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Research Article

Remote sensing in landscape ecology: experiences and perspectives in a European context

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Abstract

That the relationship between remote sensing and landscape ecology is significant is due in large part to the strong spatial component within landscape ecology. However it is nevertheless necessary to have frequent overview of the interface between remote sensing and landscape ecology, particularly in the light of developments in the types of image data and techniques. The use of remote sensing within European landscape ecology provides a rich range of examples of the interface, including application of some of the latest types of image data. This paper is an overview of the interface that remote sensing has with European landscape ecology, with seven examples of the application of image data in European landscape ecology and examination of associated landscape classification issues. These examples are discussed in terms of the trends and the different roles for image data in landscape ecology that they illustrate, and in particular their classificatory and informational implications. It is suggested that with regard to classification there is a need for re-examination of the roles of image data.

Introduction

That the relationship between remote sensing and landscape ecology is significant is due in large part to the strong spatial component within landscape ecology. The large number and range of landscape ecological studies and applications that use remote sensing in one way or another confirms their connectivity. In part, this relationship is characterised by a constant factor, namely that remote sensing provides often the spatial component in landscape ecology; indeed, as noted by Blaschke (2003) 'aerial photography and its interpretation was the starting point for Carl Troll to coin the term landscape ecology'. It is also an evolving relationship, as new possibilities are explored based upon technical developments, including those represented by newly launched satellite sensors and novel image interpretation methods.

The strong connection between landscape studies and remote sensing holds for landscape ecology work within Europe as it does elsewhere. However, associated with the distinctive characteristics of European landscape ecology (Wu and Hobbs 2002), it is the purpose of this paper to examine through a set of examples some of the characteristics of the interface between European landscape ecology and remote sensing. Sections 'Remote sensing and landscape ecology: some constant key characteristics' and 'Remote sensing and landscape ecology: new trends' discuss some of the constant and some of the evolving aspects of remote sensing that are relevant to landscape ecology. In Section 'Examples of remote sensing data used in European landscape ecology' seven examples are presented that illustrate the interface and in Section 'Discussion' the interface is discussed with reference to the examples.

Data, information and knowledge structuring are core aspects of much remote sensing work, related to its general purpose of mapping. There is therefore particular significance of remote sensing for the theme of this special issue, namely the use of classification and typology in the management of cultural landscapes. The implications that use of remote sensing in landscape ecology bring-to-bear upon classification systems in landscape ecology can be considered through the examples in Section 'Examples of remote sensing data used in European landscape ecology'. This aspect of the paper can be set as the following question: Do uses of remote sensing within European landscape ecology provide principles for classification within European landscape ecology? In this paper 'classification' is understood as the arrangement of objects into groups on the basis of their relationships (Sokal 1974). As such, classification is seen as one part of the concept of a classification system that comprises in full (European Commission 2001):

– demarcation of the thematic domain
– arrangement of objects into groups on the basis of their relationships
– naming and describing of the groups
– procedures for allocation of any object to one and only one group

In addressing the above question classificatory roles for remote sensing in European landscape ecology, as seen through the examples in Section 'Examples of remote sensing data used in European landscape ecology', are discussed with respect to these components.

Remote sensing and landscape ecology: some constant key characteristics

In the following paragraphs, the major general characteristics of remotely sensed images that drive for a large part their application in landscape ecology are presented.

Spatial coverage, synoptic overview

A key feature of the relationship between remote sensing and landscape ecology is the spatial extent of information collection that remote sensing makes possible. This is most notably associated with satellite images, with many examples of individual image scenes that cover areas extending over tens and hundreds of kilometres. Much satellite imaging operates globally, irrespective of borders, so given the large number of nation states within Europe, each with its own history in surveying and mapping, the relevance of satellite images for harmonisation of Europe-wide landscape work is also significant. Remote sensing is, compared to other survey techniques, unique in its possibilities for providing census data, i.e. complete large area coverage that can complement sample data (Inghe 2001). 'Completeness' is one of the underlying principles of a classification system, i.e. that it is exhaustively inclusive of the objects within its domain (European Commission 2001). By their blanket coverage image data provide a strong physical basis for compliance to this principle. Moreover, the synoptic overview represents for landscape ecology more than merely the possibility to capture within one data source information for a large area. More fundamentally it represents the possibility to see patterns that are only discernible when a larger part of the landscape is in view.

Repeat coverage

Compared to other major sources of spatially extensive information for landscape ecology, such as field data collection or map products, remote sensing provides significant possibilities for frequent data capture. Spatial-temporal analysis of landscapes often can only be done through the use of remotely sensed data, and archive images represent a major opportunity to re-visit the landscape of the past. Aerial photographs, which are stored in many national archives from at least the early 1940s, represent image contributions in the temporal domain with a long history, while imaging from Space plays a significant role from the 1970s. Furthermore, within the temporal domain provided by many satellite sensors, with repeat periods of between 15 min and a few weeks, it is also possible to undertake ecological work concerning the monthly, seasonal and yearly dynamics of landscapes.

Abstraction-free landscape information

To function as a science landscape ecology requires landscape information. Two important data collection methods are field survey and use of topographic maps. Notwithstanding their significance, both these methods have limitations. Field data collection is time consuming, often difficult to undertake and expensive. Potentially more problematic, existing map data may be readily available but represent a highly abstracted and filtered representation of the landscape. For example, a topographic map is a cartographic product and is the result of applying a specific set of rules of what features within the landscape should be mapped and how they are represented. This means in general a strong simplification of reality. Working with remote sensing images is therefore seen as a means that has the potential for capturing landscape information through use of a data source that is effectively free of human abstractive processes. The visual impact of remote sensing images as pictures of 'how the landscape actually is' operates highly effectively. This is particularly so with photographic image data (such as aerial photography) in which the general level of detail seen is close to that which might be noted in a live viewing. Moreover, in many types of field surveys the synoptic information provided by remote sensing images can help in preparations for efficient fieldwork.

Standardisation

As with any technique for making physical measurements it is important for their use that the individual data are comparable. Moreover, this is a fundamental requirement for a technique such as remote sensing that is largely based around visualisation. Thus, most remotely sensed data sets are characterised by high levels of internal data standardisation. Image data standardisation is also normally based upon fundamental physical principles, enabling the calculation or estimation of many land surface properties such as moisture content and biomass. Data standardisation is particularly the case for satellite remote sensing, with control possible over parameters, such as illumination and viewing angles, that can otherwise result in aberrant data values. Standardisation is also present with respect to the principle way by which remote sensing data are provided, i.e. as rasterised data in widely usable computer file types.

Remote sensing and landscape ecology: new trends

Maybe there has never been a time since the beginnings of remote sensing from Space in the 1960s when there has not been some new remotely sensed image data set providing new sources and types of information and new opportunities for applications. Indeed, the pace of technical development of imaging sensors and platforms is as rapid now as ever. Recent technical developments in remote sensing for land surface information extraction comprise a broad range. However, whilst developments such as multi-angle viewing (Gobron et al. 2002; Chen et al. 2003; Gerard 2003), hyperspectral sensing (Jacobsen et al. 2000; Foody et al. 2004; McMorrow et al. 2004) and radar (Taft et al. 2003; Wagner et al. 2003; Bugden et al. 2004) have considerable potential relevance for landscape ecology the developments discussed here are those related to image spatial resolution, data supply and classification. These developments are seen as having more general and greater immediate impact on the interface between landscape ecology and remote sensing than other developments, in which in many cases there is still major work to be undertaken in understanding the physical principles involved.

Medium spatial resolution image data

Until the late 1990s, the choice of image data from Space for landscape work was between 'high' spatial resolution data with resolutions between approximately 10 and 100 m and 'low' spatial resolution data with resolutions of at least

1000 m. Typically these two options were represented by the data from the Landsat TM/ETM, SPOT HRV or IRS LISS sensors and the NOAA-AVHRR sensors, respectively. Since 1999, the gap between these two has been filled by three Space sensing systems, namely MODIS, MISR and MERIS, with spatial resolutions of 250, 275 and 300 m, respectively (Rogan and Chen 2004). As with the low spatial resolution data, work with these newer data has been mainly for understanding their representation of global Earth surface processes, such as climate associated vegetation growth patterns (e.g. Gobron et al. 2002; Lotsch et al. 2003). Earlier approaches for national and European land cover mapping and monitoring, widely applied in landscape ecology, have used mainly high spatial resolution image data (Thunnissen et al. 1992; European Commission 1993; Thunnissen and Noordman 1997; Fuller et al. 2002; Weiers et al. 2002). Large area mapping with those data can be time-consuming due to the number of individual image scenes involved. On the other hand, studies have noted that the spatial resolution of NOAA-AVHRR data, such as was used for the PELCOM land cover data base (Mücher et al. 2000), is insufficient to identify the fragmented, fine scale land cover patterns of the European landscape. Use of medium spatial resolution images (such as those from MODIS, MISR and MERIS) for large area landscape ecology work is indicated to bridge the gap between Landsat/SPOT/IRS and NOAA image data (De Boer et al. 2000; Van der Meer et al. 2000; Addink 2001).

Very high spatial resolution image data

Since the late 1990s, there has also been a major increase in the availability of digital image data from Space with very high spatial resolution (VHSR, also referred to as 'hyperspatial'), i.e. resolutions of less than 5 m. Several satellites now provide multi-spectral and/or panchromatic VHSR image data for civil use (Table 1) with, in the case of the Quickbird satellite, spatial resolution as high as 0.6 m. These image data have found possibilities for use in landscape related work (Sawaya et al. 2003). However, given the considerable potential for use of such image data in commercial applications (e.g. media use, utilities

Table 1. The currently operating very high spatial resolution satellite remote sensing systems for civil applications.

Satellite	Began operating	Spatial resolution[a]	Swath (km)[a]	Spectral bands (nm)	Repeat time (days)[a]
IRS 1C, 1D	1C – December 1995 1D – September 1997	5.8 m	70	500–750	24 (min 5)
IKONOS 1, 2	1 – April 1999 2 – September 1999	1 m (Pan) 4 m (Multi-spectral)	11.3	Pan: 450–900 Multi-spectral: 450–520, 520–600, 630–690, 760–900	As ordered (min 1.5)
EROS 1A	December 2000	1.8 m	13.5	500–900	1.8
Quickbird	October 2001	0.6 m (Pan) 2.5 m (Multi-spectral)	16.5	Pan: 450–900 Multi-spectral: 450–520, 520–600, 630–690, 760–890	1–3.5
SPOT 5a	May 2002	2.5 m (Pan) 5.0 m (Pan)	60	510–730	26 (min 3)
ORBView-3	June 2003	1 m (Pan) 4 m (Multi-spectral)	8	Pan: 450–900 Multi-spectral: 450–520, 520–600, 625–695, 760–890	3

Several of the satellites listed here carry several sensors, but details are given in this table only concerning those instruments that provide VHSR image data. This table provides only a summary of VHSR satellite image data possibilities, since the set of data products is complex and frequently changing.

[a]Nadir viewing; certain systems can be programmed to view off-nadir, which can enable more frequent viewing and the production of stereo-pairs of images, but at the cost of coarser spatial resolution and smaller scene coverage.

and civil engineering), the VHSR image data supply sector has rapidly become highly developed; the VHSR satellite image data products market is at present not easy to overview.

Digital air photo image data

During approximately the same period that VHSR image data from Space have become widely available, the availability and quality of digital image data produced from air photos has markedly increased. Many systems and operators supply such data. National coverage digital data sets with resolutions of less than 1 m are now routinely produced, such as every one or two years, for many European countries (e.g. COWI A/S 2002). Generally, these data sets are orthorectified but not multi-spectral.

Image data compression and Internet data access

Rasterised digital image data sets are, compared to digital vector data sets, generally larger (with the raster data volume changing as a square of the change in the dimension of the spatial resolution). However, during the same period as the growth in the supply of VHSR and digital air photo image data there have been important developments in the possibilities for digitally compression of image data. Along with the development of client-server tools for handling geographic data, compression techniques have made it routine to browse, acquire and work with large quantities of image data over wide-area-networks and the Internet.

Compared to a decade ago there is therefore much greater and more varied opportunities for spatially detailed landscape work with image data. However, the various VHSR Space and air photo image data sets are associated with particular supply characteristics, such as in terms of their costs, spectral bands, coverage and ease of acquisition. There is therefore at present a rather complex range of possibilities for detailed landscape mapping from image data. Whilst there have been some research publications on the applied use of these image developments (Lau et al. 2003), much of the basic information relevant to their possibilities for landscape ecology is in grey literature (e.g. 'white papers', professional magazines, web sites).

Object-based image classification

Most work with digital image data has had as its spatial unit the image pixel. Only where manual/visual image interpretation has been applied, as for example for most of the national CORINE Land Cover mappings (European Commission 1993) have the more irregularly shaped features of real landscapes been accommodated. Thus, automated work with image data for many landscape related applications has been held back by the pixel-based approaches to image data analysis. For example, in many cultural landscapes, multi-pixel elements such as fields are generally more appropriate units, and in semi-natural situations, inter-pixel differences in surface characteristics and natural gradients can make it difficult to work in terms of image pixels. Some studies have used image texture and context (Groom et al. 1996) and subpixel analysis (Suppan et al. 1997, 1999; Steinwendner et al. 1998) for production of landscape relevant maps or for identifying landscape objects from image data. However, it has only been more recently that a number of significant developments in object-based image analysis, such as multi-scale image segmentation and object relationship modelling (Burnett and Blaschke 2003) have become available to provide a stronger basis for image work in terms of real landscape objects.

Examples of remote sensing data used in European landscape ecology

The seven examples in this paper of the use of remote sensing in European landscape ecology are presented in three groups, relating to their main thematic characteristics, namely: specific landscape elements, general landscape habitats and landscape types and structures. These examples could be arranged in various ways, and as shown in Table 2 the set covers a range of scales and scopes/purposes.

Specific landscape elements

In many European landscape ecology situations, mapping and monitoring of specific details within landscapes is required because such elements features often characterise the landscape and imply its functioning. Requirements may comprise:

Table 2. Selected landscape ecological remote sensing studies with reference to their spatial scale and scope (numbers refer to the numbering of the mentioned examples in the text).

Scale scope	Local	National/regional	Supranational/European
Extraction of descriptors of vegetation structure	1 (DK)		
Monitoring of vegetation degradation		3 (SE)	
Classification/delineation of biotopes	2 (SE)		5 (PEENHAB – EU)
Monitoring small biotopes/landscape elements		4 (NL)	
Delineation of landscape types		7 (SINUS – AT)	6 (ENVIP Nature – EU)
Optimisation of landcover information for ecological purposes		7 (SINUS – AT)	6 (ENVIP Nature – EU)
Improvement of topographical maps		4 (NL)	

- Identification of specific landscape elements in the form of area, line and point objects, such as ponds and other small biotopes, stone walls, tracks and solitary trees.
- Detailed characterisation of specific landscape objects.
- General thematic mapping at mapping scales of finer than about 1:100,000

The spatial extents involved in these detailed surveys may not be very large, providing opportunities for alternatives to image data, such as field surveys. However, as noted in Section 'Remote sensing and landscape ecology: new trends', there are now image possibilities for detailed work at this scale.

Example 1. Detailed mapping for Danish landscape modelling

As new possibilities for landscape ecological investigation develop the capturing of basic spatial information can become a significant barrier to fully implementing concepts. Even in situations in which there is a wealth of spatial data, the capture of sufficiently detailed and accurate landscape information, in a format compatible with the application can be non-trivial. The needs of a landscape map for species modelling is a case in point. The Animal, Landscape, Man Simulation System (ALMaSS) integrates ecological Species Models of organisms with a Landscape Model in a process analogous to that which occurs in the real world (Topping et al. 2003; Jepsen et al. 2004). This serves as an experimental system for comparing the effects of landscape change scenarios on animal species; the model has been developed for agricultural areas typical of northern Europe of up to 10 × 10 km. In the Species Model, the demography and behaviour of each species is modelled using individual-based techniques. The Landscape Model is a dynamic simulation of a real landscape with detailed representation of landscape. Creating a base landscape map for the ALMaSS Landscape Model has been challenging since as well as being thematically and spatially detailed and accurate this needs to be topologically complete, i.e. a full coverage polygon map. For the Landscape Model the Danish national vector AIS data (National Environmental Research Institute 2000) are superior to the Danish TOP10 map data. However, the AIS data are thematically poor in their representation of forested areas. Forest information is particular important for ALMaSS modelling of larger herbivores such as deer. The main forest types occurring in Denmark are semi-natural oak, beech and pine and plantation spruce and fir.

Pilot studies showed that manual interpretation of orthorectified true-colour aerial photographs (scale 1:25,000) was a viable option for providing the forest information required by the Landscape Model; these image data are digitised from film with a spatial resolution of 40 cm (COWI A/S 2002). Moreover, the pilot studies indicated that:

- High spatial resolution image data, such as from Landsat TM were classifiable for major forest classes, but were of insufficient spatial resolution, insufficiently well registered to the map base and unable to provide sufficient thematic information, such as regarding canopy height.
- VHSR satellite image data, such as from IKONOS-2 were potentially able to provide sufficient thematic and spatial detail by automated classification, but this would require considerable development work, the image data may not be readily available and would be expensive.
- Digital orthorectified colour aerial photography data were able to provide sufficient thematic and

spatial detail, and were available free of additional cost, but as with IKONOS data, automated classification would involve considerable development work.

Manual mapping from digital orthorectified colour aerial photography data was the chosen procedure. The first step was to merge the existing AIS forest sub-units. Mapping within the resulting forest blocks from the orthophotos was made by adding line-work to create new vector polygons with their thematic details entered to the associated database file (Figure 1). The database was designed to match the application needs with the available image information. The ALMaSS landscape model required forest mapping related to the forage possibilities for larger ground living herbivores. For the database of the mapped forest objects this objective was initially expressed as three issues (Table 3a); each of these was expressed as a surrogate parameter and each of these was expressed as a set of classifiers that could be mapped from the orthophotos (Table 3a). Application of the classifiers followed rule-based state-definition and combination (Table 3b).

In many cases the spatial resolution of the orthophotos made it possible to interpret whether the tree type was deciduous or evergreen, based on the size and shape of the individual tree crowns and also the canopy colour and texture. In Denmark most deciduous forest is comprised mainly of broad-leaved trees and most evergreen forest is comprised of needle-leaved trees. However, since dual-season infrared + visible image data provide a better indication of tree seasonality (Fuller et al. 1994), allocations of the tree type classifier were checked by overlaying the forest vector line-work on dual-season Landsat TM image data from the mid-1990s. Re-assignment between evergreen and deciduous was required in only a few cases. Tree height was interpreted in the orthophotos from tree canopy and shadow patterns, much of the terrain being level.

The different possible combinations of classifier states were used to associate mapped forest areas to the legend being used by the Landscape Model. This legend used only a small class set for forest

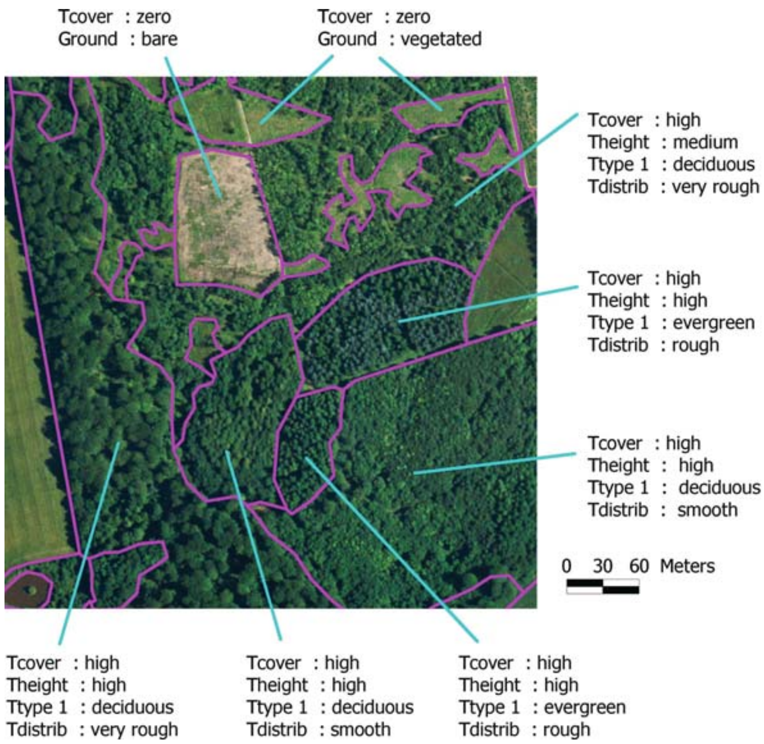

Figure 1. An example of the interpretation of digital orthophotos (0.4 m pixels) for mapping of forest characteristics for generation of a landscape map for the ALMaSS wildlife modelling.

Table 3. (a) Modelled relationships between requirements of the ALMaSS Landscape Map for forest information to classifiers interpretable from orthophoto images. (b) The states and combinations of states for the classifiers used for forest character mapping for the ALMaSS Landscape Map. N.B. if the tree cover is zero there can be no information on tree height, tree type or tree distribution; however, it is then necessary to record the character of the ground.

Parameter of interest for the landscape map	Surrogate parameter	Classifier interpretated from the orthophotos
(a)		
Presence/likelihood of ground and/or understorey vegetation	→ Openness of the tree canopy to light penetration	→ Tree cover Tree height Tree distribution/canopy roughness
Presence/likelihood of ground and/or understorey vegetation at different times of the year	→ Tree seasonality, i.e. evergreen or deciduous	→ Tree type (evergreen or deciduous)
Characteristic of ground/ understorey vegetation	→ Degree of vegetation cover and type of ground vegetation	→ Ground characteristic

(b)

Tree cover	Tree height	Tree type	Tree distribution	Non-tree covered ground
High	High Medium Low	Evergreen Deciduous	Very smooth Smooth Rough Very rough	
Medium	Low Medium High	Evergreen Deciduous	Very rough Clumped In rows Patchy Scattered	Bare Lightly vegetated Vegetated
Low	Low Medium High	Evergreen Deciduous	Clumped In rows Patchy Scattered	Bare Lightly vegetated Vegetated
Zero				Water Bare Lightly vegetated Vegetated Shadowed

areas (broad-leaved forest, needle-leaved forest, mixed forest, scrub, young plantation, grassland, wet areas, bare ground). These might alternatively have been mapped directly from the orthophotos. However, the approach using the surrogate parameters and interpretable classifiers provided important additional flexibility and understanding of the character of the mapped forest areas.

Example 2. Identification and mapping of biotopes and landscape features in the Stockholm urban/suburban areas.[1]

The use of remote sensing for spatial planning for biodiversity in urban and peri-urban areas in Sweden has been developed over 10 years, based upon colour infrared (CIR) aerial photographs, which in Sweden comprises full national coverage (Ihse 1995; Lofvenhaft et al. 2002). To obtain spatial and temporal information on biodiversity that can support urban landscape planning, a method has been developed based on interpretation in stereo models of CIR aerial photographs (scale 1:30,000, with a spatial resolution of 0.5 – 1 m). The resulting biotope (minimum area 0.25 ha), linear (minimum 6 m wide) and point (minimum 10 m across) element maps make it possible to define and consider landscape ecological aspects in planning, identifying core areas, connectivity zones, buffer zones and green development areas. Since biotope continuity is an important parameter in species diversity, older black-and-white aerial photos and historical maps are also used (Ihse 1995).

As seen in Example 1, an important factor in getting good results when using remotely sensed data is to develop a classification system adapted to the information collection goals and to the advantages and the restrictions represented by the image data. The classification system used for this work comprises 78 different units, grouped into a hierarchical system of five different levels. Landcover types constitute the first level with seven classes: developed land/built up areas, forest/woodland, semi-open areas/grassland, open areas/bedrock outcrops and cultivated land, wetland, water and remaining bare ground. The base level also includes linear elements such as water courses, culvert, road and point elements such as solitary broad-leaved trees, small dry hilly meadows, bare bedrock outcrops and small wetlands and ponds. The second level consists of biotopes, valuable key areas (patches) and matrix; this level takes consideration of soil moisture and vegetation cover in percent classes and certain species of trees. The levels three to five concern biotope quality including issues of vegetation successions, management types and other landscape features such as quantity and quality of dead wood, mature or young forests, intensive or extensive management of grasslands, sparse or dense tree cover. For application to this classification, the information derived from the aerial photos was highly reliable. The accuracy compared to field control is 93–95% for developed land and deciduous forest landcover types and for biotope type classes; for classes of biotope quality in broad-leaved deciduous forest the accuracy is 72–75%.

Since the late 1990s, there has been the additional possibility of using VHSR image data from Space and it has been necessary to consider the use of such data in place of and/or in combination with CIR aerial photos. This has been the subject of investigation using 4 m spatial resolution multi-spectral image data of the IKONOS-2 satellite. The IKONOS data have been used as a false-colour composite and as a fusion of the multi-spectral data with the IKONOS 1 m panchromatic band. A stereo-model made from a pair of IKONOS images has provided topographical information, with better recognition of the vegetation types, as many of them are distributed according to different topographical locations. However this approach is unlikely to be feasible operationally on grounds of the associated data costs since two separate IKONOS images registered with different angles are needed.

Overall it was found that it is not possible to do visual interpretation of the IKONOS data as a stereo model that is comparable with use of the CIR aerial photographs, and visual interpretation in the single IKONOS images was found to be even more difficult. The Erdas™ Stereo Analyst equipment allows change between magnifications that is beneficial since many of the classes, and especially the interpretation of biotope quality, is dependent on small details and variations in texture, colour and hue. Addition of the panchromatic 1 m bands provided a better resolution, showing structures in built-up areas, and distinguishing buildings and vegetation. However, the resolution of 4 m is too coarse to distinguish the classes mapped from the CIR aerial photos. Of 21 biotope (level-2) classes only eight could be distinguished with the same accuracy. The interpretation in the IKONOS data can give a general view of the urban areas to distinguish different types of

[1]Examples 2 and 3 have been undertaken in the Swedish research programme for strategic environmental research 'RESE' (Remote Sensing of Environment).

built-up areas and the cover of vegetation. Examples of the interpretation experiences with the IKONOS stereo model include:

- Dense coniferous areas were easy to distinguish, and there are also certain possibilities to distinguish between the different coniferous species, such as old pine forest on bedrocks and dense spruce in dry-mesic ground. The colour of the spruce can be confused with the colour of both deciduous trees and mixed forest, as the texture and structure used in CIR aerial photos could not be used with the IKONOS images.
- Semi-open areas with scarce scattered trees were easily distinguished, but the amount and type of trees and bushes cannot be distinguished and thus neither can the management state.
- Wet deciduous forest and open wetlands were easy to detect in the IKONOS images.
- The open, mesic grasslands with extensive management could be distinguished according to a certain colour and texture, but there are difficulties to define intensively managed grasslands.
- The moisture classes were possible to interpret in open and semi-open grasslands and wetland, as there is clear differences in colour and hue.

Example 3. Mapping and monitoring disturbances in Swedish mountain vegetation cover.
In the mountain areas of Sweden small scale but possibly extensive mechanical damage within areas of hummocky moraine is an issue of particular concern. The vegetation of these areas comprises dry dwarf-shrub heath, characterised by low (8–10 cm) dwarf shrubs, mainly crowberry (*Empetrum hermaphroditum)*, with wind heaths on the hillock-tops comprising frost-hardy cushion plants such as trailing azalea (*Diapensia lapponica* L.). In particular, the wind heaths and the dry dwarf-shrub heath on and around the edges of the hillocks are sensitive to mechanical damage, such as by reindeer and recreation. As well as the immediate effects of vegetation loss, with slow plant regrowth there is the risk of soil erosion. It is important to assess and follow the extent of the damage. Vegetation maps are available for all Swedish mountain areas, but the scale 1:100,000 is too coarse and the vegetation types are too generalised to be used for this application as the changes do not lead to changes in vegetation type. Visual interpretation of stereo CIR aerial photography in a scale 1:60,000, with the smallest resolution 2×2 m has been successfully developed as a viable means for this need. However, as with cultural landscapes around Stockholm (Example 2), more recently the choice of VHSR satellite image data for this work has become an issue. Economic and technical problems in obtaining aerial photos have led to the consideration of alternatives. Thus, a study was made to test whether IKONOS satellite data can be used for detection, quantification and mapping of erosion patches in mountain vegetation with a high degree of accuracy, and to test if they can be substitute for CIR aerial photos for the detection of changes (Allard 2003a, b). The overall goal for the study has been to find quick and objective methods for the monitoring of vegetation in mountainous areas.

All wind heaths within the study area were mapped and classified into three sizes, small (50–1000 m^2), medium (1000–3500 m^2) and large (>3500 m^2). Wind heaths are almost bare, with only around 25% vegetation and are therefore easily seen as blue areas in clear contrast to the surrounding vegetation, seen in brownish-red colours. The IKONOS prints were visually interpreted as a single image and information about the topographical location in the terrain was taken from the 1975-CIR aerial photo stereo model. The pixel-size of 4 m made surface texture and edge structures hard to identify, so colour, size and shape were the most important features. In the enhanced IKONOS image as well as in CIR-aerial photos, individual trees were visible, which could be used for orientation. For the detection of changes, visual interpretations on high-quality (1200 dpi, gloss paper) prints of IKONOS satellite images from 2000 and colour infrared aerial photographs from 1975 were made and the results compared. The interpretations were verified in the field. All the image interpreted changed areas were found in the field. The method by CIR aerial photographs allowed for a detailed description of changes, classified in 10% steps with respect to the classes of lichens cover, dwarf shrubs, grass, humus and mineral soil. IKONOS data needed a simpler mode of description, using only the sizes of deteriorated vegetation or humus/mineral soil patches.

The results show that it is possible to detect with good accuracy detailed changes in the size and distribution of erosion patches and wind heaths by visual interpretation in single images of IKONOS data. This implies that for monitoring these kinds of changes, these high-resolution satellite data can substitute for colour infrared aerial photographs, even when the most of the wind heaths and changes found were small (50–1000 m^2). The printout of the IKONOS colour infrared composite data merged with a digital orthophoto that was intended to improve resolution of the product to 1 m was less useful. This choice of higher resolution data was made on account of the high cost of the IKONOS monochrome data. However, the texture in this merged product detracted from the colour information as the most important indicator, with small changes in hue used for classification.

Example 4. Comparison of VHSR image data, aerial photographs and digital topographic maps for monitoring small landscape elements in the Dutch landscape.

A major study objective within the framework of the Dutch Remote Sensing Programme and the landscape monitoring project 'Meetnet Landschap' has been to investigate the added value of VHSR satellite data compared with digital topographical 1:10,000 maps and aerial photographs, especially in relation to small landscape elements. Two pilot areas were selected, one in the southern part of the Province Limburg and one in the eastern part of the Province Brabant. The monitoring of small landscape elements is an important part of landscape monitoring in general and their monitoring is in the Netherlands for a large part based on the use of the digital topographic maps (Top10-vector) and their updates. However, this study and earlier studies indicated that many small landscape elements such as solitary trees, hedges, old orchards have a low accuracy in topographic maps due to their lower priority compared with other topographic elements such built-up areas and infrastructure and are therefore not consistently mapped. Also the topographic surveyor often does not have the space anymore on the hardcopy to draw all small landscape elements. Often the mapping instructions are prone to subjectivity, for example a solitary tree has to be an orientation point in the landscape, and solitary trees are not mapped when they occur along a street, on a farmyard or in a garden. Moreover, the Top10-vector is a cartographic product and therefore many small landscape elements are simplified in their geometry. Spatial variation such as in delineation, homogeneity, compactness and structure can only be derived from VHSR satellite data and aerial photographs and not from topographic maps.

True colour aerial photographs, which cover the entire Netherlands for the year 2000, were compared with panchromatic and multi-spectral IKONOS satellite images from the same year (Figure 2). An advantage of the IKONOS images compared with the available true colour aerial photographs was that the IKONOS images include a near-infrared band, which improves the identification of green landscape elements. Although the true colour aerial photographs had a slightly better spatial resolution of 0.5 m the IKONOS images were still preferred, except for the fact that small roads were often better identified on the true colour aerial photographs. The distinction between dark shadows and water objects was more easily made on the IKONOS satellite images. Due to the fact that aerial photographs are often not orthorectified for the Netherlands the IKONOS satellite images show less geometric distortions and have a more constant radiometric quality over the whole image, which covers a much larger area (11 × 11 km) than most aerial photographs. However, from an operational point of view the aerial photographs are still often preferred due to their lower price, the difficulties in obtaining IKONOS satellite images, and the fact that surveyors are still used to aerial photographs with which they have much more experience.

General habitats in landscapes

One of the major challenges facing European landscape ecology at present is to find ways to map and monitor the European landscape in terms of its habitats. Habitats in Europe are defined by several scientific and legislative frameworks, but whichever habitat typology is considered, the complexity of their mapping for regions, nation states and Europe as a whole is the same, associated with their ranges in size and distinguishing biophysical characteristics. Even for the majority of habitat types that can in most cases be mapped at scales commensurate with high and medium spatial resolution image data, the lack of a simple relationship to a sin-

Figure 2. Comparison for hedgerows (purple line on Top10) and lines of trees (green line on Top10) on true colour aerial photograph, panchromatic IKONOS satellite image and the Top10-vector for a part of the study area of Eijsden (Zuid-Limburg, The Netherlands). (a) True colour aerial photograph, Eurosense, June 2000. (b) IKONOS panchromatic image, May 2000. (c) TOP10-vector (topographic map 1999). (d) Field photo, taken from red arrow in (a).

gular biophysical parameter restricts the possibilities for many forms of automated image classification. The possibilities for direct mapping from images for general sets of habitats are therefore limited. Instead, it is possible to identify components of the habitat complexity that image data can more directly map and develop actual habitat mapping procedures accordingly. One such component is land cover, with the capability of acting as a surrogate parameter between several major sets of habitat types, such as those of that are primarily associated with cultivated, forested, grassland, or wetland, parts of the landscape, etc. A modelling approach is therefore appropriate for identifying the likely locations of specific habitats. This is the approach to European habitat mapping with image data that has been developed as the

Pan-EuropeanHabitat Mapping (PEENHAB) method (Mücher et al. 2004) described below (Example 5). However, mapping of habitats is just one part of the tasks related to European habitat policies to which image data and GIS can be applied. The ENVIP-Nature project (Example 6) illustrates how it is necessary and possible to derive complex habitat related information from image sources.

Example 5. Extraction of habitat information from European databases and remote sensing data

The overall objective of PEENHAB is to develop a methodology to identify spatially all major habitats in Europe according to the Annex 1 (218 habitats) of the Habitat Directive (European Commission 2003). This should result in a European Habitat Map with a spatial scale of 1:2.5 M and a minimum mapping unit of 100 km^2 and a minimum width of 2.5 km. The European Habitat Map will then be used as an important data layer in the design of an indicative map for a Pan-European Ecological Network. To achieve a European Habitat Map, a methodology has to be developed that enables the spatial identification of individual habitats. This uses specific expert knowledge/decision rules on the basis of their description in Annex 1 and specific spatial data sets such as the CORINE land cover database, biogeographic regions (Emerald zones), distribution maps of individual plant species, digital elevation models, soil databases, topographic data, etc. The descriptions in Annex 1 and the availability of the spatial data sets constitute the basis for the definition of the decision rules for each habitat. The decision rules will be a combination of filters. For each spatial layer, a habitat specific filter will be defined. Most habitats will be identified by a combination of data layers. For example, for the Annex 1 habitat 'Calcareous Beech Forest' (code 9150): first a filter is defined that selects the broad-leaf forests from the CORINE land cover database, then a filter is used to select the beech distribution map from the Atlas Florae Europaeae, and a third filter is defined to select the calcareous soils from the European soil database. The combination of these three filters forms the decision rule that delimits the spatial extent, as a probability map, of calcareous beech forest (Mücher et al. 2004). Validation of the defined decision rules and resulting habitat maps will be based on the use of the CORINE biotopes database, relevés from the SynBioSys Europe project European Vegetation Survey (2003), and national expert knowledge. Within the SynBioSys Europe project the European TurboVeg databases will become available, at the moment comprising about 600,000 vegetation descriptions out of a total of more than 1,500,000 records throughout Europe. Thereby, the top-down approach of PEENHAB is linked with the bottom-up approach of SynBioSys Europe.

Example 6. Indicators for nature conservation derived from remote sensing

The ENVIP Nature project is an example of the application of remote sensing and GIS-techniques in landscape ecology and conservation biology, targeted at the development of indicators for nature conservation. For a wide range of European landscapes, the potential of satellite image data has been explored to serve the needs of a monitoring system for the European network of protected areas, i.e. Natura 2000 (The Council of the European Communities 1992). A major innovation was the transformation of a 'normal' land cover map derived from the available satellite data (Landsat TM, IRS, SPOT) into an ecologically meaningful data set – called the 'broader habitat map'. This was only possible by combining the image data with ancillary GIS data such as digital terrain model data or specific land management information derived from topographical maps (forest road network, summer cottages, tourist hot spots). By analysing the extent, spatial configuration and selected shape parameters of these newly defined polygons, indicators have been developed for the criteria 'naturalness', 'vulnerability' and 'threat' for each region separately. A visual interpretation of satellite images, elaborated by the project's core team and revised by local experts, provided the so-called landscape types as the spatial reference units for the final indicator assessment (Banko et al. 2003).

Landscape types and structures

The previous example in this paper noted mapping of landscape types as a key element in European ecological applications such as biological conservation. More generally, environmental planning processes often follow widely accepted guiding visions that have to be based on scientifically sound facts and figures. For this procedure, administrative units are often used as spatial reference units, but these are not always useful. This is due to the fact that by doing so, regions with a homogenous natural potential may be divided into different parts and conversely, ecological transition zones are not being taken into consideration. Landscape ecology can help to overcome these shortcomings, by elaborating landscape types as 'ecologically meaningful units'. Such land units can be used as the basis for analysis and assessment, as well as for the formulation of landscape ecological models for a sustainable regional development. When implementing the suggestions of such development models into a regional development policy it is necessary to come back to administrative units again in respect to political and historical issues. The possibilities for landscape characterisation are a continuing feature of European landscape ecology. A current European Union project, ELCAI, aims to explore the possibilities for Europe-wide landscape character assessment, drawing upon integration of several existing national and regional landscape typologies (see Wascher et al. in this issue). In several cases existing landscape typologies have involved the use of information derived from image data. Classification and interpretation of landscape structures has played a key role in the major landscape typology of Austria, which has been a powerful tool for applied landscape ecological monitoring and modelling in Austria.

Example 7. Image data application for Austrian landscape type mapping

In the Austrian research project, SINUS a map of the Austrian Cultural Landscape Types was elaborated on the basis of visual interpretation of Landsat TM images. As a result a total of 13,748 individual landscapes units were delineated for the whole of Austria and these were classified into 42 Cultural Landscape Type Groups (CLT – second order). These groups were then aggregated to 12 Cultural Landscape Type Series (CLT – first order). Whereas the series were primarily defined by the dominant land use system, the landscape type groups also reflect major physio-geographical units of Austria. Landscapes dominated by alpine and sub-alpine grassland, forest dominated landscapes, grassland dominated landscapes, landscapes with fodder crop production or mixed agriculture, crop land dominated landscapes, viniculture landscapes or urban and industrial landscapes were distinguished. The Classification of the Austrian Cultural Landscapes was the main spatial reference system for the analysis and assessment of land use sustainability (Wrbka et al. 1999a, b).

To allow a proper assessment of the sustainability of land use in Austrian agricultural landscapes – which was the prior aim of the SINUS project – an actual and detailed Austrian wide land cover data set was needed. Different methods of satellite imagery segmentation (e.g. subpixel analysis, watershed segmentation, etc.) were tested to select the most efficient method. Landsat TM images were used. The combination of an innovative segmentation method (region-growing algorithm) and classification procedure (knowledge based classification by using additional attributes like shape and spatial distribution of the segments) resulted in an efficient use of the resources. The result of the automatic satellite image interpretation was an Austria wide land cover data set. Eighteen different land cover types were distinguished. The spatial resolution of the segments corresponds to the units of land ownership and land use i.e. the parcels. The method of the automatic satellite image interpretation was optimised to analyse the landscape structure. Thus a clear defined field of application for the land-cover data was determined. In comparison to widely used classification methods, the results of this land cover classification are better with respect to landscape structure information, but weaker in other aspects. The segments with their attributes, describing spectral characteristics, shape and land cover type, have to be put into the context of an individual landscape they are belonging to. Therefore, much emphasis was given to calculate the percentage of a certain land cover type within a landscape and other average figures, whereas the accurate measurements of single segments were less important. The data set was used for a detailed description of the landscape types and provided the primary data set for the assessment of the sustainability of land use management in different cultural landscape types (Peterseil et al. 2004).

Discussion

The seven examples described in Section 'Examples of remote sensing data used in European landscape ecology' illustrate that the use of remote sensing data in landscape ecology is as broad as landscape ecology itself. They reveal that the strong appetite of European landscape ecology work for spatial landscape information is driven by:

- Increasing scope and breadth in the subject material of landscape ecology (Examples 3, 5, 6 and 7).
- Developing possibilities for landscape monitoring, analysis and modelling (Examples 1, 2, 4, 5 and 7).
- Increasing technical sophistication in the tools for landscape related research and interactions, such as for delivery of landscape information to stakeholders (Examples 1, 6 and 7).
- Increasing deterioration of many landscapes, habitats and landscape elements and the awareness that they need to be protected and monitored in more comprehensive ways (Examples 2, 3 and 5).

Meeting this information need through increasing use of image data is clearly an answer, but at the same time it is still at present, as shown by Examples 3, 4 and 5 only a partial solution. Indeed, the pathway for use of image data to meet the demands for landscape information capture is not as simple as it was until quite recently. For instance, the significant recent developments in VHSR image data noted in Section 'Remote sensing and landscape ecology: new trends' still require to be worked through in order to determine how they represent particular sets of landscape features and how they can be most effectively worked with (Examples 2, 3 and 4). Within this learning process it is clear that there is still an important place for the types of visual interpretation methods and skills developed and acquired in the past. The parameters for automated mapping of landscape features from VHSR image data are still a long way from being fully developed. In particular, whilst the potentials presented by recent object-based image segmentation and classification concepts and tools (Burnett and Blaschke 2003) are tantalising they are as yet insufficiently widely applied and developed for routine application.

Image data relate mainly to the geo-biophysical landscape, as is clearly evident from several of the examples described in Section 'Examples of remote sensing data used in European landscape ecology'. It is also possible, as seen in Examples 4 and 7, to map field patterns and human artefacts or interpret land use from images. However, many of the core social and cultural, not to mention perceptual and aesthetic, landscape properties expressed by many of the papers in this issue will (probably) always lie mainly beyond the reach of remote sensing.

Do uses of remote sensing within European landscape ecology provide principles for classification within European landscape ecology?

As seen in the more Earth-bound papers of this issue, data collection and data structuring are central aspects of current European landscape ecology. That these are also core aspects of remote sensing work, including its application for landscape information, inevitably juxtaposes the classification undertaken as remote sensing with that undertaken as landscape ecology. With regard to the question set in Section 'Introduction' the following points, as illustrated by the examples in Section 'Examples of remote sensing data used in European landscape ecology' need to be noted:

- Where there is already landscape ecological classification, such as that of spatial landscape topographical units discussed by Bastian et al. (in this issue), remote sensing has a major role to play in the ongoing monitoring and management of the landscape units, even if it has not been involved in their delimitation.
- Frequently image data are being used to map a thematic issue that is a subset of the 'landscape complex', such as vegetation, land cover or habitat type. The associated classification is consequently not one of 'landscape' *per se* but nevertheless a partial element of landscape. Integration of the classification associated with the use of image data with that for landscape typology is therefore, as seen in Example 7, a non-trivial undertaking.
- In addressing the question set in Section 'Introduction', there is the following overarching issue:

Remote sensing is in essence a *technique* for information gathering. It has been argued that classification in the sense presented in Section 'Introduction' should be done independent from specific data sets or techniques (Di Gregorio and Jansen 2000; European Commission 2001). This is seen as essential for ensuring longer-term use of the resulting products such as maps and legends made using specific data and techniques. The significant corollary of this rule is that remote sensing cannot take-on classificatory roles within landscape ecology, as opposed to essentially mapping roles. However, the indication, supported by the examples in this paper, is that classification, remote sensing and landscape ecology *de facto* interact in many different and rather *ad hoc*, but not unsuccessful or necessarily wrong ways. It may be considered that whether or not this situation represents a problem relates to the type of applications involved:

- for smaller, localised, more experimental landscape ecology applications, such as Examples 1 and 3, classification system principles can be regarded in rather relaxed ways;
- for regional and national applications, of environmental components of landscape, such as land cover and habitat (as in Examples 2 and 5), classification system principles are significant, and there are important international classificatory developments that need to be taken into account;
- with regard to landscape typologies and related themes, such as landscape indicators (Examples 6 and 7); within this scope for remote sensing there is a major need for investigation and development of the appropriate roles of image data within the classification system.

The title of the Symposium at which this paper was presented was 'Landscape – what's in it?' The rather straight-forward possibility for handling of landscape as a set of either 'in' or 'out' items that, intentionally or otherwise, is suggested by this title seems rather apt for consideration of the use of remote sensing in landscape ecology. It serves to focus attention on the tangible essence of what remote sensing brings to landscape ecology, or indeed to any domain. Thus, first-and-foremost remote sensing is about the delivery of real world information (into landscape ecology). This simple point seems increasingly important to bear in mind as projects of landscape ecological work become increasingly interwoven between the many issues, concepts and approaches that now comprise landscape ecology. It is not without significance for landscape ecology that remote sensing has been described in terms of the 'information extraction problem' (Danson et al. 1995). However, to see the relationship between landscape ecology and remote sensing as one of information delivery implies also a two-way process, engaging landscape ecology as an active partner too. Thus, the information delivered to landscape ecology by remote sensing sits within an 'information landscape'. It is, now as much as ever, necessary to have a holistic and reciprocal model of our informational mind-sets, regarding how image data, maps, field data, experimental data, etc. interact with each other. Our understandings and implementations of core informational issues such as classification, accuracy assessment, error modelling and metadata will shape this model.

The material presented in this paper falls short of being a comprehensive review of the recent and current work within Europe that could be considered as part of the interface between European landscape ecology and remote sensing. Furthermore, the space available within a journal paper has meant that many topics have been dealt with only lightly and many, many worthy examples omitted. However, it is hoped that this paper's intention of providing a broad overview, with consideration of a number of current developments and issues relevant to the use of image data within European landscape ecology will stimulate deeper examinations.

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References

Addink E.A. 2001. Change detection with remote sensing; relating NOAA-AVHRR to environmental impact of agriculture in Europe. Ph.D. Thesis, Wageningen University, The Netherlands. 113 pp.

Allard A. 2003a. Vegetation changes in mountainous areas – a monitoring methodology based on interpretation of aerial photos, high-resolution satellite images and on field investigations. Ph.D. Thesis, Stockholm University, Sweden.

Allard A. 2003b. Detection of vegetation degradation on Swedish mountainous heaths at an early stage by image interpretation. Ambio 32: 510–519.

Banko G., Zethner G., Wrbka T. and Schmitzberger I. 2003. Landscape types as the optimal spatial domain for developing landscape indicators. In: Dramstad W. and Sogge C. (eds), Agricultural Impacts on Landscapes: Proceedings from NIJOS/OECD Expert Meeting on Agricultural Landscape Indicators in Oslo, Norway October 7–9, 2002. Norwegian Institute of Land Inventory, Ås, Norway, pp. 317–328.

Blaschke T. 2003. Continuity, complexity and change: a hierarchical geoinformation-based approach to exploring patterns of change in a cultural landscape. In: Mander Ü. and Antrop M. (eds), Multifunctional Landscapes Vol. III: Continuity and Change. (Advances in Ecological Sciences Vol. 16.). WIT Press, Southampton, UK, Boston, pp. 33–54.

Bugden J.L., Andrey J. and Howarth P.J. 2004. A SAR process model for land-cover mapping. Can. J. Remote Sens. 32: 195–204.

Burnett C. and Blaschke T. 2003. A multi-scale segmentation/object relationship modelling methodology for landscape analysis. Ecol. Model. 168: 233–249.

Chen J.M., Liu J., Leblanc S.G., Lacaze R. and Roujean J.L. 2003. Multi-angular optical remote sensing for assessing vegetation structure and carbon absorption. Remote Sens. Environ. 84: 516–525.

COWI A/S 2002. DDO – Denmark's Digital Orthophoto. http://www.owi.dk/Projects/div04proj/Countries/div04_ddo.asp (accessed: 14-6-2004.), COWI A/S. Copenhagen.

Danson F.M., Plummer S.E. and Briggs S.A. 1995. Remote sensing and the information extraction problem. In: Danson F.M. and Plummer S.E. (eds), Advances in Environmental Remote Sensing. John Wiley & Sons Ltd, Chichester, UK, pp. 171–177.

De Boer M., De Vente J., Mücher C.A., Nijenhuis W. and Thunnissen H.A.M. 2000. An approach towards pan-European land cover classification and change detection. (NRSP-2 Report 00-18), BCRS, Delft, The Netherlands, 110 pp.

Di Gregorio A. and Jansen L.J.M. 2000. Land Cover Classification System (LCCS): Classification Concepts and User Manual. FAO, Rome, 179pp.

European Commission 1993. CORINE land cover: technical guide. (Report EUR 12585). Office for Official Publications of the European Communities, Luxembourg, 144 pp.

European Commission 2001. Manual of Concepts on Land Cover and Land Use Information Systems. (Eurostat Theme 5: Agriculture and Fisheries. Collection: Methods and Nomenclatures). Office for Official Publications of the European Communities, Luxembourg, 106pp.

European Commission 2003. Interpretation Manual of European Union habitats – EUR25. European Commission DG Environment, Brussels, 127pp.

European Vegetation Survey 2003. SynBioSys Europe. http://www.ynbiosys.alterra.nl/eu/(accessed: 14-6-2004), Alterra Green World Research, Wageningen, The Netherlands.

Foody G.M., Sargent I.M.J., Atkinson P.M. and Williams J.W. 2004. Thematic labelling from hyperspectral remotely sensed imagery: trade-offs in image properties. Int. J. Remote Sens. 25: 2337–2363.

Fuller R.M., Groom G.B. and Jones A.R. 1994. The land cover map of Great Britain: an automated classification of Landsat Thematic Mapper data. Photogramm. Eng. Remote Sens. 60: 553–562.

Fuller R.M., Smith G.M., Sanderson J.M., Hill R.A. and Thomson A.G. 2002. The UK land cover map 2000: construction of a parcel-based vector map from satellite images. Cartogr. J. 30: 15–25.

Gerard F. 2003. Single angle, dual angle and multi-temporal viewing: assessing through modelling the implications for forest structure variable extraction. Int. J. Remote Sens. 24: 1317–1334.

Gobron N., Pinty B., Verstaete M.M., Widlowski J.L. and Diner D.J. 2002. Uniqueness of multiangular measurements - Part II: Joint retrieval of vegetation structure and photosynthetic activity from MISR. IEEE Trans. Geosci. Remote Sens. 40: 1574–1592.

Groom G.B., Fuller R.M. and Jones A.R. 1996. Contextual correction: techniques for improving land cover mapping from remotely sensed images. Int. J. Remote Sens. 17: 69–89.

Ihse M. 1995. Swedish agricultural landscapes – patterns and changes during the last 50 years, studied by aerial photos. Landscape Urban Plan. 31: 21–37.

Inghe O. 2001. The Swedish landscape monitoring programme: current status and prospects for the near future. In: Groom G. and Reed T. (eds), Strategic Landscape Monitoring for the Nordic Countries (TemaNord 2001: 523). Nordic Council of Ministers, Copenhagen, pp. 61–67.

Jacobsen A., Nielsen A.A., Ejrnæs R. and Groom G.B. 2000. Spectral identification of plant communities for mapping of semi-natural grasslands. Can. J. Remote Sens. 26: 370–383.

Jepsen J.U., Topping C.J., Odderskær P. and Andersen P.N. 2004. Evaluating consequences of land use strategies on wildlife populations using multiple species predictive scenarios. Agricult. Ecosyst. Environ.105: 581–594.

Lau W.-L., Li Z.-L. and Lam K.W.K. 2003. Effects of JPEG compression on image classification. Int. J. Remote Sens. 24: 1535–1544.

Lofvenhaft K., Bjorn C. and Ihse M. 2002. Biotope patterns in urban areas: a conceptual model integrating biodiversity issues in spatial planning. Landscape Urban Plan. 58: 223–240.

Lotsch A., Tian Y., Friedl M.A. and Myneni R.B. 2003. Land cover mapping in support of LAI and FPAR retrievals from EOS-MODIS and MISR: classification methods and sensitivities to errors. Int. J. Remote Sens. 24: 1997–2016.

McMorrow J.M., Cutler M.E.J., Evans M.G. and Al-Roichdi A. 2004. Hyperspectral indices for characterizing upland peat composition. Int. J. Remote Sens. 25: 313–325.

Mücher C.A., Hennekens S.M., Bunce R.G.H. and Schaminée J.H.J. 2004. Mapping European Habitats to Support the Design and Implementation of a Pan-European Ecological Network. The PEENHAB project. (Alterra-rapport 952), Alterra, Wageningen, NL, 124 pp.

Mücher C.A., Steinnocher K., Kessler F. and Heunks C. 2000. Land cover characterization and change detection for environmental monitoring of pan-Europe. Int. J. Remote Sens. 21: 1159–1181.

National Environmental Research Institute 2000. The Danish Areal Information System. http://ais.dmu.dk (accessed: 14-6-2004.), Environment Ministry, Copenhagen.

Peterseil J., Wrbka T., Plutzar C., Schmitzberger I., Kiss A., Szerencsits E., Reiter K., Schneider W., Suppan F. and Beissmann H. 2004. Evaluating the ecological sustainability of Austrian agricultural landscapes – the SINUS approach. Land Use Policy 21: 307–320.

Rogan J. and Chen D. 2004. Remote sensing technology for mapping and monitoring land-cover and land-use change. Progress in Planning 61: 301–325.

Sawaya K.E., Olmanson L.G., Heinert N.J., Brezonik P.L. and Bauer M.E. 2003. Extending satellite remote sensing to local scales: land and water resource monitoring using high-resolution imagery. Remote Sens. Environ. 88: 144–156.

Sokal R.R. 1974. Classification: purposes, principles, progress, prospects. Science 185: 1115–1123.

Steinwendner J., Schneider W. and Suppan F. 1998. Vector segmentation using multiband spatial subpixel analysis for object extraction. Int. Arch. Photogramm. Remote Sens. 32(Part B3/1): 265–271.

Suppan F., Steinwendner J., Bartl R. and Schneider W. 1997. Automatic extraction of landscape ecology features from satellite imagery by computer vision techniques. Proc. Geospatial Inform. Age. 4: 673–682.

Suppan F., Steinwendner R., Bartl R. and Schneider W. 1999. Automatic determination of landscape elements from satellite images. In: Kovar P. (ed.), Nature and Culture in Landscape Ecology – Experiences for the Third Millennium. The Carolinum Press, Prague, pp. 327–337.

Taft O.W., Haig S.M. and Kiilsgaard C. 2003. Use of radar remote sensing (RADARSAT) to map winter wetland habitat for shorebirds in an agricultural landscape. Environ. Manage. 32: 268–281.

The Council of the European Communities 1992. Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. Off. J. Eur. Union L 206: 0070–0050.

Thunnissen H.A.M., Jaarsma M.N. and Schouwmans O.F. 1992. Land cover inventory in the Netherlands using remote sensing; application in a soil and groundwater vulnerability assessment system. Int. J. Remote Sens. 13: 1693–1708.

Thunnissen H.A.M. and Noordman E. 1997. National land cover database of The Netherlands: classification methodology and operational implementation. (BCRS report 96-20), BCRS, Delft, The Netherlands, 95 pp.

Topping C.J., Hansen T.S., Jensen T.S., Jepsen J.U., Nikolajsen F. and Odderskær P. 2003. ALMaSS, an agent-based model for animals in temperate European landscapes. Ecol. Model. 167: 65–82.

Van der Meer F.D., Clevers J.G.P.W., de Jong S.M., Bakker W.H., Epema G.F., Skidmore A.K. and Scholte K. 2000. MERILAND: MERIS potential for land applications. (USP-2 Report 1999, 99-36), BCRS, Delft, The Netherlands, 113 pp.

agner W., Luckman A., Vietmeier J., Tansey K., Balzter H., Schmullius C., Davidson M., Gaveau D., Gluck M. and Le Toan T. 2003. Large-scale mapping of boreal forest in SIBERIA using ERS tandem coherence and JERS backscatter data. Remote Sens. Environ. 85: 125–144.

Weiers S., Groom G. and Wissen M. 2002. Comparability and subjectivity of land cover maps produced with digital image classification techniques: some recent experiences from Denmark and northern Germany. Geografisk Tidsskrift (Dan. J. Geogr.) 102: 59–77.

Wrbka T., Reiter K., Szerencsits E., Mandl P., Bartel A., Schneider W. and Suppan F. 1999a. Landscape structure derived from satellite images as indicator for sustainable landuse. In: Nieuwenhuis G.J.A., Vaughan R.A. and Molenaar M. (eds), Operational Remote Sensing for Sustainable Development. Balkema, Rotterdam, pp. 119–129.

Wrbka T., Szerencsits E., Reiter K. and Kiss A. 1999b. Identifying sustainable land use by describing landscape structure. A case study in alpine and lowland agricultural landscapes of Austria. In: Brebbia C.A. and Uso J.L. (eds), Ecoystems and Sustainable Development Vol. II. (Advances in Ecological Sciences Vol. 2.). WIT Press, Southampton, UK, Boston, pp. 209–224.

Wu J. and Hobbs R. 2002. Key issues and research priorities in landscape ecology: an idiosyncratic synthesis. Landscape Ecol. 17: 355–365.