Journal for Nature Conservation 19 (2011) 116–125

Contents lists available at ScienceDirect

Journal for Nature Conservation

journal homepage: www.elsevier.de/jnc

Integrating remote sensing in Natura 2000 habitat monitoring: Prospects on the way forward

Jeroen Vanden Borre[a,*], Desiré Paelinckx[a], Caspar A. Mücher[b], Lammert Kooistra[c], Birgen Haest[d], Geert De Blust[a], Anne M. Schmidt[b]

[a] Research Institute for Nature and Forest (INBO), Kliniekstraat 25, 1070 Brussels, Belgium
[b] Alterra, Wageningen UR, Droevendaalsesteeg 3, 6708 PB Wageningen, The Netherlands
[c] Wageningen University, Centre for Geo-Information, Droevendaalsesteeg 3, 6708 PB Wageningen, The Netherlands
[d] Flemish Institute for Technological Research (VITO), Centre of Expertise in Remote Sensing and Atmospheric Processes, Boeretang 200, 2400 Mol, Belgium

ARTICLE INFO

Article history:
Received 5 January 2010
Received in revised form 16 June 2010
Accepted 27 July 2010

Keywords:
Annex I habitats
Article 17 reporting
Conservation status
Earth observation
Habitat mapping
Habitats Directive
User consultation
User requirements

ABSTRACT

Monitoring and reporting on the state of nature gained increasing importance in the European Union with the implementation of the Habitats Directive and the Natura 2000 network. Reporting habitat conservation status requires detailed knowledge on many aspects of habitats at different spatial levels. Remote sensing is recognised as a powerful tool to acquire synoptic data on habitats, but to date, its use for Natura 2000 monitoring and reporting is still very limited. One reason for this appears to be the knowledge gap between the nature conservation agencies and the remote sensing community. We conducted a review of legal monitoring and reporting requirements on Natura 2000 habitats, looked into the current use of remote sensing in habitat reporting, and consulted monitoring experts in nature conservation administrations to find out about their attitude and expectations towards remote sensing. In this paper, we disclose and summarise the real data needs behind the legal requirements for Natura 2000 habitat monitoring and reporting, analyse opportunities and constraints for remote sensing, and highlight bottlenecks and pathways to resolve them. Monitoring experts are not unwilling to use remote sensing data, but they are unsure of whether remote sensing can suit their needs in a cost-effective way. They look upon remote sensing as a one-way process of data deliverance and fail to see the importance of their active cooperation. Based on our findings, we argue that the integration of remote sensing into Natura 2000 habitat monitoring could benefit from (1) harmonising and standardising approaches, (2) focusing on data at hand to develop readily useful products, (3) a proper validation of both traditional and remote sensing methods, and (4) an enhanced sharing and exchange of ideas and results between the different research communities involved.

Introduction

Over the past decades, preserving our remaining natural heritage has become an issue of global concern, and this has been reflected in numerous legislative initiatives at different administrative levels. In the European Union, the Habitats Directive was adopted in 1992, imposing on EU member states the conservation of rare and/or threatened habitats and species of 'Community interest' (i.e. those habitats and species listed in annexes to the Directive).

From the initial steps of implementing the Directive, it became clear that many member states faced a great lack of knowledge on habitat distribution (Evans 2006). Although most member states have tackled this problem through intensive mapping projects, often by manual field surveys and with varying levels of detail, this is just the first step. Future stages in the implementation of the Directive involve setting up a monitoring and surveillance scheme by 2013, and reporting on the 'conservation status' of the habitats on a six-yearly basis. These stages will require detailed, reliable and up-to-date habitat distribution maps, stretching further than merely attributing a given vegetation patch to a habitat type, but also giving indications on its quality. National and regional authorities liable for nature conservation are thus faced with a major and urgent need for data, but limited means to acquire it.

Remote sensing is the science and art of obtaining information about an object, area or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area or phenomenon under investigation (Lillesand et al. 2008). This definition highlights the two basic steps of the process: image data acquisition; and subsequent information extraction.

* Corresponding author. Tel.: +32 2 525 03 44; fax: +32 2 558 18 05.
E-mail addresses: jeroen.vandenborre@inbo.be, jeroen.vandenborre@scarlet.be (J. Vanden Borre).

1617-1381/$ – see front matter © 2010 Elsevier GmbH. All rights reserved.
doi:10.1016/j.jnc.2010.07.003

Image data acquisition is performed by sensors, operated from airborne or spaceborne platforms, that measure electromagnetic energy emitted and reflected by the Earth's surface. Originally, images were recorded on film and subsequently developed into analogue photographs, but digital sensors have now gradually replaced these early cameras. Progress in sensor development has led to images with ever higher spatial and spectral resolution. Imaging spectroscopy, lidar, radar and multiangle remote sensing constitute new technologies of particular relevance to (vegetation) ecology (Aplin 2005). Today, just over 100 observation satellites are in orbit round the Earth, mostly at altitudes of 600–900 km, carrying a wide variety of sensors each with their spatial, temporal, spectral and radiometric resolutions, depending on the purpose (CEOS 2009). Nagendra and Rocchini (2008) present a brief overview of satellite sensors useful for biodiversity research.

The process of information extraction has evolved rapidly too. Visual interpretation has long been the most obvious way to extract information from images, and it is still widely used. However, it is time- and labour-intensive and relies on subjective judgements (Lillesand et al. 2008). Throughout the last decades, numerous computer-assisted analytical tools have been developed to enhance information extraction. These mainly exploit the spectral information in the image, and incorporate reference data (e.g. from field-checks) to assign pixels to a certain class. More recently, there is a growing field of object-based analysis methods that incorporate spatial information in the image for classification, thus mimicking the way the human eye evaluates spatial patterns for object recognition (Blaschke et al. 2008).

Using remote sensing for habitat mapping and monitoring offers multiple advantages over traditional field mapping, such as faster map production, insight into inaccessible terrain (e.g. large wetlands, remote mountain areas, restricted military areas), and increased repeatability of the mapping process (Buiten & Clevers 1990). Nature conservation agencies have long recognised the potential of remote sensing, and have integrated visual interpretation of aerial photographs as an important tool in their operational workflow. In contrast, the adoption of more advanced, computer-assisted analysis techniques is lagging behind (Gross et al. 2009; Mehner et al. 2004), a finding which is also seen in the related discipline of landscape ecology (Newton et al. 2009; but see Groom et al. 2006). Ecologists, in general, seem to be reluctant to adopt new approaches (Aplin 2005). In the application field of Natura 2000 habitat mapping and monitoring, the operational use of computer-assisted remote sensing analysis is seemingly limited to pilot projects and exemplary cases (e.g. Bock et al. 2005a; Diaz Varela et al. 2008; Förster et al. 2008; Frick et al. 2005). In the past, advanced remote sensing techniques indeed fell short in mapping very detailed and specific biotopes like Natura 2000 habitats (Bock et al. 2005b), but technology is evolving rapidly, and newly emerging methodologies are opening up opportunities for novel applications of remote sensing data in monitoring (Aplin 2005; Gross et al. 2009; Turner et al. 2003).

The main reason for the gap between the remote sensing community and the potential user community of monitoring experts seems to result from unfamiliarity and continued misperceptions of each other's fields of work (Kennedy et al. 2009; Turner et al. 2003): Nature conservation organisations are generally unacquainted with remote sensing, and may not know what to expect from it or how to interpret and use it. Remote sensing scientists on the other hand may be focusing on technological development in their own field of specialism in the first place, without knowing exactly what nature conservationists need and how they intend to use it. This may lead to unreasonable expectations of end-users, the application of remote sensing methods that are not fully suited for the given purpose, disappointment of the end-users when the final products are delivered, and eventually a general disbelief in the added value of remote sensing.

This paper focuses on defining the opportunities and bottlenecks for future application of advanced remote sensing methods in the mapping and monitoring of Natura 2000 habitats. By specifically concentrating on the existent gap between producer and stakeholder expectations, we identify some of the most important issues that need to be tackled to pave the way for a closer integration of both areas. The paper consists of four sections. Firstly, we analyse the legal context of Natura 2000 and the Habitats Directive, and identify the data needs that follow from it at different spatial levels. Secondly, we take stock of the current use of remote sensing in Natura 2000 habitat reporting, as disclosed by a recent EU-wide reporting event. Thirdly, we explore the attitude of the monitoring community towards the use of remote sensing, and define opportunities and constraints for remote sensing in the process of Natura 2000 habitat mapping and monitoring. Finally, we formulate recommendations to facilitate the adoption of remote sensing in this application field.

Methods

In order to reach our objectives, we carried out a careful screening of relevant literature and existing data, and conferred with key parties involved in the Natura 2000 process.

The Habitats Directive lays down the general outline of the monitoring and reporting obligations on Natura 2000 habitats. Detailed reporting requirements are elaborated, not in the Directive itself, but in several accompanying notes, guideline documents and appendices issued by the European Commission and other European institutions (e.g. European Commission 2005a; ETC/BD 2006a). Additionally, member state representatives have produced numerous reports, short notes and discussion papers that explore the consequences of the reporting for their particular cases. In the first part of this study, we reviewed and analysed many of these documents and deduced which kind of data member states need at what spatial level, to fulfil their reporting obligations. In the second part, we took advantage of data on habitat conservation status recently (2007) reported by 25 member states to the EU, to get a view on the actual use of remote sensing in Natura 2000 habitat status reporting. In the third and fourth part, we took a more direct approach by consulting members from the Natura 2000 monitoring community, to analyse their attitude and expectations towards the use of remote sensing in their specific application field. We paid special attention to the opportunities for remote sensing as perceived by these potential users, the preconditions to its use, and apparent bottlenecks that hinder its application. Two workshops that brought together the remote sensing and the monitoring communities, one in Brussels, Belgium (24 October 2008; see http://habistat.vgt.vito.be), and one in Bonn, Germany (22–23 January 2009; see Graef et al. 2009), laid out the major foundations of this part of the study.

In this paper the terms 'habitat' and 'habitat type' refer to the habitats of Community interest, listed in the Annex 1 of the Habitats Directive and further defined in European Commission (2007). The term 'remote sensing' is used here to indicate the more advanced, computer-assisted analytical tools for information extraction from imagery, in particular from advanced sensors (e.g. multi- and hyperspectral, LiDAR, radar). Thus, we specifically exclude the purely visual interpretation of aerial photographs or other (analogue or digital) images.

Natura 2000 reporting obligations

The European Union Council Directive on the conservation of natural habitats and of wild fauna and flora (92/43/EEC), also known as the 'Habitats Directive' or the 'Fauna-Flora-Habitats (FFH) Directive', was adopted in 1992 as an implementation instrument of the 1979 Bern Convention on the Conservation of European Wildlife and Natural Habitats. Together with the Birds Directive (79/409/EEC), it constitutes the main legal framework for nature conservation in the European Union. Its aim is to contribute to the conservation of natural habitats and species of wild fauna and flora in the European territory of the member states (European Commission 2003).

The habitats protected by the Habitats Directive are listed in its Annex 1. Originally, this annex listed 168 habitats. It was amended at various occasions, especially upon accession of new member states, and currently lists 231 habitat types in nine major habitat formations. Each habitat is coded with a unique four-digit number. The list of habitats is very heterogeneous; the majority are defined by vegetation, but some are defined by physiographic features that may contain vegetated and unvegetated parts of different kinds (e.g. 1130 Estuaries). They may occur at a high variety of scales (from point locations up to complete landscapes), and also differ greatly in their inherent variability. The term 'biotopes' or 'biotope complexes' would therefore be scientifically more correct (Evans 2006). Guidance on the definition of the habitats is given in the European Interpretation Manual (European Commission 2007 and earlier versions), which was subsequently translated by the member states into national interpretation guides (e.g. Bensettiti 2001–2005; Ellmauer & Traxler 2000; Gathoye & Terneus 2006; Janssen & Schaminee 2003; Sterckx et al. 2007).

In order to achieve the aims of the Habitats Directive, member states have to bring or maintain the habitats on their territory to a favourable conservation status. The latter concept refers to a situation where the habitat is prospering (in both quality and extent) and has good prospects to do so in the future as well (ETC/BD 2006a). More specifically, member states have a number of liabilities to achieve the general aim of the Directive: (1) designate Natura 2000 sites where habitats occur (Art. 3 and 4 of the Directive); (2) set up monitoring schemes to follow the status of these habitats (Art. 11); and (3) report the findings of this monitoring to the European Commission on a six-yearly basis (Art. 17).

Designation of Natura 2000 sites

In the past two decades, member states have identified the most valuable sites where habitats targeted by the Directive occur, and have granted these sites protection through inclusion in the Natura 2000 network. Upon site proposal, member states provided relevant data to the European Commission through the Standard Data Forms (European Commission 1997), including site name and location, list of all habitats present with their surface area and conservation status in the site, management activities applied in the site, etc. The Commission expects this database to be kept accurate and valid, with at least six-yearly updates (European Commission 2005b). The Natura 2000 network is now nearing completion and includes at present about 17% of the terrestrial area of the EU (European Commission 2009a).

Formal protection as a Natura 2000 site means a.o. that the integrity of the site must be preserved. Any plan or project with potential significant impacts on the site must therefore be subject to an 'appropriate assessment' prior to its execution, and any negative effects must be mitigated or compensated. A proper implementation of this obligation requires detailed, spatially explicit baseline data of the location, extent and quality of the habitats within each site. Unfortunately, for present-day practice such data is often missing (European Commission 2008).

Monitoring and surveillance

Setting up monitoring systems to keep track of the conservation status of habitats is a legal obligation under Article 11 of the Habitats Directive. These monitoring systems should not be limited to the Natura 2000 sites only, but should enable founded conclusions on the conservation status of the habitats in the whole administrative territory of the member state. The European Commission does not provide guidelines as to how this monitoring should be done. Member states are free to choose their means and methods of gathering data, as long as the resulting data proves useful for the reporting under Article 17 (Cantarello & Newton 2008). Unfortunately, this makes it more difficult to provide consistent figures on habitat conservation status across Europe, since monitoring methods differ significantly between countries and/or regions (Bunce et al. 2008; Mücher 2009).

Reporting the conservation status of habitats

Article 17 of the Directive obliges member states every six years to report on the conservation status of the habitats within their territory, drawing on the results of the monitoring under Article 11. The assessment of conservation status is based on four parameters (European Commission 2005a; ETC/BD 2006a): (1) *area*, being the sum of the patches that are actually occupied by the habitat; (2) *range*, being the region in which the habitat is likely to occur provided local conditions are suitable; (3) *specific structures and functions*, encompassing typical species and various indicators of habitat quality; and (4) *future prospects* for the survival of the habitat in the member state. The assessment involves application of a traffic-light scheme, where each parameter can be in a 'favourable' (green), 'unfavourable-inadequate' (amber) or 'unfavourable-bad' (red) state. Criteria and thresholds for identifying the state of each parameter are provided in the general evaluation matrix (Table 1; European Commission 2005a). These include trend magnitudes for area and range (maximum 1% decline per year), the difference between area/range and a given reference value (maximum 10% below the reference), and the amount of habitat area with specific structures and functions in bad condition (maximum 25% of area in bad condition).

Interpretation of the parameters *area* and *range* is rather straightforward, but is associated with a high demand of data, i.e. knowledge on the nationwide distribution of habitats. Interpreting the parameter *specific structures and functions* is more difficult, since it covers all aspects of habitat quality. Several member states have elaborated a framework to assess the local quality of habitat locations, using indicators and threshold values that are adapted to the country-specific variability of the habitats (e.g. Ellmauer 2005; Søgaard et al. 2007; T'jollyn et al. 2009; Verbücheln et al. 2002). The assessment is first carried out on individual habitat locations. Weighted integration of these outcomes to the country- or biogeographical level then reveals whether more or less than 25% of the habitat area is in bad condition. Table 2 presents an example of such an assessment matrix for the habitat 2310 ('Dry sand heaths on inland dunes') in Flanders (Belgium). Fig. 1 shows an extract from a habitat map of a heathland site, indicating the type and condition of individual habitat patches. Finally, the parameter *future prospects* is intended to indicate anticipated future trends in area, range and habitat quality, and estimates the expected impact from threats in the upcoming reporting period. Its assessment is mainly based on expert judgement.

Using the information reported by all member states, the European Commission draws up a six-yearly composite report with an overview of the actual conservation status of all habitats in Europe, integrated to the level of the European biogeographical regions (ETC/BD 2006b). The latest reporting event under Article 17 took place in 2007 (reporting period 2001–2006) and involved the EU-25 (all member states except Romania and Bulgaria). The subsequent composite report, which appeared in 2009, showed that overall only 17% of the 701 habitats assessments at European level led to the conclusion of favourable condition (European Commission 2009b; see also http://biodiversity.eionet.europa.eu/article17).

Data needs at three levels

In summary, the data needs resulting from the Natura 2000 reporting obligations can be grouped at three spatial levels: (1) site level; (2) member state level; and (3) European level.

Table 1
General evaluation matrix for the assessment of overall conservation status of a habitat per biogeographical region within a member state (MS), as used in the process of reporting under Article 17 of the Habitats Directive (from: European Commission 2005a).

Parameter	**Conservation Status**			
	Favourable ('green')	**Unfavourable – Inadequate ('amber')**	**Unfavourable - Bad ('red')**	***Unknown (insufficient information to make an assessment)***
Range	Stable (loss and expansion in balance) or increasing AND not smaller than the 'favourable reference range'	Any other combination	Large decrease: Equivalent to a loss of more than 1% per year within period specified by MS OR More than 10% below 'favourable reference range'	*No or insufficient reliable information available*
Area covered by habitat type within range	Stable (loss and expansion in balance) or increasing AND not smaller than the 'favourable reference area' AND without significant changes in distribution pattern within range (if data available)	Any other combination	Large decrease in surface area: Equivalent to a loss of more than 1% per year (indicative value MS may deviate from if duly justified) within period specified by MS OR With major losses in distribution pattern within range OR More than 10% below 'favourable reference area'	*No or insufficient reliable information available*
Specific structures and functions (including typical species)	Structures and functions (including typical species) in good condition and no significant deteriorations / pressures.	Any other combination	More than 25% of the area is unfavourable as regards its specific structures and functions (including typical species)	*No or insufficient reliable information available*
Future prospects (as regards range, area covered and specific structures and functions)	The habitats prospects for its future are excellent / good, no significant impact from threats expected; long-term viability assured.	Any other combination	The habitats prospects are bad, severe impact from threats expected; long-term viability not assured.	*No or insufficient reliable information available*
Overall assessment of CS	All 'green' OR three 'green' and one 'unknown'	One or more 'amber' but no 'red'	One or more 'red'	Two or more 'unknown' combined with green or all "unknown'

Table 2
Indicators and thresholds for the assessment of the local conservation status (CS) of patches of the habitat type 2310 (‘Dry sand heaths with *Calluna* and *Genista* on inland dunes’) in Flanders (Belgium) (after: T'jollyn et al. 2009).

Habitat type 2310	Indicator	Good local CS: A – good quality	Good local CS: B– moderate quality	Bad local CS: C – low quality	Explanatory notes
Habitat structure	cover of dwarf shrubs	≥ co-dominant		< co-dominant	dwarf shrubs include: *Calluna vulgaris*, *Erica tetralix*, *Genista anglica*, *G. pilosa*, *Vaccinium vitis-idaea*
	Age structure of *Calluna vulgaris*	all phases present	2 or 3 phases present	only 1 phase present	phases are: pioneer, building, mature and degenerate phase
	bare sand	> 10%	1 – 10%	< 1%	
	cover of mosses and lichens	> 10%	1 – 10%	< 1%	includes all mosses and lichens except *Campylopus introflexus*
Vegetation	presence of key species	*Calluna* and 3 or more other key species (at least occasionally) present	*Calluna* and 1 or 2 other key species (at least occasionally) present	only *Calluna* present or all key species less than occasionally present	key species include: *Calluna vulgaris*, *Agrostis vinealis*, *Aira praecox*, *Carex arenaria*, *Corynephorus canescens*, *Cuscuta epithymum*, *Filago minima*, *Genista anglica*, *G. pilosa*, *Spergula morisonii*, *Teesdalia nudicaulis*
Indicators of disturbances	cover of grasses and tall herbs	< 30%	30 – 50%	> 50%	grasses include: *Molinia caerulea*, *Deschampsia flexuosa*, *Agrostis* spp.; tall herbs include: *Pteridium aquilinum*, *Rubus* spp.
	cover of trees and shrubs	< 10%	10 – 30%	> 30%	
	cover of invasive alien species	0%	< 10%	≥ 10%	in particular: *Campylopus introflexus*

At the level of individual Natura 2000 sites, effective conservation management and appropriate impact assessments of plans and projects require high-standard, spatially explicit data. A detailed and up-to-date inventory of the habitats in the sites is indispensable, providing accurate indication of the location, size and shape of each habitat patch, and not least, its quality (Mehner et al. 2004). Stakeholders at this level are site owners and managers (public, private and non-governmental), local authorities, and companies doing environmental impact analyses.

At the member state level, the need for data mainly stems from the six-yearly requirement of reporting under Article 17. Habitat distribution maps are an indispensable part of the report and should be up-to-date and accurate enough to allow for reliable area, range and trend estimates. Equally important is the assessment of habitat quality, in particular the proportion of the habitat area in bad quality (to be reported as a figure, not as a map). Basic data on driving forces and pressures may further be necessary to assess the habitat's future prospects. Stakeholders at this level are national and regional nature conservation administrations that are responsible for reporting to the EU, and/or that want to evaluate the effectiveness of their proper nature conservation policies.

At the European level, the so-called composite report is the main instrument for assessing progress towards the aims of the Habitats Directive. The data used is those reported by the member states, but despite guidelines, there is a clear lack of consistency in member states' approaches. This renders the integration of data at a European level difficult and in some cases even impossible (ETC/BD 2008). Member states have for example reported habitat distribution data in various ways (point locations, fine or coarse grids, polygons with varying minimum mapping units, etc.), making even the simplest of integration actions, the compilation of a Europe-wide habitat distribution map, an extremely difficult task. As a consequence, there is a clear need for a more harmonised approach at this level. Stakeholders are the European Commission and its Directorate-General Environment, the European Environment Agency (EEA) and the European Topic Centre on Biological Diversity (ETC/BD).

Current use of remote sensing for habitat reporting

For the latest Art. 17 report (2007), member states were asked to indicate the method used for the area estimation of each habi-

Fig. 1. Extract from a habitat map of a heathland area in Flanders (Belgium). Annex I habitat types were mapped in the field, and local conservation status of each patch was scored using T'jollyn et al. (2009; see Table 2). Habitat types: 2310 – 'Dry sand heaths with *Calluna* and *Genista*'; 2330 – 'Inland dunes with open *Corynephorus* and *Agrostis* grasslands'; 4010 – 'Northern Atlantic wet heaths with *Erica tetralix*'; 7150 – 'Depressions on peat substrates of the *Rhynchosporion*'; nh – no Annex I habitat. Vertical (green) hatching: good local conservation status. Horizontal (red) hatching: bad local conservation status. Habitat map taken from Paelinckx et al. (2009), property of INBO. Base image property of AGIV and Provincie Limburg. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

tat type, as one or more of the following three options: (1) only or mostly based on expert opinion; (2) based on remote sensing data (possibly including an element of 'ground-truthing'); or (3) ground based survey. 18 out of 25 member states indicated having used remote sensing data (alone or in conjunction with other methods) for estimating the area of in total 130 different habitat types in 382 habitat conservation status assessments (14% of all habitat assessments, total $N = 2759$, data provided by ETC/BD). By contrast, information on the underlying remote sensing projects that actually produced the data used for the reporting is hard to find, since only little is published and the persons responsible for the reporting are mostly not the people that were involved in the remote sensing projects. Experts in Belgium, Ireland, Luxembourg, Spain and Sweden confirmed that the remote sensing data they used for their reports were all or to a large extent derived by visual interpretation of airborne or satellite imagery (see e.g. Departament de Medi Ambient i Habitatge 2006; National Parks & Wildlife Service 2007; Sanz Trullén & Benito Alonso 2007; Skånes et al. 2007). We could not find enough details to be conclusive for other member states, but since this technique is widely integrated into vegetation and habitat mapping, we can assume that the same situation applies to many of them. The actual use of more advanced (semi-automated or automated) remote sensing methods in the latest reporting event remains unknown, but is seemingly very limited.

On the reporting form, the 'methods used'-field was followed by a field asking for the quality of the data used for habitat area estimation. This field allowed only one entry per habitat and per biogeographical region, with three options to choose from: poor; moderate; or good. Table 3 shows a contingency table of the entries of both fields. Interestingly, there is a clear dependency of the chosen value for data quality upon the methods by which this data was gathered (Pearson Chi^2 test: Chi^2 = 822.18, d.f. = 4, $P < .001$, $N = 2088$; 671 records with missing values were omitted from the analysis). The administrations that did the reporting generally considered ground survey to deliver good or moderate quality data, while remote sensing was overall seen as moderately reliable, and expert opinion was judged to yield only moderate to poor reliability. This shows that nature conservation administrations generally have less confidence in remote sensing than in field work. Most likely, this stems from their view of remote sensing as comprising visual interpretation of an image by an operator at his desk, based on his knowledge and experience, but without (or with only limited) subsequent field checking.

Opportunities for remote sensing

Discussions with over 30 monitoring experts from administrations in 13 EU-member states, aiming to explore their expectations towards remote sensing, revealed that they look upon it with an open but critical attitude. They see clear opportunities for its application in their work processes, and relate these opportunities to the following three main data requirements on habitats.

Habitat distribution

The production of habitat distribution maps, at various scale levels, constitutes an obvious area of high potential for remote sensing, as experts indicated. The advent of hyperspatial and hyperspectral sensors has indeed greatly enhanced the possibilities of distinguishing related habitat types at very fine scales (Turner et al. 2003). The end-users need such maps in the first place for estimat-

Table 3
Contingency table of methods used and perceived data quality for habitat area estimation, as reported by member states in the Art. 17 reporting on habitat conservation status in 2007. Records with missing values and records where two or more methods were reported were omitted. Source data provided by ETC/BD.

Used method	Quality of data			
	Good	Moderate	Poor	Total
Ground survey	421	415	72	908
Remote sensing	27	236	31	294
Expert opinion	22	407	457	886
Total	470	1058	560	2088

ing range and area of habitats, but they could also serve to define and update the sampling frame (the statistical 'population') of habitats for which field sample surveys are in place. The use of remote sensing also provides a major opportunity for harmonising Natura 2000 habitat mapping throughout Europe.

Change detection

Remote sensing is frequently identified as a powerful tool for detecting change (Kennedy et al. 2009; Mücher et al. 2000). Remote sensing driven change maps not only provide excellent instruments for estimating trends in range and area, but they also localise the areas where change has occurred. Monitoring experts highly value this asset, because it allows subsequent field work to concentrate on these areas, possibly yielding a significant increase in cost-efficiency.

Habitat quality

Although the usefulness of remote sensing for habitat quality assessment is less straightforward for many monitoring experts, our consultations did reveal that there is an interest in remote sensing mediated delivery of data on selected indicators of habitat quality. Its potential for spatial indicators (e.g. patch size, fragmentation and connectivity measures; Mitchley & Xofis 2005) and coverage of invasive (e.g. Andrew & Ustin 2008) or other unwanted species (e.g. shrub and tree encroachment; Waser et al. 2008) has already been demonstrated. But remote sensing can also provide methods to monitor specific biophysical and biochemical indicators of ecosystem functioning (e.g. leaf area index, normalised difference vegetation index, chlorophyll content, fractional cover, phenology, vegetation height; Kerr & Ostrovsky 2003; Mücher 2009). Currently, many of these parameters are mainly applied at large scales (global, continental), see e.g. the Core Services on Bio-Geophysical Parameters of the EC-funded Geoland project (http://www.gmes-geoland.info/CS/CSP/index.php), which aims to facilitate policy-supporting applications in the fields of climate change (carbon fluxes), food security (crop monitoring), and global landcover change. The relation of such parameters with the more traditional habitat quality approach at the scale of the habitat patch is still to be investigated.

The strength of remote sensing is its ability to deliver quantitative measures of such parameters in a standardised manner with full coverage over larger areas, whereas field surveys can only deliver this through point sample measurements and subsequent interpolation. The provision of such data by remote sensing may open new ways of looking at quality of Natura 2000 habitats.

Preconditions for the use of remote sensing

Despite their open attitude, monitoring organisations and managers are not prepared to use remote sensing at any price. Instead, experts indicated that there has to be a clear benefit to its use as compared to traditional methods, especially in terms of cost-effectiveness. To convince monitoring experts and hence enable future use in Natura 2000 reporting, remote sensing products should meet the following preconditions:

Remote sensing products should be equal or higher in quality than what can be achieved through field surveys

Nature conservation organisations want to work with reliable and high-quality data. Quality can however be reflected in many different aspects of the product, such as classification accuracy, thematic detail, spatial resolution, geometric accuracy, areal extent covered, product type (vector/raster, pixel-/object-based), repeatability and stability of the product, and representativeness for the actual situation. Depending on the strengths and weaknesses of their current products, organisations will value each of these quality aspects differently when evaluating new products. For instance, organisations that dispose of detailed maps of habitats on their territory will set high standards for the level of detail and accuracy of a new, remote sensing driven map, while administrations that lack such maps may already find benefit in a remote sensing map of broad habitat groups.

Thematic accuracy of remote sensing maps is perhaps seen as the most important quality aspect by monitoring experts in our study. Since this accuracy is rarely above 80%, the latter perceive these maps as, at least partly, unreliable. Unfortunately, some fail to recognise that the same may apply to field-based maps: repeatability of traditional field mapping is known to be low if no adequate quality control/assurance system is included (e.g. Cherrill & McClean 1999; Stevens et al. 2004). Nevertheless, an accuracy assessment of field maps is often neglected or non-existent, leading users to the false belief that the field map represents the 'truth'. It is only fair that accuracy standards for remote sensing products should be based as much as possible on a comparison with existing field-based products, and not be set to unrealistically high values.

Remote sensing products should be available at equal or lower cost than products deduced from field surveys

Nature conservation organisations are faced with limited means to accomplish their tasks, and are therefore reluctant to dedicate large sums to the development of a product without knowing exactly what they will get. To date, remote sensing products are often still very expensive, mostly due to the high cost of image data. In the mid- to long-term, a cost reduction can be expected from bringing techniques into wider operation. Meanwhile, a short-term option is to make use of imagery that is already available at no extra cost to the organisation. Often this includes data provided by other public service organisations, such as national mapping agencies. Agreements can be sought with other sectors that have similar data needs (e.g. agriculture), to ensure that newly acquired data is suitable for vegetation applications (implying acquisition during the growing season, with sensors that provide appropriate spatial and spectral resolution).

In reality, there is of course a trade-off between the importance that is attached to the different quality specifications and the cost of the product. A remote sensing product that is lower in thematic detail, but much more up-to-date than a comparable field survey product, may be well worth using, especially when it is also cheaper to produce. Conversely, a considerable gain in quality of the data may justify using a product that is more expensive. On the other hand, monitoring experts also indicated that a product should not deliver higher quality than is strictly needed, if that implies that part of the cost for the product could have been diverted to other purposes.

Bottlenecks and pathways to the integration of remote sensing in Natura 2000 habitat monitoring

In the following, we discuss a number of bottlenecks that hamper the general application of remote sensing in habitat monitoring. Concentrating efforts on tackling these issues may significantly enhance its applicability in this field.

Harmonisation and standardisation of approaches

Remote sensing, as a science, is a very diverse field. Potential users are mostly unfamiliar with the large variety of imagery and methodologies that are available, making it impossible for them to find the most suitable method for their needs. They call for the development of standardised approaches (in terms of image specifications, processing and classification techniques, time of image acquisition, ...) that work best for their specific applications and which they can apply easily. However, the possible requirements and applications in the field of habitat monitoring are equally diverse. Since member states are free to determine their own methods and means for the monitoring of Natura 2000 habitats, nature conservation agencies take the type and amount of data they already have at their disposal as a starting point to identify their specific monitoring needs. Standardised remote sensing products will therefore rarely suit the specific requirements of more than one or two end-user agencies. A harmonisation of monitoring approaches across the European Union, as an interdisciplinary collaboration between both research communities, could pave the way for remote sensing products that are applicable in several member states. We illustrate this potential with two examples.

Ex. 1: What pixel size is appropriate?

Spatial resolution is perhaps the most important characteristic of a remote sensing product, because it has huge impacts on its applicability. Remote sensing specialists are aware of the importance of matching the spatial resolution with the object under investigation (e.g. Nagendra 2001), yet they rarely receive valuable input on the matter from the future users, because the latter generally assume that higher spatial resolution will lead to better results. Hence, spatial resolution is usually determined by the choice of sensor or imagery, instead of the other way around.

It is plausible to assume that a habitat can be characterised by what we call here an 'intrinsic scale', by which we mean that the surface area of most patches of that habitat falls within a typical size range. Such an intrinsic scale will not be the same for all habitats in a given area, and this should be taken into account when defining the required spatial resolution of the map product. The choice of certain imagery, through its spatial resolution, could limit the applicability of the product to certain habitats and at the same time exclude others. For instance, a field mapping of heathland habitat 4010 ('Wet heaths with *Erica tetralix* L.') in the Campine region of northeast Belgium revealed that 10% of the mapped habitat patches were under 700 m^2 (total $N = 872$; data from Paelinckx et al. 2009). For habitat 7150 ('Depressions with *Rhynchosporion*') in the same area, the corresponding value was 200 m^2 (total $N = 27$). Following the practical rule-of-thumb that pixel area should be 2–5 times smaller than the area of the objects of interest (O'Neill et al. 1996), mapping the larger 90% of these habitat patches would require spatial resolutions of 12–18 m and 6–10 m pixel side, for habitat 4010 and 7150 respectively (where pixel side is calculated as the square root of half or one fifth of the patch size). In addition, mapping also the smallest 10% of patches with sufficient accuracy, or mapping internal patch heterogeneity for e.g. quality assessment, would require even much smaller pixel sizes (<5 m; Lechner et al. 2009).

Förster et al. (2008) note that there is at present no standard which defines a spatial reference size (e.g. a minimum mapping unit) for habitat mapping, and we have not found any study on intrinsic scales of habitats either. Handbooks for mapping do give minimum mapping units, but these are usually the same for all mapped elements and are based on other arguments than intrinsic habitat scales (e.g. operability of the method in the field). It is possible that research on this topic was hitherto hampered by the limits of field mapping methods: one cannot map down to the smallest detail in the field, and (subjective) decisions have to be made on what to group together as an element. Yet, with monitoring becoming more and more important, and remote sensing becoming common practice, this knowledge gap will become more and more prominent. The question needs to be addressed by ecologists, but thanks to its versatility, remote sensing may well prove a useful tool for this type of research.

Ex. 2: Harmonising habitat typologies

Natura 2000 habitat typology may seem uniform throughout the EU, but this is just in appearance: member states have established different interpretations of the habitat definitions, often arising from relating the Natura 2000 types to their national vegetation classifications. Moreover, Natura 2000 habitats can be very heterogeneous in nature, including many possible subtypes. Both aspects hinder the data compatibility between member states and the integration to a higher, European level. A common and consistent typology of European biotopes, to replace the present multitude of both European and national classification systems, could provide an important step towards a harmonisation of habitat mapping across Europe, and is even a prerequisite to enable the establishment of a long-term habitat monitoring system (Keramitsoglou et al. 2005). Such a typology should be comprehensive (include all parts of the domain), hierarchical in structure (to allow for accommodation of the thematic detail of the map legend to the map's scale level; Lengyel et al. 2008), and enable unambiguous translation into Natura 2000 habitats.

It is probably illusive, though, to think that such a typology could also become the standard legend for all remote sensing based habitat mapping. Remote sensing and field work measure different aspects of the same reality, mainly mediated by the scale at which they operate. Many remote sensing projects therefore include the development of linkage systems to relate remote sensing data with field data, and to translate remote sensing measures into meaningful information pertaining to the desired classes (in this case Natura 2000 habitats; see Haest et al. submitted for publication for an elaborated example). The integration of such dedicated linkage systems into a common information framework, encompassing relationships at different scales, is however very likely to stimulate the interchangeability of remote sensing methods between different sites and member states across Europe.

Development of readily useful products with readily available data

In recent years, nature conservation administrations have been faced with high data needs over short time. Some monitoring experts have looked into the possibilities offered by remote sensing, but noticed that many of these products are still in an early development phase, and that it will require many more years to reach a fully operational phase. They feel that an important reason for this is in the desire of remote sensing scientists to contribute to technological progress in their own specialisms. Such cutting-edge science very often makes use of new and expensive sensors and methods, for which the large scale applicability in the near future still needs to be demonstrated. These users suggest that remote sensing scientists should focus on developing products and services that fulfil the existent data needs, using imagery and technology that is and will be easily available now (e.g. Landsat) or in the near future (e.g. GMES Sentinel-2).

Integration of RS-products into existing GIS-systems

Potential users of remote sensing products do not want to be burdened with the need for new software or extensive training to learn to work with it. They want remote sensing products and services to be user-friendly and intuitive and to integrate seamlessly with the GIS-systems and geo-databases that they already have in place (Bock et al. 2005b).

Validation of methods using a proper validation framework

The most effective way to stimulate the adoption of remote sensing in the field of habitat monitoring is by providing considerable gain on cost-effectiveness when compared to traditional (field) methods. But assessing the merits and limitations of several possible approaches, including field methods, should be done in an objective manner. This requires a dedicated validation framework. Such a framework should evaluate not only the classical thematic map accuracy (of both remote sensing *and* field maps), but also include compliance to other requirements such as suitability for the intended use, repeatability of the obtained result, transferability to other settings, a comparison of the associated costs, and others.

Strengthening the dialogue between the remote sensing and nature conservation communities

Mutual understanding requires a common language to be used. In order to resolve misunderstandings and perceived mismatches, increased cooperation and communication between producers and final users is needed. On the one hand, this can be achieved by setting up facilities for an enhanced sharing of ideas and results. Monitoring experts expressed their need for comprehensive, plain overviews of what is feasible with remote sensing. Attempts to compile such overviews have been made before (e.g. Ahlcrona et al. 2001; CEH 2007), but they are often rapidly outdated or too specific to serve the broader community. Remote sensing scientists from their side expressed a wish for more information on what kind of field data is available among nature conservation organisations, and what data is still needed. Such information could be brought together in databases or web-based compendia, to facilitate exchange and enable easy updating.

On the other hand, end-users need to get involved in the development of remote sensing products from as early as possible. This requires efforts from both sides; remote sensing scientists have to include users in the development process, listen to their requirements and expectations and take these into account. Monitoring experts have to give up their passive attitude towards remote sensing, and be prepared to think and re-think about their requirements, express them in terms that remote sensing scientists can understand and work with, and cooperate to find solutions to apparently insurmountable problems. As stated by Kennedy et al. (2009), success is the responsibility of both parties.

Conclusions

In this paper, we aimed to define opportunities as well as constraints for a wider integration of advanced remote sensing methods in the mapping and monitoring of Natura 2000 habitats. The Natura 2000 programme and the Habitats Directive have indeed set high standards for nature conservation in Europe. Numerous stakeholders are involved, each with their specific data needs at the European, national or site level. The one thing they have in common, is that the extent or required detail of their needs generally goes well beyond what is practically achievable with field survey alone.

Up to now, the use of advanced (semi-)automatic remote sensing in operational Natura 2000 habitat monitoring has been very limited. This will have to change, but the solution will not come from remote sensing specialists alone. Fortunately, monitoring experts do see potential applications for remote sensing in habitat mapping, change detection and even quality assessment. They are also willing to adopt remote sensing methods, provided that they are affordable and offer good quality products. But they often fail to see the importance of their active cooperation in the process.

A number of actions could be taken to enhance the integration of remote sensing and habitat monitoring, such as an enforced effort for harmonisation and standardisation of approaches, an increased interest in developing readily useful products, which integrate seamlessly with existing workflows, and a fair validation of both traditional and remote sensing methods. Most importantly though, there is a need for a more active involvement from both parties, especially the monitoring community, in order to develop products that really suit the needs of their future users. We call upon monitoring experts and remote sensing scientists to enter into a dialogue, discover what can reasonably be expected, define exact user and product requirements, exchange ideas, data and results, set standards for a common validation framework and strive for integration and synergies between remote sensing and field approaches. Only this way can the potential of remote sensing be exploited to the benefit of the preservation of Europe's natural heritage.

Acknowledgements

This paper contains material from workshops held in Brussels and Bonn. The authors wish to thank the Brussels workshop participants from all over Europe for sharing their ideas with us. Thanks also to Dr. F. Graef (Bundesamt für Naturschutz, Germany) and the participants in the Bonn workshop for allowing the first author to join in the discussion. We gratefully acknowledge the European Topic Centre on Biological Diversity (ETC/BD) for kindly providing data on the use of remote sensing in the latest Article 17 reporting event, as well as all colleagues across Europe who provided more details on the approaches in their country. The comments of two anonymous referees were very helpful to improve the paper. This research was carried out as part of the Habistat project (http://habistat.vgt.vito.be), funded by the Belgian Science Policy Office through its STEREO II programme (contract no. SR/00/103).

References

Ahlcrona, E., Bronge, L. B., & Willén, E. (2001). *Satellitdata och svenska naturtyper i Natura 2000. Möjlighetsstudie*. Solna: Metria, Lantmäteriet.

Andrew, M. A., & Ustin, S. L. (2008). The role of environmental context in mapping invasive plants with hyperspectral image data. *Remote Sensing of Environment*, *112*, 4301–4317.

Aplin, P. (2005). Remote sensing: Ecology. *Progress in Physical Geography*, *29*, 104–113.

Bensettiti, F. (Ed.). (2001–2005). *Cahiers d'habitats Natura 2000 – Connaissance et gestion des habitats et des espèces d'intérêt communautaire*. Paris: La Documentation française.

Blaschke, Th., Lang, S., & Hay, G. J. (Eds.). (2008). *Object-based image analysis: Spatial concepts for knowledge-driven remote sensing applications*. Berlin, Heidelberg: Springer.

Bock, M., Rossner, G., Wissen, M., Remm, K., Langanke, T., Lang, S., et al. (2005a). Spatial indicators for nature conservation from European to local scale. *Ecological Indicators*, *5*, 322–338.

Bock, M., Xofis, P., Mitchley, J., Rossner, G., & Wissen, M. (2005b). Object-oriented methods for habitat mapping at multiple scales – Case studies from Northern Germany and Wye Downs, UK. *Journal for Nature Conservation*, *13*, 75–89.

Buiten, H. J., & Clevers, J. G. P. W. (Eds.). (1990). *Remote Sensing, theorie en toepassingen van landobservatie*. Wageningen: Pudoc.

Bunce, R. G. H., Metzger, M. J., Jongman, R. H. G., Brandt, J., De Blust, G., Elena-Rossello, R., et al. (2008). A standardized procedure for surveillance and monitoring European habitats and provision of spatial data. *Landscape Ecology*, *23*, 11–25.

Cantarello, E., & Newton, A. C. (2008). Identifying cost-effective indicators to assess the conservation status of forested habitats in Natura 2000 sites. *Forest Ecology and Management*, *256*, 815–826.

CEH. (2007). Annex 5: Fit of various EO sensors to selected habitat classes. In *Development of 'Land' Earth Observation Requirements as Input to the Defra Earth Observation Strategy. Final report v1.0*. Infoterra Ltd.

CEOS. (2009). CEOS Mission, instruments and measurements database online. Updated October 2009. In: Committee on Earth Observation Satellites (CEOS) (Ed.), *The Earth Observation Handbook. Climate Change Special Edition: 2009–2010*. Online at: http://database.eohandbook.com; accessed: 15/06/2010.

Cherrill, A., & McClean, C. (1999). The reliability of 'Phase 1' habitat mapping in the UK: The extent and types of observer bias. *Landscape and Urban Planning*, *45*, 131–143.

Departament de Medi Ambient i Habitatge. (2006). *Cartografia dels hàbitats a escala 1:50.000. Metodologia.* Barcelona: Government of Catalonia. Online at: http://mediambient.gencat.net/cat/el_medi/habitats/habitats_metodologia.htm; accessed: 15/06/2010.

Diaz Varela, R. A., Ramil Rego, P., Calvo Iglesias, S., & Muñoz Sobrino, C. (2008). Automatic habitat classification methods based on satellite images: A practical assessment in the NW Iberia coastal mountains. *Environmental Monitoring and Assessment*, *144*, 229–250.

Ellmauer, T. (Ed.). (2005). *Entwicklung von Kriterien, Indikatoren und Schwellenwerten zur Beurteilung des Erhaltungszustandes der Natura 2000-Schutzgüter. Band 3: Lebensraumtypen des Anhangs I der Fauna-Flora-Habitat-Richtlinie*. Vienna: Umweltbundesamt GmbH.

Ellmauer, T., & Traxler, A. (2000). *Handbuch der FFH-Lebensraumtypen Österreichs. Monographien Band 130*. Vienna: Umweltbundesamt GmbH.

European Commission. (1997). Commission decision of 18 December 1996 concerning a site information format for proposed Natura 2000 sites (97/266/EC). *Official Journal of the European Communities*, *L107*, 1–156 (24.04.1997)

European Commission. (2003). *Natura 2000 and forests: 'Challenges and opportunities' – Interpretation guide*. Luxembourg: Office for Official Publications of the European Communities.

European Commission. (2005a). *Note to the Habitats Committee. Assessment, monitoring and reporting of conservation status – Preparing the 2001–2007 report under Article 17 of the Habitats Directive. DocHab-04-03/03 rev.3*. Brussels: European Commission.

European Commission. (2005b). *Note to the members of the Habitats Committee. Updating of the Natura 2000 Standard Data Forms and Database. JAC D(2005)*. Brussels: European Commission.

European Commission. (2007). *Interpretation manual of European Union habitats – EUR27*. Brussels: European Commission, DG Environment.

European Commission. (2008). *Implementation of Article 6(4), first subparagraph, of Council Directive 92/43/EEC during the period 2004–2006. Summary report*. Brussels: European Commission, DG Environment.

European Commission. (2009a). *2008 Environment Policy Review – Annex 1 – Part 1: Environmental data and trends in EU-27*. Luxembourg: Office for Official Publications of the European Communities.

European Commission. (2009b). *Composite Report on the Conservation Status of Habitat Types and Species as required under Article 17 of the Habitats Directive. COM(2009) 358 final*. Brussels: European Commission.

ETC/BD. (2006a). *Assessment, monitoring and reporting under Article 17 of the Habitats Directive: Explanatory Notes & Guidelines. Final draft, October 2006*. Paris: European Topic Centre on Biological Diversity.

ETC/BD. (2006b). *The indicative Map of European Biogeographical Regions: Methodology and development*. Paris: European Topic Centre on Biological Diversity.

ETC/BD. (2008). *Article 17 Technical Report (2001–2006). Ch. 2: Data completeness, quality and coherence*. Paris: European Topic Centre on Biological Diversity. Online at: http://biodiversity.eionet.europa.eu/article17; accessed: 15/06/2010.

Evans, D. (2006). The habitats of the European Union Habitats Directive. *Biology and Environment*, *106B*, 167–173.

Förster, M., Frick, A., Walentowski, H., & Kleinschmit, B. (2008). Approaches to utilising QuickBird data for the monitoring of NATURA 2000 habitats. *Community Ecology*, *9*, 155–168.

Frick, A., Weyer, G., Kenneweg, H., & Kleinschmit, B. (2005). A knowledge-based approach to vegetation monitoring with Quickbird imagery. In *Proceedings of the ISPRS Workshop 2005: High-Resolution Earth Imaging for Geospatial Information* Hannover, 17–20 May 2005,

Gathoye, J.-L., & Terneus, A. (Eds.). (2006). *Cahiers "Natura 2000". Habitats de l'Annexe I de la Directive Habitats présent en Wallonie. Version 3 provisoire*. Gembloux: Centre de Recherche de la Nature, des Forêts et du Bois.

Graef, F., Bilo, M., Weddeling, K., & Hölzel, N. (Eds.). (2009). *Einsatz von Fernerkundung im Rahmen des FFH-Monitorings in Deutschland – Workshop. BfN-Skripten 249*. Bonn: Bundesamt für Naturschutz.

Groom, G., Mücher, C. A., Ihse, M., & Wrbka, T. (2006). Remote sensing in landscape ecology: Experiences and perspectives in a European context. *Landscape Ecology*, *21*, 391–408.

Gross, J. E., Goetz, S. J., & Cihlar, J. (2009). Application of remote sensing to parks and protected area monitoring: Introduction to the special issue. *Remote Sensing of Environment*, *113*, 1343–1345.

Haest, B., Vanden Borre, J., Thoonen, G., Spanhove, T., Delalieux, S., Kooistra, L., Mücher, C. A., Paelinckx, D., Scheunders, P., & Kempeneers, P. (submitted for publication). Hyperspectral remote sensing for detailed heathland habitat assessment in the framework of NATURA 2000. *Remote Sensing of Environment*.

Janssen, J. A. M., & Schaminee, J. H. J. (2003). *Europese natuur in Nederland: habitattypen*. Utrecht: KNNV Uitgeverij.

Kennedy, R. E., Townsend, P. A., Gross, J. E., Cohen, W. B., Bolstad, P., Wang, Y. Q., et al. (2009). Remote sensing change detection tools for natural resource managers: Understanding concepts and tradeoffs in the design of landscape monitoring projects. *Remote Sensing of Environment*, *113*, 1382–1396.

Keramitsoglou, I., Kontoes, C., Sifakis, N., Mitchley, J., & Xofis, P. (2005). Kernel based re-classification of Earth observation data for fine scale habitat mapping. *Journal for Nature Conservation*, *13*, 91–99.

Kerr, J. T., & Ostrovsky, M. (2003). From space to species: Ecological applications for remote sensing. *Trends in Ecology and Evolution*, *18*, 299–305.

Lechner, A. M., Stein, A., Jones, S. D., & Ferwerda, J. G. (2009). Remote sensing of small and linear features: Quantifying the effects of patch size and length, grid position and detectability on land cover mapping. *Remote Sensing of Environment*, *113*, 2194–2204.

Lengyel, S., Kobler, A., Kutnar, L., Framstad, E., Henry, P.-Y., Babij, V., et al. (2008). A review and a framework for the integration of biodiversity monitoring at the habitat level. *Biodiversity and Conservation*, *17*, 3341–3356.

Lillesand, T. M., Kiefer, R. W., & Chipman, J. W. (2008). *Remote sensing and image interpretation* (6th edition). Hoboken (NJ): Wiley.

Mehner, H., Cutler, M., Fairbairn, D., & Thompson, G. (2004). Remote sensing of upland vegetation: The potential of high spatial resolution satellite sensors. *Global Ecology and Biogeography*, *13*, 359–369.

Mitchley, J., & Xofis, P. (2005). Landscape structure and management regime as indicators of calcareous grassland habitat condition and species diversity. *Journal for Nature Conservation*, *13*, 171–183.

Mücher, C. A. (2009). *Geo-spatial modelling and monitoring of European landscapes and habitats using remote sensing and field surveys*. Ph.D. thesis, Wageningen University.

Mücher, C. A., Steinnocher, K. T., Kressler, F. P., & Heunks, C. (2000). Land cover characterization and change detection for environmental monitoring of pan-Europe. *International Journal of Remote Sensing*, *21*, 1159–1181.

Nagendra, H. (2001). Using remote sensing to assess biodiversity. *International Journal of Remote Sensing*, *22*, 2377–2400.

Nagendra, H., & Rocchini, D. (2008). High resolution satellite imagery for tropical biodiversity studies: The devil is in the detail. *Biodiversity and Conservation*, *17*, 3431–3442.

National Parks & Wildlife Service. (2007). *Conservation Status Report – Annex I habitats. Backing documents*. Dublin: Department of the Environment, Heritage & Local Government, National Parks & Wildlife Service. Online at: http://www.npws.ie/en/PublicationsLiterature/ConservationStatusReport/Habitats/; accessed: 15/06/2010.

Newton, A. C., Hill, R. A., Echeverría, C., Golicher, D., Rey Benayas, J. M., Cayuela, L., et al. (2009). Remote sensing and the future of landscape ecology. *Progress in Physical Geography*, *33*, 528–546.

O'Neill, R. V., Hunsaker, C. T., Timmins, S. P., Jackson, B. L., Jones, K. B., Riitters, K. H., et al. (1996). Scale problems in reporting landscape pattern at the regional scale. *Landscape Ecology*, *11*, 169–180.

Paelinckx, D., De Saeger, S., Oosterlynck, P., Demolder, H., Guelinckx, R., Leyssen, A., et al. (2009). *Habitatkaart, versie 5.2. Indicatieve situering van de Natura 2000 habitats en de regionaal belangrijke biotopen. Integratie en bewerking van de Biologische Waarderingskaart, versie 2. INBO.R.2009.4*. Brussels: Research Institute for Nature and Forest.

Sanz Trullén, V., & Benito Alonso, J. L. (2007). Mapa de Hábitat de Aragòn: la cartografía de hábitats CORINE como herramienta para la gestión de la biodiversidad y de los espacios naturales protegidos. *Boletín EUROPARC*, *23*, 36–41.

Skånes, H., Mäki, A.-H., & Andersson, A. (2007). *Flygbildstolkningsmanual för basinventeringen Natura 2000. Version 7.1*. Stockholm: Swedish Environmental Protection Agency.

Søgaard, B., Skov, F., Ejrnæs, R., Pihl, S., Fredshavn, J., Nielsen, K. E., et al. (2007). *Criteria for favourable conservation status in Denmark. Natural habitat types and species covered by the EEC Habitats Directive and birds covered by the EEC Birds Directive. NERI Technical report No. 647*. Aarhus: National Environmental Research Institute, Aarhus University.

Sterckx, G., Paelinckx, D., Decleer, K., De Saeger, S., Provoost, S., Denys, L., et al. (2007). Habitattypen Bijlage 1 Habitatrichtlijn. In K. Decleer (Ed.), *Europees beschermde natuur in Vlaanderen en het Belgisch deel van de Noordzee. Habitattypen/Dier- en plantensoorten*. Brussels: Research Institute for Nature and Forest, pp. 59–359

Stevens, J. P., Blackstock, T. H., Howe, E. A., & Stevens, D. P. (2004). Repeatability of Phase 1 habitat survey. *Journal of Environmental Management*, *73*, 53–59.

T'jollyn, F., Bosch, H., Demolder, H., De Saeger, S., Leyssen, A., Thomaes, A., et al. (2009). *Criteria voor de beoordeling van de lokale staat van instandhouding van de Natura 2000-habitattypen. Versie 2.0. INBO.R.2009.46*. Brussels: Research Institute for Nature and Forest.

Turner, W., Spector, S., Gardiner, N., Fladeland, M., Sterling, E., & Steininger, M. (2003). Remote sensing for biodiversity science and conservation. *Trends in Ecology and Evolution*, *18*, 306–314.

Verbücheln, G., Börth, M., Hinterlang, D., Hübner, Th., Michels, C., Neitzke, A., et al. (2002). *Anleitung zur Bewertung des Erhaltungszustandes von FFH-Lebensraumtypen*. Recklinghausen: Landesanstalt für Ökologie, Bodenordnung und Forsten Nordrhein Westfalen.

Waser, L. T., Baltsavias, E., Ecker, K., Eisenbeiss, H., Feldmeyer-Christe, E., Ginzler, C., et al. (2008). Assessing changes of forest area and shrub encroachment in a mire ecosystem using digital surface models and CIR aerial images. *Remote Sensing of Environment*, *112*, 1956–1968.