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Approaches to utilising QuickBird data for the monitoring of NATURA 2000 habitats

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Abstract: The implementation of standardised methods for the monitoring of NATURA 2000 sites in Europe is still a key topic in environmental research. Effective, economically priced and, as far as possible, automated applications are required. Rapidly developing sensor technology together with advanced image processing methods offer new possibilities for application of remote sensing data to NATURA 2000 monitoring. The studies presented here combine commonly available GIS data, such as Biotope Type Maps or Forestry Site Maps with remote sensing classifications of the very high spatial resolution (VHSR) QuickBird sensor. Two knowledge-based approaches under inclusion of *a priori* object-based information are utilised to detect the extent of habitats as well as their quality according to the German NATURA 2000 mapping guidelines. While one method used a segmentation of forested sites in Bavaria (southern Germany), the second technique applied available objects to classify heathland habitats in the Brandenburg Region (northern Germany). The results were subsequently compared, in close cooperation with local environmental authorities, with habitats mapped terrestrially for NATURA 2000 management plans. These results indicate that different remote sensing methods can be a valuable support for terrestrial mapping. Woodland habitats can be detected and specific NATURA 2000 quality parameters (e.g., percentage of natural forest types) are recognisable. In the case of heath-dominated sites, terrestrial mapping can even be replaced by remote sensing of certain habitat types for which it is also possible to obtain adequate measures of quality. Having evaluated the quality of forest and heathland NATURA 2000 habitats, two general challenges when implementing the guideline regionally could be indicated. Firstly, the very general scope of the Habitats Directive contradicts to specific local protection purposes. Secondly, the protection aims given for NATURA 2000 areas are very static. The Directive could be improved by adapting existing management and conservation strategies to pro-actively respond on likely anthropogenic influences.

Abbreviations: MF – Membership Function, SCI – Sites of Community Interest, VHSR – Very High Spatial Resolution.

Nomenclature: European Commission (2007) for European Union habitats, Rennwald (2000) for syntaxa and Wisskirchen and Haeupler (1998) for higher plants.

Introduction

The EU is committed to the protection of biodiversity; not least by a political commitment to halt biodiversity loss within the EU by 2010 ("2010 Biodiversity Target"), first adopted by EU Heads of State at the EU Summit in Gothenburg in June 2001. As part of the attempt to fulfill this objective, over the last 25 years the EU has built up a vast network of over 26,000 protected areas including all the member states and a total area of around 850,000 km^2, representing more than 20% of total EU territory. This vast array of sites, known as the NATURA 2000 network, is the largest coherent network of protected areas in the world. At the 9th Conference of the Parties to the UN Convention on Biological Diversity (CBD) held from 19-30 May 2008 in Bonn (Germany), worldwide attention was paid to the European NATURA 2000 network. The legal basis for the NATURA 2000 network derives from the Birds Directive (Council Directive 79/409/EEC on the conservation of wild birds), which dates back to 1979, and the Habitats Directive of 1992 (Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora). Together, these Directives constitute the backbone of the EU's internal policy on biodiversity protection.

As the selection of sites for the NATURA 2000 Network nears completion, attention is increasingly focused on the issue of management in accordance with the provisions of Article 17 of the Habitats Directive (92/43/EWG). As stated above, almost a fifth of the EU territory has to be supervised. The Directive requires that standardised monitoring of the habitat types be undertaken and a report on this submitted every six years. For this reason, an easily operated, economically priced and as far as possible automated application is required which can support cost-intensive terrestrial monitoring.

A traditionally used method is the terrestrial mapping of stratified samples from the monitoring-site. The full geographical extent of the species or habitat is extrapolated from these small scale measurements using modelling techniques. Therefore, the mapping is very detailed and often includes different search-spaces to facilitate up-scaling of the results (Stohlgren et al. 1997). However, terrestrial mapping is very costly, reducing the number of stratified samples obtained. Moreover, there is not always sufficient knowledge about appropriate extrapolation of the results, because of inadequate research on distribution patterns of species (Whittaker et al. 2005). A combination of terrestrial mapping with a top-down method, such as remote sensing classification, could prevent these difficulties arising.

Newly available sensors make it possible to directly measure certain aspects of biodiversity by remote sensing (Turner et al. 2003). While the detection of species still remains a difficult task, often solved with indirect approaches (Nagendra 2001, Jobin et al. 2008), promising possibilities for the classification of habitats with VHSR sensors seem to exist. The potential of remote sensing and Geographic Information System (GIS) techniques for identifying and monitoring of NATURA 2000 habitats according to the Habitats Directive are evaluated on a general basis by the EU projects SPIN (Langanke et al. 2004) and EON 2000+ (Sell et al. 2004). However, results for different habitats show considerable variation in accuracy of detection and monitoring. Especially Mediterranean habitats (Boteva et al. 2004), wetlands, dry grasslands (Bock et al. 2005) and mires (Küchler et al. 2004, Langanke et al. 2007) have yielded good classification results.

Since the introduction of the Habitats Directive in 1992, the legislative as well as technical specifics have changed. Firstly, more precisely defined monitoring guidelines are now available at national and European levels (Burkhardt et al. 2004, European Commission 2006). In Germany, a set of monitoring indicators was developed for different main types of habitats (e.g., forest, wetland, heathland). Taking forest as an example, this assessment matrix includes amongst other parameters the existence of different forest development stages, the quantity of biotope trees, deadwood, percentage of natural forest types, quality of understorey herb layer, faunal quality, disturbances of soil, hydrology and forest structure, as well as disturbances caused by forest fragmentation. According to the guidelines of the EU Commission, the monitoring matrix distinguishes between a favourable, unfavourable-inadequate, and unfavourable-bad conservation status. For the example of deadwood, the German monitoring guidelines require the presence of more than three trees per hectare for favourable conservation status, while more than one deadwood object indicates unfavourable-inadequate status and less than one an unfavourable-bad conservation status.

Clearly, not all of the indicators of the assessment matrix are detectable by remote sensing methods. However, rapidly developing sensor technology and image processing methods offer new possibilities for use of remote sensing in combination with GIS for these types of NATURA 2000 monitoring. With the launch of VHSR satellite systems, such as IKONOS or QuickBird, the interpretation of remote sensing images has developed from a pure pixel-based semi-automatic classification, depending on the spectral information, into a more object-based classification taking into account vector or segment information (Blaschke and Strobl 2001). In Fig. 1, the workflows of three different classification strategies are schematically shown for the example of single deciduous tree detection. A pixel-based classification (cf. Fig. 1a) is based on the spectral values. Because the shape of the observed object is not taken into account, a so-called "salt and pepper" effect occurs, which can be reduced with filter techniques (Meinel et al. 2001). The results of pure pixel-based approaches are difficult to interpret for VHSR data, be-

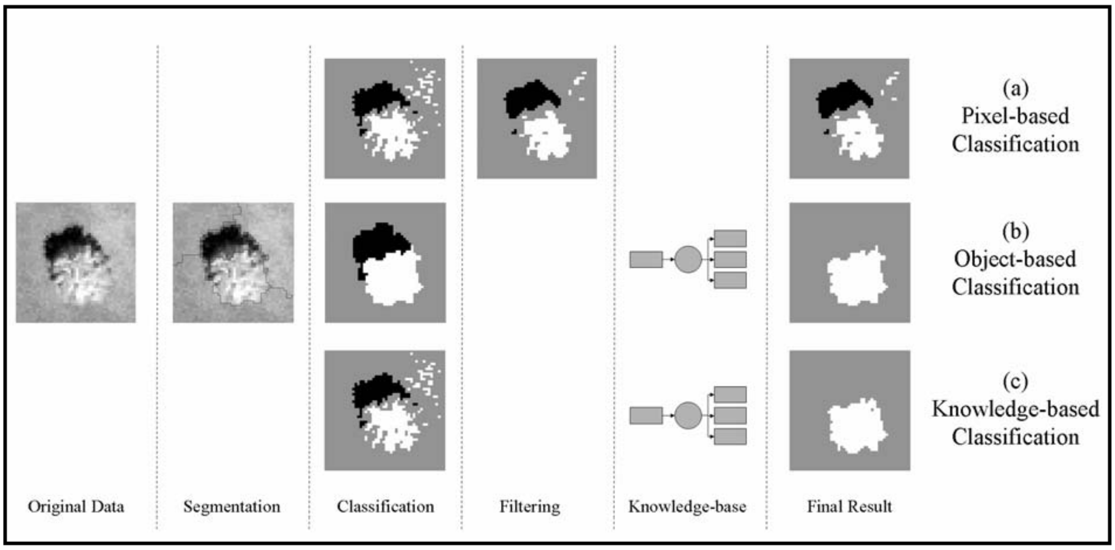

Figure 1. Schematic comparison of different classification strategies for the example of a single tree (*Fagus sylvatica* f. *purpurea;* data source: QuickBird Image; near infrared band; 48 × 48 pixel).

cause the shape of objects is often fragmented and proximity relations (e.g., tree / shadow) can be lost (Burnett and Blaschke 2003).

The methods explained in this section are illustrated with two examples for detecting habitat objects by resolving the complex data basis. An object-based classification (cf. Fig. 1b) starts with the creation of vectors. After this segmentation, the objects are classified. Proximity and different sizes of object can be included in the classification process. A knowledge-based classification (cf. Fig 1c) carries out a pixel-based classification, but resolves the results in an existing vector data-set, which can be edited to reveal significant changes in geometry.

The merging of classification results as objects (as in Fig. 1b and 1c) is a highly important step in the process of habitat classification, because the minimum classification unit of VHSR data is not identical with the classification mapping unit usually applied in, for example, NATURA 2000 mapping keys. The average size of a mapped habitat is much larger than the pixel size; therefore a combination of pixels to objects better reflects the target size of the habitats. To give an example, the average size of terrestrial mapped habitats in the study site "Angelberger Forst" is 7,350 m^2, while the QuickBird pixel size is approximately 0.37 m^2. Obviously, if a single vegetation type has to be detected (e.g., beech as a proxy for the habitat type *Luzulo-Fagetum*) the spectral variance within the single pixels of the crown is less important than the shape of the tree crown (see Fig. 1). Apart from this aggregation of pixels to form an object, or a habitat defined by a mapping key, the habitat can also consist of more than one detected object. A heathland habitat may be composed of vegetation classes like dry heathland, grassland, scrub and open sand within a certain area (cf. Fig. 6, 7). These examples of aggregation to an object (a) and subdivision of an existing vector (b) illustrate that although VHSR data have detection limitations (e.g., understorey vegetation), the high spatial resolution necessitates simplification, as demonstrated below.

The objective of the studies presented here is to illustrate and compare the strengths and weaknesses of different methods for classifying VHSR data obtained with the sensor QuickBird. The approaches combine spectral and textural information of QuickBird images with ancillary data, to identify forest and heathland habitats. Firstly, a per-parcel-based hierarchical classification approach is used for the detection of heathland. Secondly, an object-based approach is applied for the detection of forest habitat types.

Ecological background of the study sites

Four NATURA 2000 areas in Germany were selected as test sites (see Fig. 2 for geographical location and Table 1 for area specification). The sites selected in the pre-Alpine area of Bavaria are mainly forested, while those in the north-eastern lowlands of Brandenburg are predominantly heathland. Apart from the interest of the regional environmental agencies in these sites, they were selected because they represent a wide range of NATURA 2000 habitats. Moreover, data suitable for validation are available for these areas in the form of terrestrial mapping results and existing management plans.

Bavarian sites

Two forested Sites of Community Interest (SCI) were chosen as test areas: Angelberger Forst and Taubenberg (Kleinschmit et al. 2006). The sites cover respectively approximately 650 ha and 1,847 ha. In both areas a wide variety of semi-natural, mixed forest types exists. The natural distribution of forest types primarily depends on soil moisture and acidity, but can equally be determined by relief or anthropogenic influences.

The Angelberger Forst (SCI no. DE-7829-301) is situated in the landscape "Donau-Iller-Lech-Platte" (D64) within the Middle Swabian Upland at altitudes from 580 to 650 m a.s.l. The natural vegetation is submontane deciduous forest. Tree species occurrence in the actual forest vegetation indicates a significant, human impact by cultivation of conifers. Today, the Angelberger Forst comprises 24% broadleaved forest, against 66% conifer-broadleaved forest. The actual broadleaved forest area is dominated principally by *Luzulo-Fagetum* (habitat type 9110: 17.9%) and *Asperulo-Fagetum* (habitat type 9130: 3.5%). The requirements of *Stellario-Carpinetum* (habitat type 9160: 1.3%) are satisfied by periodically moist locations, but occur less fre-

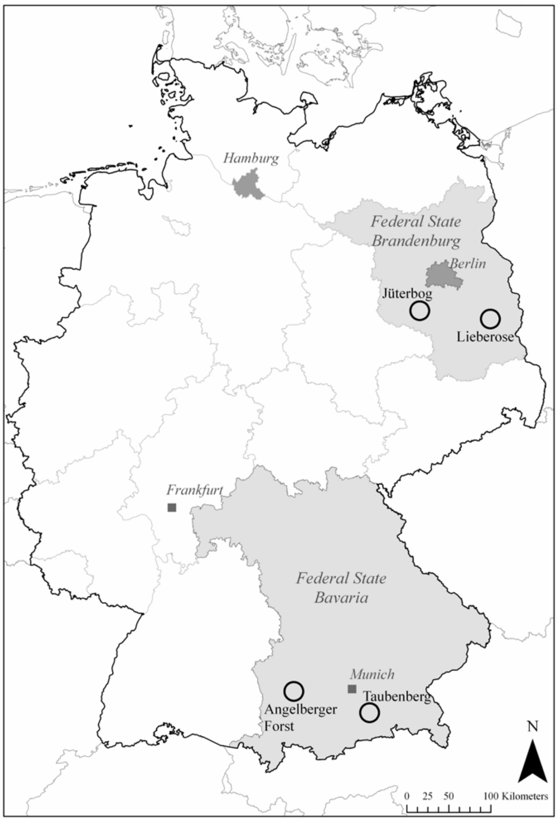

Figure 2. NATURA 2000 test sites in Germany.

Table 1. Main characteristics of the test sites and the utilised QuickBird data. Environmental Quality is assessed on the portion of imagery not affected by clouds, but influenced by particles such as haze, fog, or smoke. The distributor of the QuickBird product divides the image quality in excellent (0 – 10% imagery affected), good (11 – 25%), and fair (26 – 50%).

Study Area	Area in km²	Acquisition date	Cloud cover	Environmental quality	Off Nadir View angle	Land use characteristics	Existing NATURA 2000 habitat types	Predominantly existing species
Jüterbog	82	04 August 2003	0%	excellent	14.6°	dry, open, forest	Dry sand heaths (2310) Inland dunes (2330) Oligotrophic to mesotrophic base poor standing waters (3130)	*Calluna* and *Genista* *Corynephorus* and *Carex* *Littorelletea uniflorae and/or Isoeto-Nanojuncetea*
Lieberose	163	06 September 2004	0%	fair	20.5°	dry, open, forest	Natural eutrophic lakes (3150) European dry heaths (4030) Xeric sand calcareous grasslands (6120*)	*Maganopotamions and/or Hydrocharitions*
Angelberger Forst	7	11 August 2005	1%	fair	11.3°	forest	*Luzulo-Fagetum* beech forests (9110) *Asperulo-Fagetum* beech forests (9130) Oak-hornbeam forest (9160) Forest of slopes, screes and ravines (9180)	*Luzulo-Fagetum* *Asperulo-Fagetum* *Stellario-Carpinetum* *Tilio-Acerion* *Alnus glutinosa*
Taubenberg	18	05 July 2005	0%	excellent	7.0°	forest	Alluvial forests (91E0) Acidophilous Picea forests of montane levels (9410)	*Fraxinus excelsior* *Vaccinio-Piceetea*

quently. Very moist habitats, mostly along streams, are covered by alluvial forests with *Pruno-Fraxinetum* and *Carici remotae-Fraxinteum* (habitat type 91E0: 2.0%). Additionally, some small sites carry *Larix decidua* and *Acer pseudoplatanus*.

The Taubenberg is situated about 15 km north of the Alps close to Miesbach, Upper Bavaria, and covers an area of approx. 1,600 ha. The altitude ranges from 620 to 896 m a.s.l. The hill is formed from an alluvial fan of the "Obere Süßwassermolasse" (Upper Tertiary epoch). The basic material was deposited 10 – 15 million years ago, when the rivers transported debris from the uplifting Alps to their foothills and heaped up massive deltas. The unconsolidated fluvial sediments were transformed to conglomerates by diagenesis. The distinctive meso-relief is caused by soft clay marls lying between the hard conglomerate banks, visible in spring horizons and landslips. Where the impervious clay prevents a rapid infiltration of rainfall, the large surface flow has caused gully erosion and created ravines. The foot of the hill and its surroundings are covered by glacial moraines and river terraces of the Riss Era. Mean annual precipitation is around 1,500 mm (800 mm from May to September), mean annual temperature ranges from 6.2 to 7.6°C. The area has recently been designated as a protection area according to the Habitats and the Birds Directives of the European Union (SCI no. DE-8136-302). The Taubenberg region is an important drinking water reserve for the city of Munich. In accordance with the water protection function, forest management attempts to emulate natural processes. Clear-cutting is avoided. Large areas are in transition from pure spruce stands to mixed mountain forests of spruce, fir and beech. *Abies alba* participates substantially in stand regeneration of many of these transitional stands. With regard to β diversity of fir forests, the Taubenberg is of outstanding importance, not only for the "Alpine foothills" (nature unit D 66), but for the whole biogeographic region. A nutrient gradient from very poor to rich soils causes a remarkable species turnover within *Abies alba* forests at the local scale. Four different Silver fir associations were recorded (Walentowski et al. 2005). Of special relevance is the most extensive occurrence of *Myrtillus* type spruce-fir forests within the Bavarian Alpine foothills. They correspond to the spruce-fir forests of the Swiss Midland. Assigned to Annex-I-Habitat types the Taubenberg region is dominated by *Asperulo-Fagetum* (28.9%), while *Luzulo-Fagetum* (1.9%) occurs less frequently. It is important to note that *Asperulo-Fagetum* contains a considerable percentage of fir-mixture. The proportion of alluvial forests (7.9%) is even higher than in the Angelberger Forst. Smaller areas (1 to 15 ha) are covered by *Tilio-Acerion* (habitat type 9180), and acidophilous *Picea* forests (e.g., *Vaccinio-Piceetea*; habitat type 9410).

Brandenburg sites

Jüterbog – Forst Zinna/Keilberg (SCI no. DE-3944-301) and Lieberose – Endmoräne/Staakower Läuche (SCI no. DE-4051-301) are former military training areas with widespread open and dry habitats as well as large forest areas. The sites cover approximately 6,750 ha and 11,300 ha. Natural conditions on both sites were shaped during the glacial period. One of the last actively drifting inland sand dunes in northern Germany can be found in Jüterbog.

In both areas, decades of intensive military exercising have caused mainly nutrient-poor biotope types to develop. The area is situated in a landscape subunit strongly influenced by glacial events and with very sandy soils. Military activities drove the deforestation of the area. Particularly, the repeated destruction of soil and vegetation cover by tanks and explosives helped to keep large areas open, allowing sandy dunes, heathlands and dry grasslands with *Vaccinio-Genistetalia* and *Corynephoretalia canescentis* to evolve, which would not occur if the area had remained undisturbed. Biodiversity in those areas is very high and a large number of endangered species live there. In particular, species adapted to nutrient poor sites were able to colonize the degraded land. At landscape level, lowland heathland occurs as

Table 2. Additional data sources for the knowledge-based and the object-based classification methods. Further descriptions of the data can be found in Frick (2007), for the knowledge-based method and Förster and Kleinschmit (2008), for the object-based method.

Data source	Knowledge-based		Object-based	
	Date	Usage	Date	Usage
topographic data (ATKIS) and topographic maps	2004	image pre-processing	2005	image pre-processing
Digital Terrain Model (DTM)			2004	image pre-processing fuzzy logic-based integration
biotope types and land use data	1992-1993	knowledge-base	1996	fuzzy logic-based integration
soil data (Forest Site Map – only Angelberger Forst Region), Conceptual Soil Map			2004	fuzzy logic-based integration
habitat type maps from terrestrial survey	2003-2004	evaluation of classification / knowledge-base	2002-2004	Evaluation of classification
stereoscopic CIR aerial-photographs	1998	evaluation of classification		
True color aerial photographs			2003	evaluation of classification

a patchwork of fragments of varying sizes embedded in a matrix of other biotopes and managed land. Like other semi-natural biotopes, the heathland habitat is not stable, because of successional changes/dynamics and interactions with adjacent patches of different habitats. A continuous state of flux exists. The remarkable ß-diversity is caused by a mosaic of spatial niches and successional phases which provide distinct microhabitat conditions for very specialised species. The main matrix of the habitat complex is made up of inland dunes with open *Corynephorus* grasslands (habitat type: 2330) and dry sand heathlands as well as European dry heathland with *Calluna* and *Genista* (habitat types: 2310 and 4030).

Since the sites were abandoned by the Russian army in 1994, natural succession threatens the non-forested habitats, because regular destruction of successional vegetation by military activities no longer takes place. The best way of preserving the existing species richness would be the regular removal of larger vegetation, as has been intensively discussed within the nature protection agencies of the federal state of Brandenburg. However, there are few means of impeding the process because of the pervasive contamination with unexploded ammunition. Nevertheless, large areas still exist which up to now were not affected by succession. Hence, a regular monitoring of these NATURA 2000 sites is very important, because changes in the plant communities occur quite rapidly and unpredictably. Since the danger caused by explosive objects restricts a terrestrial monitoring over large areas, a remote sensing method is an especially valuable alternative in such cases.

Satellite data and classification methods

For the present investigation, four QuickBird data sets were acquired between 2003 and 2005 (Table 1). The sensor's panchromatic band collects data with a 61 cm resolution at nadir with a multispectral (visible and near infrared) ground sampling distance of 2.44 m.

Different types of additional geo-data are used for specific tasks in the classification process (Table 2). The topographic data of the German ATKIS (Authoritative Topographic Cartographic Information System), biotope type and land use maps developed from interpretation of colour infrared (CIR) aerial photographs and habitat type maps from terrestrial survey are used for the knowledge-based approach. The object-based method used additionally a Digital Terrain Model (DTM 5 and DTM 25), soil information from a Conceptual Soil Map, forest specific land-use and soil information derived from a Forest Site Map as well as topographic maps and information from terrestrial survey. The geometrical quality of the data sources varies up to approximately one meter. Therefore, the geometrical accuracy was assumed to be sufficient for detection of natural vegetation. Both methods were evaluated with the help of CIR or True Colour aerial photographs and terrestrial survey.

Knowledge-based classification

The complex nature of imagery with a very high geometric resolution requires advanced methods for analysis. Promising results have been achieved with knowledge-based approaches (e.g., Peddle 1995, Friedl and Brodley 1997). The method can be adapted to such different domains and objectives as, for example, the classification of agricultural fields (Cohen and Shoshany 2002), the detection of urban objects (Gerke 2002) or the delineation of areas of peat extraction (Pakzad 2001). Knowledge can thus be gathered from existing data. The inclusion of *a priori* information in the form of geo-data has been applied very successfully to solving various problems and improving classification algorithms (e.g., Maselli et al. 1995, McIver and Friedl 2002, Eiumnoh and Shresta 2000). It seems important to note that several studies show that the use of only one data source often leads to an unsatisfactory classification accuracy (e.g., Hahn and Baltsavias 1998).

The aim of this part of the study was to develop a method for the analysis of heathland habitats with Leica Geosystems ERDAS IMAGINE. The structure of the knowledge-based method is shown in Fig. 3. This classification procedure integrates *a priori* information (e.g., biotope type and land use maps) in a rule-base. Firstly, the images are pre-processed, including a conversion to spectral radiance, georeferencing and pansharpening (Zhang 2002). As a second step a pre-structuring of the image was performed, which is based on ratios (e.g., NDVI), principal components, and textural information. This kind of information is derived from the original images and is subsequently included in the rule-base together with information from ancillary data (see Fig. 4). Three different types of rules were taken into account:

- formalised experience of the human interpreter (e.g., trees have shadows),
- spectral characteristics from a large set of samples and the pre-stucturing of the image, and
- additional land-use data (e.g., biotope type and land use maps).

The knowledge-base explained above is not used for classifying the whole image, but to select signatures for training areas (automatic signature extraction in Fig. 3). With these extracted signatures, the image and derived information are classified either with a Maximum Likelihood or an ISODATA algorithm (iterative hierarchical MaxLike classification in Fig. 3). Pixel-based classes of distinct vegetation units are obtained as a first result. Habitat borders are then derived through visual interpretation of the satellite images or taken from the first terrestrial inventory (Fig. 6). These vector-data are then integrated in the pixel-based classification results. This second result can be used for evaluation of the conservation status of a chosen area according to the German NATURA 2000 mapping guidelines.

A limitation of the automated signature extraction is that certain sub-classes not present in *a priori* data and/or in the rules cannot be detected. For instance, if no water habitat was included in the *a priori* data, no signatures would be extracted for the class water. These limitations can be reduced by the integration of visual image analysis (Fig. 3).

Object-based classification

An object-based approach is applied to the detection of forest habitat types. Object-based classification is a relatively new method based on the segmentation of the image into polygons that are homogeneous with regard to spectral or spatial characteristics (Jensen 2005). An advantage of object-based classification is that the objects can be detected by their texture and pixel spatial continuity, e.g., with reference to

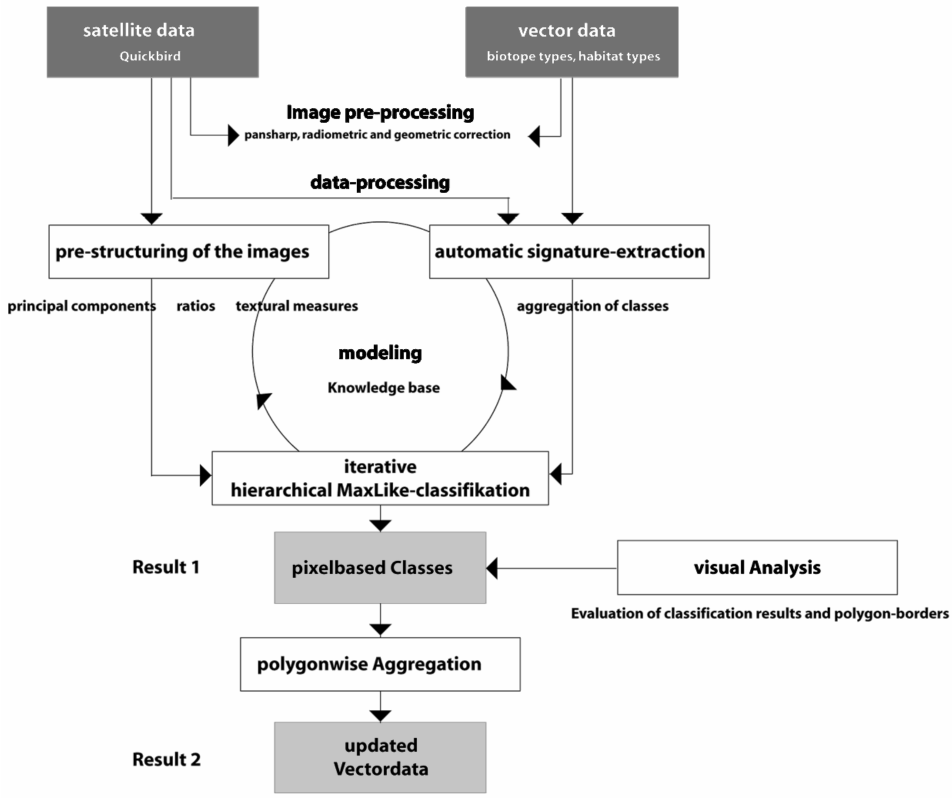

Figure 3. Process scheme of the knowledge-based classification (Frick 2005).

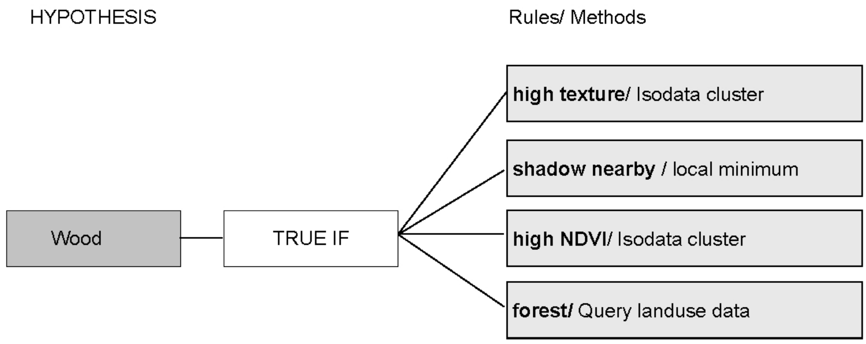

Figure 4. Example for a rule-base to detect training areas for signature extraction.

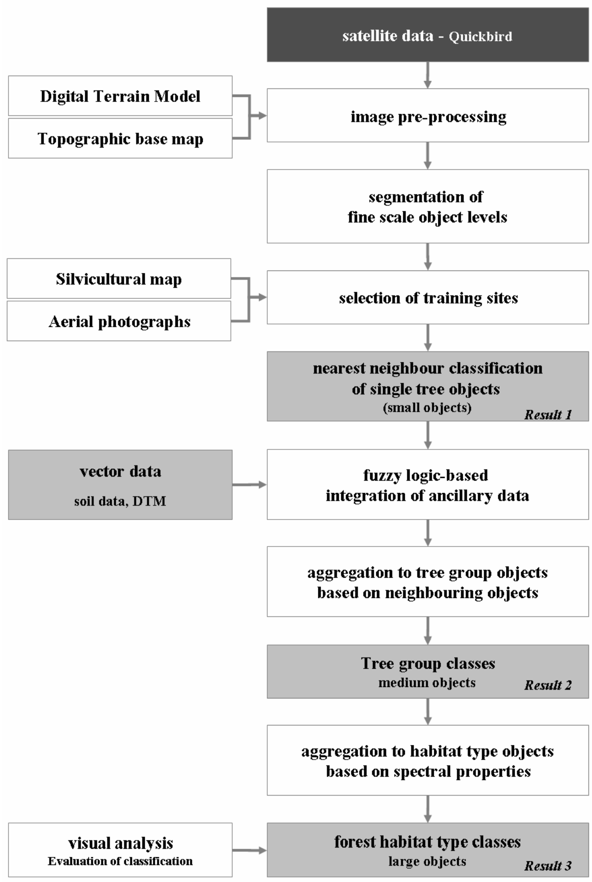

Figure 5. Process scheme of the object-based classification.

those of neighbouring objects (Burnett and Blaschke 2003). Furthermore, when they include segmentations at different levels of detail, object-based methods can represent classes at different landscape scales and utilise these levels to increase classification precision. For the present study the satellite data were processed with a multi-scale segmentation method (Benz et al. 2004) in an object-oriented approach, using the software Definiens Professional (basic concept described in: Baatz and Schäpe 2000). This method produces good visual results and low over-segmentation compared to other segmentation approaches (Neubert et al. 2008a).

The classification process is shown in Fig. 5. In the first step, a geometric correction and the pan-sharpening of the original data to a resolution of 0.61 m is undertaken (Zhang 2002). The object-based classification performs a hierarchical segmentation of the QuickBird images, following a bottom-up approach that defines objects sequentially (Fig. 5). The process commences with segmentation at the finest scale (Single Tree / Small Tree Group Level – see Table 3) followed by a classification procedure before the next level of segmentation, which defines larger objects (e.g., tree groups at medium scale).

To enhance the accuracy of classification, additional vector data are included (Table 2) by means of fuzzy-rules, which are combined with the nearest neighbour classification, based on the selection of training sites, using a fuzzy knowledge-base (Stolz and Mauser 1996). The occurrence of different forest habitats depends on specific ecological and

Table 3. Segmentation Parameters developed to identify forest habitats.

Segmentation level	Scale	Color	Shape	Compactness / Smoothness	Medium object size (in m²)
1: small objects (single tree / small tree group)	15	0.9	0.1	0.5/0.5	10.5
2: Medium objects (tree group)	40	0.9	0.1	0.5/0.5	27.7
3: Large objects (habitat size)	150	0.9	0.1	0.5/0.5	103.7

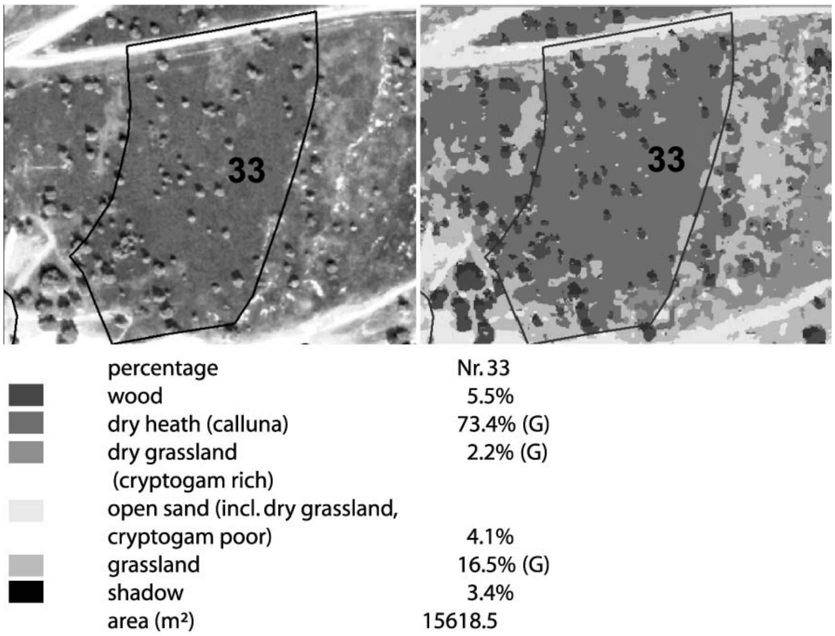

Figure 6. Classification results for the habitat type European dry heath (4030) in Jüterbog. The area borders are taken from the first terrestrial inventory (left: QuickBird subset, pansharpened; right: classification result overlaid with habitat borders).

anthropogenic influences. These conditions allow or prevent existence of species and habitats. They can be related to geodata, which describe and quantify the ecological quality of a specific location. The probability of assignment for each object (values from 0 to 1) classified with the nearest neighbour is combined with a fuzzy knowledge-base. In combining the fuzzy sets and the hierarchical nearest neighbour classification results of the segmentation level 1, the approach uses the minimum (AND-) rule, which specifies that the most unacceptable factor is the critical value for the occurrence of the forest type. In a next step the minimum possibility of each possible class is compared. The class with the highest membership will be assigned to the object (maximum – OR – rule). The extended fuzzy-classification includes in this process the possibility of occurrence of forest types within certain natural conditions.

A 30 per cent share of different tree types within an object is defined as mixed forest. Therefore, the results of level 1 were aggregated to the tree-group patch (level 2), where an object is assigned to a single species class if 70 per cent of the sub-objects are classified as one species. Mixed stands are assigned to a newly introduced group "Mixed deciduous" and "Mixed". The third level (Combined Patch Level) is used to improve the classifications of the sub-levels and to derive potential NATURA 2000 habitat type classes, such as beech habitats, alluvial forest habitats, or *Stellario-Carpinetum* habitats.

Results

Knowledge-based classification

The knowledge-based classification approach described here is applicable for the evaluation of heathland habitats. The derived habitat classes can be grouped satisfactorily to form indicators, in accordance with the prescribed national quality standard. Similarly to the example for forest given in the introduction, the indicator set for European dry heathland includes area size, wood cover, percentage of open sandy spots, percentage of moss covered area, percentage of grass covered area and percentage of heath covered area. Fig. 6 shows the classification results for a reference habitat in the Jüterbog study area. According to the German assessment matrix for the category „completeness of typical structures" the conservation status of the habitat used in this example is in favourable condition, because areas of tree cover and grass are quite small, but conversely the conservation status is inadequate because heath forms a compact layer and only 4.1% of the area is covered by the class „open sand".

Table 4. Accuracy assessment for the habitat type European dry heathland (only a subset of vegetation classes is shown, e.g., water is omitted since it does not occur at this site). Kappa measures the percentage of data values in the main diagonal of an accuracy assessment table (observed vs. classified samples) and then adjusts these values for the amount of agreement that could be expected due to chance alone. Producers Accuracy (Prod. Acc.) gives information whether the assigned data of the result belonging to a specific class (Correctly classified samples divided by sum of reference samples), while Users Accuracy gives information whether the classified area of the satellite image are assigned correctly (Correctly classified samples divided by sum of classified samples).

class	Jüterbog			Lieberose		
	Prod. Acc.	Users Acc.	No. of Points	Prod. Acc.	Users Acc.	No. of Points
open sand	1.00	0.88	16	1.00	0.95	21
nutrient-rich grassland	0.93	0.83	30	1.00	0.77	44
dry grassland , cryptogam-poor 1 + 2	0.85	0.90	19	1.00	1.00	21
dry grassland , cryptogam-rich 1	0.89	0.89	27	0.83	0.95	21
dry grassland , cryptogam-rich 2	0.88	0.83	18	0.80	0.80	20
dry sandy heath (calluna)	0.95	0.95	21	1.00	0.92	26
wood	0.92	1.00	23	1.00	0.91	82
sealed	0.78	0.82	22	0.95	0.95	20
Overall Accuracy	0.91			0.88		
Kappa	0.90			0.87		
P	< 0.00001			< 0.00001		

The main problem inherent to all remote sensing applications still remains, that classes overlaid by others cannot be classified and quantified. Since the terrestrial NATURA 2000 inventory also considers overlapping layers, e.g., if open sand or moss is hidden beneath the dwarf shrubs, the total sum can add up to far more than 100% cover. The terrestrial inventory of certain indicators can not therefore be compared directly to a satellite or aerial photograph-based inventory. To overcome this limitation at least roughly, the following assumption is made: the classes present within the habitats occur with the same distribution in wooded areas, hence the percentage of non-forest classes is interpolated (marked in Fig. 6 with G).

The transferability of the classification procedure and the knowledge-base was tested for the same habitat types on the study area Lieberose. The imagery has quite different characteristics than for Jüterbog; the viewing angle is larger and the resulting image quality was not so good as for the Jüterbog-area. The acquisition was made in September whereas Jüterbog was captured in August. The classification results show the main problem in Lieberose: the heathland is giving way to spreading, grass-covered areas or is being overgrown by woodland.

The accuracy assessment is realised with 525 points for Lieberose and 358 points for Jüterbog (Table 4). Most of the classes were evaluated by visual examination of CIR aerial photographs. The points used for assessing the classes were selected with a stratified random sample, ensuring that all classes are assessed, even if they are only classified as a small percentage of the overall area, while the classes occurring more often are assessed with a greater number of points, proportional to their abundance. Classes that can only be assessed by terrestrial investigation (e.g., *Corynephorus* grassland) were evaluated by terrestrial surveys.

With an overall accuracy of approximately 90% (Jüterbog = 91%, Lieberose = 88%) the method shows results which recommend its further use for NATURA 2000 monitoring. Especially, woody structures and dry heathland are detectable at above average accuracy rates. As can be expected, the differentiation of the two types of grassland (e.g., cryptogam-rich and cryptogam-poor) is difficult, because the spectral and textural features of these classes are very similar. The slightly lower accuracy rates of the Lieberose area could be related to the poorer quality of the image. However, the method is transferrable to this region. The classification accuracy obtained permits the evaluation of the conservation status for most of the heathland indicators defined by the German NATURA 2000 mapping guidelines at an adequate level of quality (as explained for the example of Fig. 6 above).

Object-based classification

As a first step the different tree type classes within the forested NATURA 2000 areas were evaluated. For validation purposes 121 level 1 objects in Angelberger Forst and 82 level 1 objects in Taubenberg were chosen within a random-stratified scheme of occurring classes. The segments were compared with the Silvicultural Map. Additionally, to check for errors in this map it was compared to recent (2003) true colour aerial photographs. The results of the accuracy assessment are shown in Table 5.

With an overall accuracy between 70 and 80% (Angelberger Forst = 77%, Taubenberg = 71%), the method shows results which are slightly less satisfactory for NATURA

Table 5. Accuracy assessment for tree types classified with the object-based classification for the NATURA 2000 areas Taubenberg and Angelberger Forst. The No. of objects is quoted, but the accuracy assessment was calculated on a grid-cell basis.

class	Angelberger Forst			Taubenberg		
	Prod. Acc.	Users Acc.	No. of objects	Prod. Acc.	Users Acc.	No. of objects
Beech	0.81	0.78	37	0.77	0.70	19
Beech – young	0.32	0.31	19	0.29	0.26	11
Spruce	0.75	0.74	22	0.78	0.84	15
Spruce old	0.33	0.32	9	0.28	0.27	6
Black Alder	0.96	1.00	8	0.86	0.92	5
Afforestation	0.95	1.00	11	0.88	0.93	8
Larch	0.93	1.00	9	-	-	-
Sycamore	0.85	0.88	6	0.73	0.79	4
Fir	-	-	-	0.63	0.77	9
Picea	-	-	-	0.80	0.77	5
Overall Accuracy	0.77		121	0.71		82
Kappa	0.71			0.68		

2000 monitoring than the classification of heathland classes. Especially, classes which are adapted to very small ecologcal niches and are not abundant in this region (e.g., Black Alder) are detected at above the average accuracy rates. These encouraging results are mainly due to the incoporation of additional soil and terrain information. Therefore, the slightly lower classification accuracies of the Taubenberg area can be explained by the absence of one of the soil maps (Forestry Site Map). Nevertheless, the method proved to be transferable. As for the heathland habitats, the classification accuracy obtained makes it possible to evaluate the conservation status for NATURA 2000 indicators of forest habitats.

For the segmentation and classification level 3 (Table 3), NATURA 2000 habitat types and their qualities were assessed. This is shown with an example for a *Luzulo-Fagetum* habitat (9110, see Fig. 7). According to the German evaluation scheme for this category, parameters such as number of forest development phases, number of biotope trees per ha, amount of dead wood per ha, or percentage of natural forest types have to be evaluated. To give an example, for the parameter "percentage of natural forest types" the habitats are identified as:

- favourable conservation status (A) = 90% natural forest types,
- unfavourable-inadequate conservation status (B) = 80% natural forest types, and
- unfavourable-bad conservation status (C) = 70% natural forest types.

Similarly to the heathland habitats, it is only possible to a limited degree to derive habitat types automatically, because of existence of parameters which cannot be detected by remote sensing (e.g., understorey vegetation). Moreover, it is less likely that privately owned forests will be mapped as NATURA 2000 habitats than those that are state owned, even if the former are equally suitable as nature protection areas. These merely administrative decisions may play a role when defining habitat types, but obviously cannot be detected with remote sensing (Förster et al. 2005).

If the shape of the polygon of the detected habitats in level 3 is compared to the borders mapped terrestrially, the polygons are not located at the same place (see example in Fig. 7). This is obviously due to the different mapping methods (remote sensing and terrestrial). The areas delineated with the object-based method are more detailed, differently structured, and the detected areas are smaller. The finer delineation of the object-based process results in a higher share of the main tree type in the polygon. Hence, even the assessed quality of the classified habitat objects can differ from terrestrially mapped ones (e.g., polygons A and C). There are different reasons for this observation. Terrestrial mapping (especially in forested areas) might face difficulties in estimating the actual extent of an area, especially when the criteria are related to the size of a habitat (e.g., percentage of natural forest type). Moreover, transitions between habitat types are rarely clearly detectable as a habitat border. Furthermore, terrestrial mapping tends to include large areas, even if a target species covers only a small percentage of an area. This is due to the potential development of habitats, which can be seen in the field (e.g., amount of shoots) but not detected by remote sensing.

Discussion and outlook

Two methods based on remote sensing to evaluate NATURA 2000 habitats for the purpose of an objective monitoring are presented for forest and heathland areas in Germany. Both methods achieved good results in classifying habitats and land uses. It is also possible to use these methods to provide information about the quality of habitats and their alteration through time. These results indicate that different remote sensing methods can be a valuable support for terrestrial mapping. In the case of heath-dominated sites, even a substitution of terrestrial mapping by remote sensing for certain habitat types and their qualitative attributes is possible. Both methods are therefore capable of improving existing moni-

Table 6. Comparison of the usability of the knowledge-based method and the object-based method for the monitoring of NATURA 2000 areas.

Criteria	Knowledge-based method applied in heathland habitats	Object-based method applied in forest habitat
Classification Accuracy	88 % to 91 %	71 % to 77 %
Amount of indicators of the monitoring guideline which are fully detectable with remote sensing	8 indicators for habitat 2310 8 indicators for habitat 2330 8 indicators for habitat 4030	3 indicators for habitats 9110 and 9130 4 indicators for habitats 91E0, 9410, 9160, 9180
Transferability	possible for all lowland dry heathland habitats	Possible for submontane forested areas
Utilization of additional data	required	Especially soil data required - increasing classification accuracy up to 13 % (see Förster and Kleinschmit 2008)
Basic geometry of the habitat type	Usage of existing defined habitat borders / geometry or visual interpretation	Definition of new borders or extend of a habitat type with delineated segments possible
Operational usability in the regional environmental agency	Fully operationally used in the federal state of Brandenburg	Applied as a case study in test areas in the federal state of Bavaria

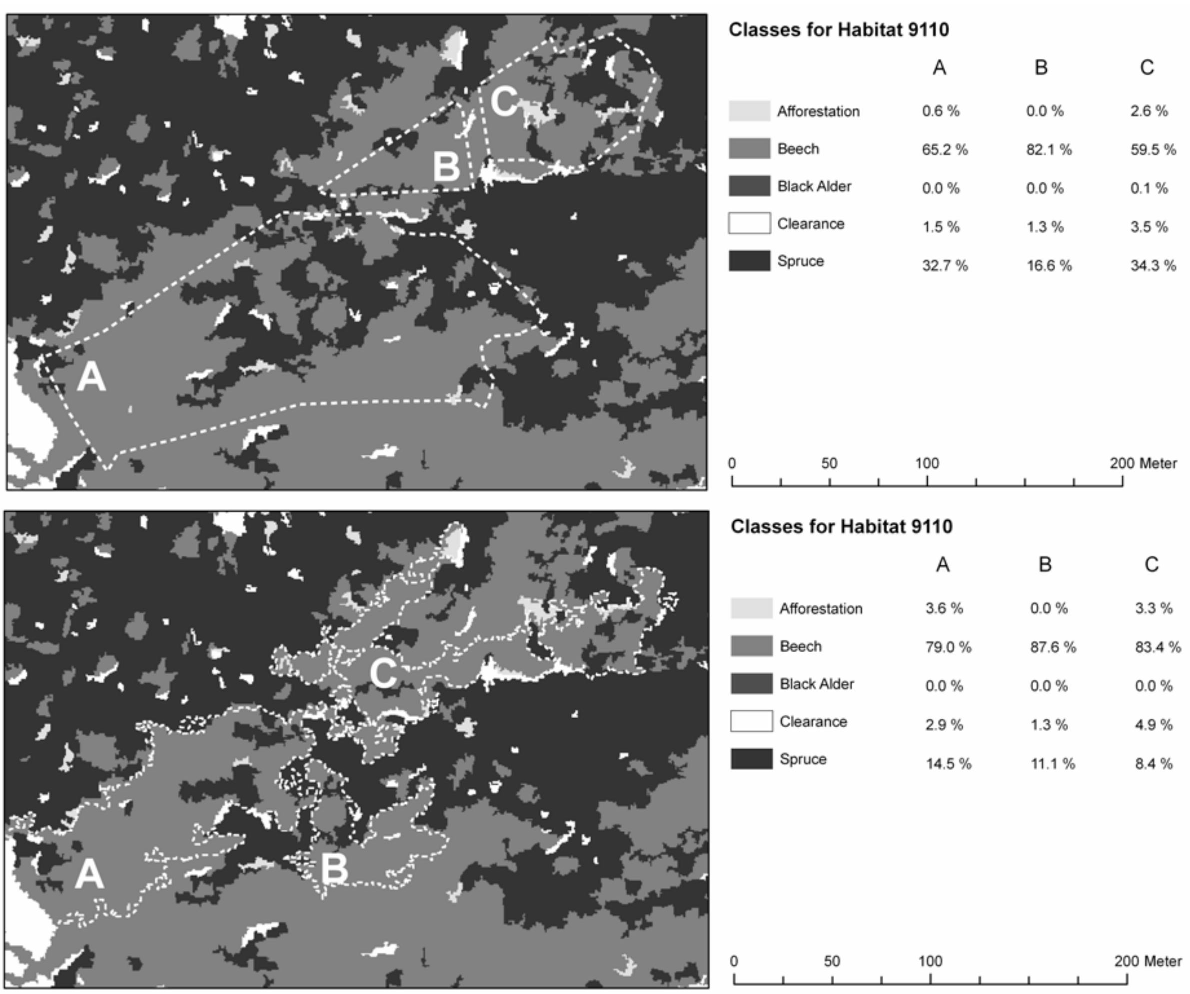

Figure 7. Luzulo-Fagetum habitat - exemplary subset for three reference habitats on the study area Angelberger Forst. The percentage of classified tree types is shown for terrestrially mapped habitats and for segmented habitats (70% of typical tree types are required).

toring approaches, because they can be applied objectively and in a standardised manner.

Comparison of the methods

Because the target habitats and defined classes of the methods are very different, it is not possible to compare these directly. However, Table 6 gives a comparative overview of the two techniques. Although the classification accuracies are shown, it is very difficult to draw conclusions from these, because it is a challenging task to detect different forest types, especially in a mixed deciduous area. Nevertheless, the accuracy of the knowledge-based method makes it very suitable for efficient monitoring and it is a technique which also permits the detection of a high number of indicators. One difficulty for the object-based method is that the indicators for forest habitats are defined less quantitatively than qualitatively, making it more complicated to derive these by remote sensing. Additionally, in forest habitats some indicators are related to the understorey vegetation (e.g., quality of the forest ground vegetation), a problem somewhat less serious in heathland habitats. Both methods are transferable without problems within the range of the classified habitats, as shown by successful application in two different areas. It is important to stress that for both techniques additional geo-data and information are crucial for classification success. Depending on the habitats, different types of geo-data might be important. While soil data are very important for the classification of pre-alpine forest habitats (Förster and Kleinschmit 2008), existing biotope maps are required for heathland habitats. For monitoring purposes, the existing and terrestrially defined habitat borders are normally utilised. Both methods work quite well with these spatial specifications (see Fig. 6 and 7). However, the object-based method can define new extents of a habitat type by means of its delineated segments. The derived segments have a spatial extend similar to the terrestrial ones, but a more detailed granularity, which gives a better expression of the habitat's borders. Therefore, the object-based method could provide useful support in identification and monitoring of a habitat's size. This would greatly support the terrestrial delineation of habitat areas and could increase efficiency of monitoring.

A further improvement to the methods used in this study can be obtained by the integration of other remote sensing data, such as LIDAR or hyperspectral information. The methods which are described should be applied to other habitat types in other areas, especially in other biogeographical regions, to validate the reliability of the technique and improve its general applicability. Moreover, a comparison of other techniques of integrating geo-data into classifications, such as neural networks, could be useful for a quality assessment (Baltsavias 2004).

Ecological implications of the results for heathland and forest

The knowledge-based procedure has been successfully validated for the habitat types dry heathlands and inland dunes, using results from many areas, and is now used operationally in the German federal state of Brandenburg. The application of VHSR satellite data and the classification procedure developed here can substantially support the monitoring of heathland habitats. It is possible to automatically derive indicators for assessing their structure and existing impairments. The habitat borders have to be verified visually. The automated classification has the advantage that large areas can be assessed in a short time and the accuracy and stability of the visual interpretation of habitat borders can be increased. Percentages of important indicators can be calculated at a high level of detail. This represents a basis not only for the monitoring of the effects of conservation measures, but also for their detailed planning.

The classification of the study sites indicated a distinct decline in the quality of the habitats inland dunes (2330) and European dry heathlands (2310 and 4030). For European dry heathland, the conservation status is inadequate in most of the defined habitat areas with respect to the indicators "share of open soil" and *cryptogam*-poor grassland, present on less than 5% of the area. Moreover, the cover of woody structures and trees is increasing (often above 25%), which also indicates inadequate conservation status. Under such conditions the still abundant species of *Calluna* and *Genista* are threatened. For inland dunes, the situation is slightly less difficult. The percentage of open sandy areas is still much more than 10% of the total habitat area (a criteria for a good conservation status). But here also, the cover of trees and bushes is increasing above 10% in some areas, an indicator of unfavourable conservation status.

For forested areas, NATURA 2000 habitat types are derived from a tree-type classification. It is shown that the share of habitat qualities can differ significantly from the results of terrestrial mapping. In comparison to terrestrial mapping, the object-based approach delineates the areas in much greater detail. At present there is no standard which defines a spatial reference size (e.g., minimum mapping units) for the quality of biodiversity. This question should be addressed by ecologists and included in mapping guidelines. If a certain habitat requires a coherent large area, a larger segmentation scale should be applied, while small-sized habitats should be classified with a finer object size.

The NATURA 2000 forest habitat types, especially the indicators "amount of woodland development types" and "percentage of natural forest types" are well suited to detection with remote sensing methods. For the two study areas the classification results show that for habitat types with more distinctly defined ecological niches, such as *Pruno-Fraxinetum* habitats, the percentage of natural forest types is above 90%, indicating a favourable conservation status. Habitat types covering large areas, such as *Asperulo-Fagetum* beech forests, are more often in an unfavourable condition for conservation purposes, containing less than 80% of beech. However, for these large areas, more than three different woodland development types exist, which conversely indicates a favourable conservation status. An important consideration in forested European NATURA 2000 areas is that *Abies alba* forests, which are particularly well represented in the Taubenberg region, should be recorded carefully as special habitats. Because of their partly site-determined, ecologically transitional character between temperate beech forests (habitat type 9130) and boreal spruce forests (habitat type 9410), this forest type is at risk of being neglected in the European network NATURA 2000: The Habitats Directive does not list *Abies alba* forests as a distinct habitat type according to Annex I. How should they then be dealt with in protected areas? It is certainly not acceptable to classify them as Non-EU-habitat and thus equate them to coniferous plantations. Alternatively, they could be assigned to the Annex I-habitat types 9110, 9130 and 9410, which appear to be closest in synsystematical terms (Walentowski et al. 2005).

Having evaluated the quality of some forest and heathland NATURA 2000 habitats, two general problems with the implementation of the NATURA 2000 guidelines became obvious.

Firstly, the very general scope of the Habitats Directive contradicts the specific objectives of regional nature conservation. As one example, the unavailability of a protection measure for *Abies alba*, which has a very important place in regional ecology, is highlighted above. NATURA 2000 protection status is often used to support regional protection status. Therefore, the strict guidelines for defining habitat types should be made more flexible and partly adaptable to a region. Secondly, the protection aims conferred on NATURA 2000 areas are very static. Especially for areas with fast developing processes (as in succession on the heathland sites in Brandenburg), it must be possible to adapt the measures prescribed in the guidelines. Climate change acting as a new driver may lead to the targets of conservation becoming invalid (Neubert et al. 2008b). Therefore, adapting existing management and conservation strategies in protected sites as a pro-active response to likely anthropogenic influences may be an inevitable consequence.

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