unsupervised ISODATA classification approach was employed. Over 11 years, the area covered by *P. mugo* gradually increased. It covered 4.5% of the area in 1986, 6.1% in 1989 and 10% in 1997; this represents 40% increase in 1986-1989 and 50% increase in 1989-1997, resulting in more then doubled area over the whole period (Figure 4). The average increase calculated for the 11 years was 2.8 hectares per year.

Discussion

Aerial data analysis

The present study has shown that aerial data can provide valuable information about vegetation in sub-alpine region, with comparatively high classification accuracy and low class confusion. Still some vegetation types were not possible to identify due to their spectral or species similarities or small size of

Table 4. Comparison of the ground and the remote sensing approach in vegetation mapping (the field vegetation survey of Fišerová 1991, and the aerial photo digital interpretation).

	Traditional field mapping, according to the Braun-Blanquet floristic approach (percentage of the total area in brackets)	Unsupervised classification (ISODATA)	Supervised classification Maximum Likelihood
A – Pine stands	*Chamaemoro-Pinetum mughi* Hadač et Váňa 1967 (11 %)	Pine stands (class 1.)	Pine stands (class 1.)
	Myrtillo-Pinetum mughi Hadač 1956 (1.1 %)	Pine stands (class 1.)	Pine stands (class 1.)
	Myrtillo-Pinetum mughi – open stands with abundance of *N. stricta*, transition to *Carici fyllae-Nardetum* (4 %)	Pine stands (class 1.)	Pine stands (class 1.)
B – Mat-grass	*Carici fyllae-Nardetum* Jeník 1961 (50.4 %)	Mat-grass communities (class 2., mixed class 5., 6.)	Mat-grass communities (class 2.)
C – Tall grasses & herbs	*Molinia caerulea* stands (10.7 %)	Tall grass & herb communities (class 3., mixed class 4.)	Tall grass & herb communities (class 3.)
	Crepido-Calamagrostietum villosae Jeník 1961 (0.6 %)	Tall grass & herb communities (class 3., mixed class 4.)	Road-altered vegetation (class 4., 48%) or tall grass & herb communities (class 3., 40%)
D – Road-altered vegetation	*Bistorto-Deschampsietum alpicolae* Burešová 1976 (4.7 %)	Road-altered vegetation (mixed class 4.)	Road-altered vegetation (class 4.)
	water (0.2 %)	classified mostly as Pine (class 1.)	Water (class 6.)
E – Residual group	*Salicetum lapponum* Matuszkiewicz 1965 (0.3 %)	classified as class 4. (58 %) or class 3. (17%)	classified as class 4. (48 %) or class 3. (37%)
	stands dominated by *Carex rostrata* (0.4 %)		
	Scirpo caespitosi-Sphagnetum compacti Waren 1926 (5.3 %)	classified as class 4. (35 %), class 3. (29%), class 2. (19%) or class 1. (14%)	Tall grass & herb communities (56%)
	transition *Carici fyllae- Nardetum* → *Myrtillo-Pinetum mughi* (8.8 %)	classified as class 2. (37 %), class 3. (27%) or class 4. (24%)	classified as class 3. (37 %), class 2.3 (29%), class 2.1 (18.5%) or class 4. (18%)
	transition *M. caerulea* → *Carici fyllae-Nardetum* (2.5 %)	classified as class 2. (47%), class 1. (30%) or class 3. (14%)	classified as class 1. (32%), class 3. (24%), class 2.1. (20%) or class 2.3. (15.5%)
		classified as class 2. (57 %), class 3. (23,5%) or class 4. (15%)	classified as class 2.3. (30 %), class 3. (29%) or class 2.1. (27%)

Table 5. Correspondence matrix of the aerial photography interpretation (unsupervised approach) and the field survey. Numbers correspond to the number of pixels.

ISODATA classification (RS)	Pine stands	Mat-grass communities	Tall grass & herb communities	RS/FS correspondence
Pine stands	40475	12612	3810	71.1%
Mat-grass communities	23978	140789	15527	78.1%
Tall grass & herb communities	5368	57776	20112	24.2%
FS/RS correspondence	58.0%	66.7%	51.0%	62.8%

Table 6. Correspondence matrix of the aerial photography interpretation (supervised approach) and the field survey. Numbers correspond to the number of pixels.

Maximum Likelihood (RS)	Pine stands	Mat-grass communities	Tall grass & herb communi-ties	Road-altered vegetation	Water	RS/FS corre-spondance
Pine stands	49383	16534	4726	1275	572	68.1%
Mat-grass communities	19069	146528	20418	2164	114	77.8%
Tall grass & herb communities	7052	63794	25515	6520	13	24.8%
Road-altered vegetation	2984	18371	6929	9811	0	25.8%
Water	171	0	0	0	245	58.9%
FS/RS correspondence	62.8%	59.8%	44.3%	49.6%	26.0%	57.6%

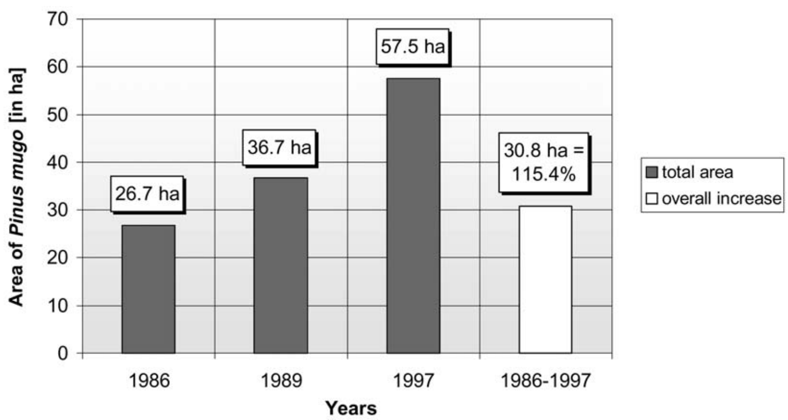

Figure 4. Changes in the area covered by *Pinus mugo* over the period of 1986-1997 detected from multispectral aerial photographs. The black column gives the total area covered by *P. mugo* in particular years in hectares, the white column discribes its overall increase.

patches. Yet the not discerned vegetation types were not of main importance. Stands of uniform vegetation showed higher classification accuracy compared to those with heterogeneous, atypical or transitional vegetation, which were difficult or impossible to map. As Treitz et al. (1992) pointed out, the more spectrally unique the class is and the lower species variation it shows, the higher is its classification accuracy.

The supervised classification technique (Maximum Likelihood method), providing higher overall accuracy, proved to be more successful and accurate than the unsupervised (ISODATA algorithm). As the unsupervised approach produced mixed classes and did not differentiate some land-cover types (e.g., road-altered vegetation), it appears to be insufficient for a detailed vegetation study. However as a fast and easy method it worked well for a simple task of *Pinus mugo* mapping, showing comparably high classification accuracy of 74% (user's) and 72% (producer's). The overall accuracy and the KHAT statistic are over-estimated since they represent only the three unmixed classes, two of them belonging to the most distinct vegetation types.

In the supervised approach, class confusion occurred in some cases. Mat-grass communities were sometimes misclassified as roads or as *P. mugo* stands. Road-altered vegetation and tall grass and herb communities were confused, which is not surprising considering that they have a similar species composition. Pine stands were mis-classified as water or wet areas; *P. mugo* krummholz often grows on humid soils or surrounded by standing water at stem, which changes the resulting spectral reflectance.

Comparison of different approaches

The ground inventory achieved a higher number of vegetation classes, and the vegetation units were larger, with more homogeneous and less complex texture. Not all the categories classified by FS could be discriminated from aerial data and vice versa and the mapped vegetation units differed. It was therefore not possible to compare the aerial-based vegetation map directly to the field survey based on phytosociological methods. For example, different plant community types dominated by *P. mugo* could not be discriminated on aerial photographs, because dominating shrubs covered under-storey grasses and herbs and contributed strongly to the resulting spectral reflectance. Transitional classes of field mapping were related to photo-interpreted classes that included plant species engaged in transition, and could therefore be regarded as correctly classified. The term 'transitional' is subjective and such stands could hardly be classified equally by a different analyst. Some classes, such as stands dominated by *Carex rostrata* and the community *Crepido-Calamagrostietum villosae*, were not separated on aerial photographs; however, their prevailing inclusion into classes representing stands of higher biomass (such as tall grass and herb communities or road-altered vegetation) seems to be just. Some classes obtained by photo-interpretation were not determined by the field mapping (wet areas and division of mat-grass communities into three sub-categories), or were delineated only partly such as the road-altered vegetation (*Bistorto-Deschampsietum alpicolae* in Fišerová 1991).

For the purpose of a correspondence assessment, the FS vegetation types that were impossible to relate to the RS classes were joined into a large residual group, covering over 17% of the total area. This fact biased the correspondence and supposedly lowered the level of correlation; still it is probable that an attempt to make questionable relationships between all RS and FS classes would significantly amplify the error. The best correspondence values resulted from pine and mat-grass classes (both RS classification types). Higher correspondence values for the unsupervised approach, compared to the supervised, were caused by a lower number of assessed classes. In the unsupervised classification only the three unmixed classes were taken into account, two of them rating among the best discernible. This fact artificially enhanced the resulting correspondence (as well as the accuracy) of the unsupervised classification.

As for the supervised classification and the FS, the proportion of water bodies (that are easy to discriminate) was very similar, and those of pine stands and mat-grass communities were approximate (Figure 3). Slightly larger area of pine stands (RS) seems closer to reality, as ground inventory included only larger polygons and small individual shrubs were omitted. The RS approach gave comparably higher proportion of tall grasses and herbs (two times higher) and of the road-altered vegetation (three times higher). The category of tall grasses and herbs seems to be overestimated by the RS approach and underestimated by FS. The amount of vegetation classified as road-altered was more than three times larger when using RS approach, compared to FS. This can be explained by the fact that human-made sites with this vegetation type were not in the focus during FS, which resulted in its underestimation. Still some of the pixels included into the road-altered vegetation RS class are located further off the road and belong to tall grass and herb communities that show similar characteristics and share some plant species. Some categories were difficult to compare, as they only partly overlap (e.g. transitional types).

The results are consistent with those reported on the comparison of ground- and remote sensing-based vegetation mapping in arctic (Mosbech and Hansen 1994, Spjelkavik 1995) and alpine regions (Frank 1988).

Problems with interpretation of aerial photography

Digital processing minimized inaccuracy originating from the subjective element. Nevertheless, co-registering the channels of the multispectral images prior to RS classification process was not perfect and produced mis-registration error (mentioned e.g., in Cihlar et al. 1996). As for both types of RS classification (compared in Ferguson 1991 and Joria and Jorgensen 1996), results could not have been field-verified by the author at the same year the aerial data were gathered. Some causes of misclassification are therefore unknown. The vegetation map of Fišerová (1991) is not completely reliable as it was drawn into raw, non-rectified photographs and was therefore subject to a geometric distortion. Nevertheless, since the alteration of cell dimension did not change markedly the RS/FS correspondence values it seems that the impact of registration errors was not fundamental. Hereafter there is a question of the FS vegetation map accuracy. As Congalton (1991) stated, accuracy of ground surveys has been traditionally accepted without any confirmation and digital classifications are often assessed with its reference. An assumption that the ground inventory is 100% correct is rarely valid and can bias the digital classification assessment.

RS methods do not produce sharp boundaries between vegetation types, which in reality form a continuum rather then a well-defined mosaic. It can be argued that the classification error is partly caused by an attempt to place a boundary where in reality a gradient of change exists (Wood and Foody 1989). Mixed pixels in transition zones contribute to the heterogeneity of the resulting map, reflecting natural conditions (Mosbech and Hansen 1994).

Change detection

An analysis of vegetation changes from available multispectral aerial data failed to provide satisfactory results, because the field verification of older data was not possible. The results of change detection were also distorted by problems related to the nature of aerial data, i.e., the mis-registration and image exposure differences (see Bakker et al. 1995 and Holmgren et al. 1997). Only the best recognizable vegetation type, *P. mugo* dominated stands, was therefore chosen for the analysis. The ISODATA algorithm, previously proven to be convenient for such a task, was employed as a fast and simple method, possible to apply over the large area of the National Park with satisfactory results. Since all three photographs were taken at the end of the growing season (the second half of September) problems caused by the shift of the phenological stage and consequent over/under estimation of changes were eliminated. The rapid increase of the area covered by *P. mugo* was caused mainly by aging of already established pine polycormons (growth and expansion of branches).

Relevance to nature conservation

Previous dendrochronological studies (Soukupová et al. 1995) showed that under extreme climatic conditions the establishment of *P. mugo* on the Plateau is a delicate process and progressive spontaneous dispersal of its population is slow. Still the expansion of *P. mugo* represents a potential threat to local herb species, valuable from the conservation point of view, and to the unique geomorphologic components, such as relic polygonal and patterned soils. These unique soils were developed in periglacial conditions of glacial periods and can be still preserved and actively shaped if cryogenic processes (periodical soil regelation and deflation) continue. Such processes are disrupted if the surface is overgrown with shrubs. The description of *P. mugo* dynamics is thus of an eminent interest to the nature conservation authorities and the resulting maps will be used for conservation purposes.

Field inventory of vegetation is a time-consuming and laborious process. RS analysis, conducted in detail in one area, represents a methodology that can be extrapolated over larger areas covered by similar vegetation. The possibility of time-series studies of RS data allow us to follow vegetation changes, and possibly to separate the natural variation in vegetation attributable to natural factors from that induced by human impact.

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