Geo-spatial modelling and monitoring of European landscapes and habitats using remote sensing and field surveys

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‘We came all this way to explore the Moon, and the most important thing is that we discovered the Earth’. Astronaut Bill Anders, Apollo 8

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Photo: *Mentha aquatica* (water mint) in the floodplain of the river Rhine, near Wageningen.

CHAPTER 1

Introduction

1.1. Background

During the last two centuries in particular, the world population grew rapidly, in conjunction with technological developments, which led to a significant expansion of industrialisation, urbanisation and agricultural activity (Stanners and Bordeaux, 1995; Moran et al., 2004; EEA, 2005). As a result, land use and associated land cover changed at an increasing rate, intensifying the pressures on landscapes, habitats and biodiversity in general. A global analysis by Klein Goldewijk (2004) showed that between 1700 and 1990 the area of arable land increased by approximately 500%, from 3 million km^2 to 15 million km^2, and that of grassland by approximately 600%, from 5 million km^2 to 31 million km^2, both at the expense of semi-natural vegetation and forests. Over the same period, forest area decreased by approximately 17%, from 53 million km^2 to 44 million km^2. Types and rates of land cover change vary over time and space. Europe, for example, has experienced an opposite trend over the last 40 years, which included a net forest increase of approximately 10%, a net loss of arable land of about 11% and a net loss of permanent grassland of about 11% (source: FAO land use statistics). The EU project BIOPRESS showed, by analysis of historical aerial photographs over the period 1950-1990-2000, that of these land cover changes urbanisation was predominant. Alarmingly, the project showed that in the 59 transects across Europe the rate of land cover change remained almost constant; respectively, 15% and 14% per decade over the periods 1950-1990 and 1990-2000 (Köhler et al., 2006). In The Netherlands, between 1950-1990, in parallel with a net loss of agricultural land and a net increase of forest and urbanisation, there was a dramatic 44% decline of natural areas (Van Duuren et al, 2003). The amount of heathland was reduced by 68%, of salt marshes by 60%, of raised bogs (moors and peat-land) by 81% and of inland sand dunes by 52%. Only wetlands increased, by 9% (http://www.pbl.nl/nl/publicaties/mnp/2003/Natuurcompendium_2003.html) due to land reclamation from the sea resulting in the creation of new wetlands (e.g., Oostvaardersplassen).

Global biodiversity is declining, and habitat destruction and degradation are caused mainly by changes in land use which, next to climate change, remains the most important driver of biodiversity loss (Hansen et al., 2004). Changes in land use that are related to intensification and marginalization in agriculture are seen as major threats to European landscapes and their biodiversity (Jongman, 1996).

Therefore, there is an increasing need for reliable, up-to-date, Europe-wide data on land use and land cover to inform current environmental policies and nature conservation planning

(Stanners and Bourdeau, 1995). The impact of land use change is widely recognised and has forced national and international agencies to take policy measures to afford a higher degree of protection to our landscapes and habitats, in association with an increasing demand for monitoring and identification of potential sites for nature conservation. In Europe, the Convention on the Conservation of European Wildlife and Natural Habitats (the Bern Convention) that was adopted in Bern, Switzerland, in 1979 was a step forwards. The principal aim of the Convention is to ensure conservation and protection of wild plant and animal species and their natural habitats. To implement the Bern Convention in Europe, the European Community adopted Council Directive 79/409/EEC on the Conservation of Wild Birds (the EC Birds Directive), in 1979, and Council Directive 92/43/EEC on the Conservation of Natural Habitats and of Wild Fauna and Flora (the EC Habitats Directive), in 1992. The Directives facilitate, among other things, the establishment of a European network of protected areas (Natura 2000), to tackle the continuing losses of European biodiversity due to human activities.

The loss of biodiversity has a clear global dimension. The United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro, in 1992, led to the Rio Declaration, confirming the need to work towards international agreements to protect the integrity of the global environment. Countries acknowledged the responsibility that they bear in the international pursuit of sustainable development, in view of the pressures their societies place on the global environment and of the technologies and financial resources they command. In addition to the Rio Declaration, the 1992 Rio Earth Summit resulted in other important documents, such as the Agenda 21 and the Convention on Biological Diversity (CBD, 1992). The objectives and activities in Chapter 15 of Agenda 21 are intended to improve the conservation of biological diversity and the sustainable use of biological resources, and also to support the CBD (http://www.un.org/esa/sustdev/documents/agenda21/english/agenda21toc.htm). The CBD draws attention to the need to identify and monitor ecosystems, habitats, species, communities, genomes and genes (Spellenberg, 2005). Article 7 of the CBD (*Identification and Monitoring*) pursues monitoring the components of biological diversity through sampling and other techniques. Biological diversity – or biodiversity – is defined here as the variety of life on Earth and the natural patterns it forms. In 1995, at the 3rd Conference of Ministers *An Environment for Europe* in Sofia, a Pan-European response to the CBD was approved through the endorsement of the Pan-European Biological and Landscape Diversity Strategy (PELBDS) by 55 states present at the conference (Council of Europe, 1996). The PEBLDS strategy provided the only platform for Pan-European cooperation on tackling biodiversity loss (EEA, 2007). The PEBLDS Strategy aims to ensure the conservation of habitats and species, maintain genetic diversity and preserve important European landscapes. The Action Plan for European Landscapes (Theme 4) included the objective to establish of a Pan-European Landscape Map, next to the development of landscape assessment criteria, and a Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis of European landscapes (Council of Europe, 1996). The PEBLDS Strategy was reconfirmed by the leaders of the European Union at the Gothenburg Summit in 2001 and was adopted in 2003 in the Kyiv Resolution on Biodiversity at the fifth Ministerial Conference *An Environment for Europe*.

Conventions become especially focused when specific targets are set, such as the *2010 Biodiversity Target*, adopted in 2002 by CBD (CBD, 2002; Secretariat of the Convention on Biological Diversity, 2006). All CBD parties have committed themselves to achieving the 2010 Biodiversity Target: to protect and restore habitats and natural systems and halt the loss of biodiversity by 2010. To fulfil these targets, a Pan-European initiative; Streamlining European Biodiversity Indicators 2010 (SEBI 2010); was launched in 2004. This initiative is co-ordinated by the European Environment Agency (EEA) in collaboration with Directorate General (DG) Environment of the European Commission (EC), the European Centre for Nature Conservation (ECNC), United Nations Environment Programme – World Conservation Monitoring Centre (UNEP-WCMC) and the UNEP/PELBDS secretariat. An important objective of SEBI 2010 is the development of indicators to monitor and promote progress towards the achievement of the 2010 target. The SEBI process (EEA, 2007) proposed 26 indicators, with amongst others two important headline indicators: i) trends in extent of selected biomes, ecosystems and habitats, and ii) fragmentation of these selected classes.

All these policies show that the provision of quantitative figures on fragmentation and extent of habitats and their trends is fundamental for general policy formulation in relation to the maintenance and enhancement of biodiversity across Europe (Bunce et al., 2008). The development of the series of Natura 2000 sites based on the above mentioned Directives is the major EU initiative for the protection of primary nature conservation areas (EU Council Directive, 1992; Ostermann, 1998). However, at the same time, these sites do not guarantee the maintenance of biodiversity in the wider countryside, because inevitably many habitats and species are outside protected areas (Bunce et al., 2008). Therefore, there is a need to develop additional policy instruments for nature conservation outside protected areas that are equally appropriate to those applied within. The development of the Pan-European Ecological Network (PEEN) is the most significant tool in the implementation of PEBLDS (ECNC, 2004). The PEEN concept (Jones-Walters, 2007) is designed to strengthen the ecological coherence of Europe as a whole, with a common set of criteria consisting of core areas, corridors, buffer zones and nature development areas. One of the major goals of PEEN is to develop an indicative map of the Pan-European Ecological Network for the whole of Europe (van Opstal, 1999). The design of such an indicative PEEN map requires information about the spatial distribution of habitats and species in Europe, both inside and outside protected areas (Mücher et al., 2005). This spatial information is also necessary to determine the spatial cohesion of habitat networks for viable populations in the landscape (Opdam et al., 2003). Information about the spatial distribution of species is already being collected by many international organisations (e.g., Birdlife International), but methodologies for spatial modelling of European habitats and landscapes need to be developed, because there are currently no quantitative figures available for these.

In this thesis methodologies are proposed to identify the spatial distribution and extent of habitats and landscapes at a Pan-European scale, but there is also an urgent need for monitoring. Remote sensing provides excellent methods towards this objective, especially with regard to large areas such as Pan-Europe. These methods have merits, but also limitations, especially when considering small and fragmented habitats and gradual changes within them. Therefore it is additionally necessary to monitor the components of European landscapes, by the use of standardised procedures for the surveillance of habitats (points, lines and patches), in order to enable habitat changes to be assessed. The proposed field surveying method can facilitate the integration with remote sensing for baseline monitoring of habitats with a regional to global extent. Appendix I provides a sampling framework and a baseline monitoring strategy based on the experiences in field surveying techniques within the EU project BIOHAB, and the use of remote sensing within the EU project BIOPRESS.

The study area in this thesis concerns Pan-Europe, the western extension of Eurasia. The European continent is divided from Asia, North to South, by the Ural Mountains, the Ural River and the Caspian Sea, and includes here also Turkey and Armenia. Pan-Europe is the area from Iceland in the north-west to Azerbaijan in the south-east and from Gibraltar in the south-west to Nova Zembla in the north-east and covers an area of approximately 11 million km^2. Pan-Europe has 50 sovereign states with approximately 800 million people – about 12%

of the world's population. The area has a long and complex coastline and wide variations in altitude, with many mountain ranges and extensive lowlands. It encompasses major contrasts in geology and soils and has a broad climatic spectrum, from the Arctic to near desert conditions in the Mediterranean. There is also a strong west-east gradient from the Atlantic to the steppic climates. The long land use history, in combination with all these factors, has led to a rich amalgam of habitats, landscapes and biodiversity in general; ranging from the nearly untouched landscapes of Svalbard to the artificially constructed landscapes of the Dutch polders. Not only cultural landscapes, such as peat meadows, are endangered but also semi-natural and natural habitats; for example, coastal and halophytic habitats, semi-natural and natural grasslands and raised bogs and fens. Their decline is mainly being caused by changes in land use associated with a reduction in the area of natural and semi-natural habitats and increasing pressures (Council of Europe, 1996).

1.2 Geo-spatial modelling of European landscapes and habitats

For the spatial modelling of European landscapes and habitats, use has been made of Geographic Information Science defined as Geographic Information Systems (GIS) combined with remote sensing methods and exploiting digitally available environmental data sets to indentify the spatial patterns or spatial distribution of landscapes and habitats. Burrough and McDonnell (1998) define GIS as a powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world for a particular set of purposes. Remote sensing is strongly related to GIS, since it is the science of obtaining information about an object, an 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). Landscape ecology makes use of these methods and techniques to study and describe spatial configurations (Groom et al. 2006). The spatial configurations are scale dependent. For example in landscape ecology, landscapes are conceived as a mosaic of land cover or habitat patches whose spatial pattern was significant in some profound sense (Potschin and Haines-Young, 2006). The definition of our objects of interest, namely landscapes and habitats is not that straightforward, since the interpretation of these concepts is very divergent, and differs according to the context and type of application. In this thesis landscapes are defined as recognizable, although often heterogeneous, parts of the earth's surface, which show a characteristic ordering of elements (Vos and Stortelder, 1992).

Landscapes result from long-term interactions of natural abiotic, biotic and anthropogenic processes and are complex systems in which many components are interdependent (Mücher et al., 2009b). Habitats are defined on the European Nature Information System (EUNIS) website (http://eunis.eea.europa.eu) as follows: plant and animal communities as the characterising elements of the biotic environment, together with abiotic factors (soil, climate, water availability and quality, and others), operating together at a particular scale. More strictly habitats can be defined as ecotopes, defined by Runhaar and De Haes (1994) as spatial units that are homogenous in vegetation structure, succession stage and site factors that determine the species composition of the vegetation.

Ecological systems are characterized by diversity, heterogeneity and complexity (Wu and David, 2002) and need a multi-scale or hierarchical approach to their analysis, monitoring, modelling and management (Hay et al., 2002). Wu and David (2002) advocate the Hierarchical Patch Dynamics Model (HPDM) which provides a powerful framework for breaking down complexity and integrating pattern with process (Wu and Marceau, 2002). HPDM uses a spatially nested patch hierarchy which consists of local ecosystems, local landscapes and regional landscapes. Jongman and Bunce (2000) propose a more comprehensive hierarchy, which is adapted here into the following hierarchical levels: (1) *biosphere* as the global sum of all ecosystems including its interactions with the lithosphere, hydrosphere and atmosphere; (2) *biogeographic region*s or environmental zones such as the Atlantic region which is dominated by a specific climate regime; (3) *landscape*, e.g., Atlantic lowlands dominated by clayey sediments and arable land such as the Dutch polders, characterized by a dominant biome and land use pattern at the regional scale. This is similar to the regional landscape of Wu and David (2002). (4) *Ecosystem* or *habitat* such as a fresh water habitat. In principle these ecosystems or habitats consist of relatively homogenous vegetation-soil complexes and resemble the local ecosystem in HPDM; (5) *species* and *ecotypes*. Within a species, an ecotype is a genetically unique population that is adapted to its local environment. In this thesis, we adopt the above mentioned modification of HPDM and use its terminology as discussed above.

This thesis focuses on the levels 1 – 4, with emphasis on the spatial modelling and monitoring of landscapes and habitats. There have been many modelling studies on components of the European environment at the landscape level. Examples of these components are: composition, pattern and complexity (Perry and Enright, 2002; Papadimitriou, 2009), soil genesis (Sommer et al., 2008), landscape change (De Aranzabal et al., 2008), potential change (Brown, 2006) and nitrogen fluxes (Theobald et al., 2004). Moreover, most of these studies concern a study area in one particular landscape type. Strikingly, there are no spatial modelling studies of the landscapes themselves at the European scale. Only the Burnett and Blaschke (2003) and Blaschke (2006) methodology for analysis of multi-scale segmentation/object relationship provides linkages for small-scale and large-scale landscape modelling. However, it is limited to the use of very high resolution satellite imagery. There are a number of regional and national landscape classifications, but they differ widely in methodological approaches, data sources and nomenclatures (Groom, 2005), and as a consequence they can not be integrated for Europe as a whole. Landscape classifications that are available for the whole of Europe, such as the ones from Meeus (1995) and Milanova and Kushlin (1993), are based on environmental data sets with coarse spatial resolution, and do not incorporate satellite imagery combined with modern GIS and remote sensing methods.

There are many more studies existing at the habitat level. Guisan and Zimmermann (2000) give an extensive review of predictive, niche, and species distribution modelling (see also Guisan and Thuiller, 2005). Niche-based species distribution models (Guisan and Zimmerman, 2000; Guisan and Thuiller, 2005; Dullinger et al., 2009) have become an important tool for assessing the potential range of species under current as well as predicted future environmental conditions. The quantification of such species/environment relationships represents the core of predictive geographical modelling in ecology (Guisan and Zimmermann, 2000). Conservation biologists increasingly rely on spatial predictive models of biodiversity to support decision making (Steinmann et al., 2009). Guisan and Zimmermann (2000) give an overview of the wide range of statistical methods that is in use to simulate the spatial distribution of terrestrial plant and animal species, biomes and other global vegetation groups, and plant functional types. In the majority of cases, the purpose of the statistical modelling is to predict species distribution (Austin, 2002). Studies that concentrate on the spatial modelling of European plant communities or vegetation types are less common. The paper by Zimmermann and Kienast (1999) concerns the predictive mapping of alpine grasslands using a species versus community approach, but is limited to the Swiss Alps. The two types of models presented in that paper yield patterns that are significantly correlated with real patterns observed in the field. Most of the statistical models in niche modelling rely to a large degree on bioclimatic and topographic data, and to some extent of soil properties. Almost no information is used on land use and land cover which determine to a large extent the actual distribution of species and habitats. Zimmermann and Kienast (1999) conclude that major problems arose from the lack of spatially explicit information of land use/history and the associated influence of soil development and secondary succession. Aready several studies included remotely sensed information for predictive habitat distribution modelling. Thuiller et al. (2004) investigated the extent to which the remotely sensed land cover classification PELCOM (Mücher et al., 2000; 2001) improved the predictive power when added to bioclimatic predictors in models for a range of taxonomic groups. Although they found that remotely sensed predictors clearly improve the fit of individual species models, it did not improve the cross-validated accuracy of the models. Zimmermann et al. (2007) interpret this as an indication that land cover patterns are highly correlated with bioclimatic gradients. In addition, Pearson et al. (2004) state that remotely sensed habitat information helps to discriminate between suitable and unsuitable sites which cannot be distinguished from bioclimatic layers alone. Pearson et al. (2004) show that that there is good potential for integrating land cover into the existing bioclimatic modelling frameworks. Land cover determines habitat availability and its interaction with climate plays an important role in determining the biogeography of species.

Nevertheless, most of these studies concentrate on particular species, have a limited extent, or use coarse resolution spatial maps for large areas and they do not include high resolution land cover data. Since up-to-date quantitative figures on European habitats were missing, a methodology was developed to predict the actual distribution of habitats (and not individual species), as defined in the Annex I of the Habitats Directive, at a European scale, using environmental data sets with a high spatial resolution in rule-based classifications. Guisan and Zimmermann (2000) state in relation to this aspect that higher accuracy and resolution of biophysical input maps, e.g. land use and soil units that can act as powerful 'filters', are still considered as primary requirements for improving model predictions. Finally, they state that progress in GIS-modelling and in remote sensing could pave the way for obtaining more accurate information.

1.3 Monitoring European habitats using Remote Sensing

The increasing deterioration of many landscapes, habitats and landscape elements demonstrates that they need to be protected and monitored in a more comprehensive fashion, ranging from regional to global scales. Monitoring is defined here as a procedure that involves the systematic measurement of a targeted object in time (at least two times) to be able to assess changes and trends in quantity and/or quality of the targeted object. And finally to understand the processes that are behind these changes. The use of remote sensing is an obvious means of providing the necessary information (Nagendra, 2001; Battrick, 2005; Battrick, 2006; Groom et al., 2006) because, compared to other survey techniques, it is unique in its potential for providing census data; i.e. complete coverage of large areas which is able to complement sample data (Inghe, 2001). Amongst other things, the synoptic overview represents more for landscape ecology than the mere possibility of capturing a large area at one moment (Groom et al., 2006). More fundamentally, it represents the possibility of identifying spatial-temporal patterns that are only discernible when a larger part of the landscape is repeatedly in view. Given that each nation state has its own history in surveying and mapping; the relevance of remote sensing for the coordination of Europe-wide landscape and habitat monitoring is significant, since satellite imagery operates irrespective of borders. Field surveys provide higher levels of accuracy than remote sensing, but its use makes it possible to increase the speed and frequency with which one can analyse a landscape (Strand et al., 2007). Groom et al. (2006) state that the relationship between remote sensing and landscape ecology is an evolving relationship, because new possibilities for exploration are emerging through technological advancements, including those represented by newly launched satellite sensors and novel image interpretation methods. The wide array of satellite sensors differ in their spatial, temporal, spectral, and radiometric resolution. Developments in multi-angle viewing (Chen et al., 2003; Su et al., 2007), radar (Bugden et al., 2004), imaging spectroscopy (Foody et al., 2004) and Lidar (Hall et al., 2009) all have considerable potential relevance for monitoring. However, consistent measurements are vital for long term monitoring of the environment. Therefore, it is important that consistent products are used throughout a project.

Noss (1990) describes a hierarchy concept for monitoring biodiversity. The different levels of information that can be considered for biodiversity and ecosystems studies are the *compositional*, *structural* and *functional* aspects of the landscape at multiple levels of ecological complexity. The compositional aspects discussed in this thesis are landscape and habitat types (Chapters 3 and 4) including structural aspects like habitat structure and physiognomy (life forms as discussed in Chapter 6). Functional aspects are landscape and habitat processes, which can be monitored by habitat field surveying techniques (as discussed in Chapter 6), and the study of land cover changes (as discussed in Chapter 5). The conceptual framework of Noss (1990) may facilitate the selection of indicators to represent the different dimensions of biodiversity that provide a basis for monitoring. An indicator can be defined as a measure used to determine the performance of functions, processes, and outcomes over time (Strand et al., 2007). Important 2010 biodiversity indicators selected by the Secretariat of the Convention on Biological Diversity 2006 (CBD 2006) and SEBI 2010 (EEA, 2007) to which this thesis can contribute include: (1) trends in the extent of selected biomes, ecosystems and habitats, (2) their fragmentation and (3) threats to biodiversity, such as land use and land cover changes. There are already a number of successful remote sensing studies which concentrate on a specific habitat, vegetation, or plant functional type using very high resolution satellite data (Küchler et al., 2004; Mander et al., 2005; Keramitsoglou et al., 2005, Kobler et al., 2006; Förster et al., 2008.; Schaepman-Strub et al., 2009), but they are limited in their spatial extent. Even for the majority of habitat types that could be mapped with high resolution image data, the lack of a simple relationship to a single biophysical parameter restricts the possibilities for many forms of automated image classification (Groom et al., 2006). The possibilities for direct mapping from satellite imagery for general sets of habitats, therefore have limitations. Instead, it is possible to identify components of the habitat complexity that satellite imagery can more directly map and develop actual habitat mapping procedures accordingly. One such component is land cover, which has the capability of acting as a surrogate parameter between several major sets of habitat types. Examples are those that are primarily associated with certain parts of the landscape, such as forest, arable land, grassland and wetlands (Groom et al., 2006; Duro et al., 2007). A spatial modelling approach starting with remotely derived land cover as proposed in this thesis, therefore, is appropriate to identify the likely locations of specific habitats.

Land cover provides essential information for the spatial identification of landscapes and habitats and is the most dynamic part capable of being monitored using remote sensing. Duro et al. (2007) give a good overview with referring to studies in which indicators of biodiversity have been modelled or mapped from Earth Observation (EO), and show that land cover is a key component. As mentioned before, land use and climate change are the most important drivers of biodiversity loss. Habitat destruction and degradation are caused mainly by changes in land use. At the same time, land use and associated land cover have been changing at an increasing rate over recent centuries and decades, causing increasing pressures on landscapes, habitats, and biodiversity in general. Therefore, land cover monitoring is a central issue in biodiversity monitoring. Land cover is not the same as land use. In the simplest case, land cover is an expression of a specific land use intervention – including no intervention at all –

on a specific type of land at a specific point of time (Stomph et al., 1997). As stated by Stomph et al. (1997), the problem with the term land use is that land use refers both to the way land is used i.e. manipulated (the interventions by man) and to the use or economic function that land has to man (the purpose of these interventions). Land cover can be defined as ‘the attributes occupying a part of the earth’s surface, such as vegetation, artificial constructions, rocks and water which can be distinguished from a distance’ (Anderson et al., 1976). In principle everything that is seen by a satellite sensor is land cover. However, in many cases the land use can be inferred from the land cover by its spatial configuration and context. Sports fields, as an example, can be distinguished from grassland by their specific size and shape and the fact that they are often located within urban areas. Urban area is also a land use, as inferred from the built-up area seen from a distance. Land use and land cover have a many-to-many relationship and as such should be used as separate terms.

Important past and current activities in the derivation of Pan-European land cover information from remotely sensed data include: (1) the on-going CORINE (Coordination of Information on the Environment) land cover project (CEC, 1994) under the co-ordination of the European Environment Agency (EEA) that was initiated in 1985, (2) the 1 km global land cover product DISCover (Loveland et al., 2000) established under the coordination of the International Geosphere and Biosphere Programme’s Data and Information System (IGBP-DIS), (3) the 1 km Pan-European land cover database PELCOM established under the coordination of Alterra (Mücher et al., 2000), (4) the 1 km GLC2000 global land cover data for the year 2000 established under the coordination of the Joint Research Centre (JRC) of the European Commission (Bartholomé and Belward, 2005), and (5) the recently finished 300 m global GLOBCOVER database (Arino et al., 2008). Accuracy assessments are of utmost importance for the use of these land cover data sets.

Validation of the CLC2000 (CORINE land cover database for the year 2000) with LUCAS field samples from Eurostat indicated an average accuracy of 74.8% (Büttner and Maucha, 2006). Validation of the IGBP DISCover global land cover set indicated an area-weighted global accuracy of 66.9% (Scepan et al., 1999). Validation of the PELCOM land cover database showed an overall accuracy of 69.2% (Mücher et al., 2001). Validation of the GLC2000 global land cover set indicated an area-weighted global accuracy of 68.6% (Mayaux et al., 2006; Herold et al., 2008). Validation of the 300 m GLOBCOVER indicated an area-weighted global accuracy of 73% (Defouney et al., 2009). As stated already by Mücher et al., (2000) and reconfirmed by Herold et al. (2008) the overall accuracy of continental or global land cover databases with low resolution satellite imagery barely exceeds 70% and medium resolution only achieves 73%. Such levels make it impossible to detect changes by comparing different land cover maps, while for biodiversity and environmental monitoring it is a prerequisite that the land cover databases can be easily updated. This means that additional techniques have to be developed to detect changes for Europe as a whole. Remote sensing definitely has limitations, especially with regard to habitats, and therefore needs to be complemented by field surveys. Sampling strategies or designs as proposed in Appendix 1 are crucial for the monitoring of habitats. Consistent biodiversity measurements in time and space are rare in Europe, with almost no consistent quantitative figures apart from butterflies and birds. Therefore a standardized procedure for the surveillance and monitoring of European habitats has been proposed (Bunce et al., 2008).

1.4 Objectives

The main objective of this thesis is to develop quantitative methodologies for the spatial identification and monitoring of European landscapes and habitats. In a broader context, it concerns biodiversity monitoring using Earth Observation data and methods as well as geo-information tools integrated with available European environmental data sets and field surveying techniques, with emphasis on habitats across European landscapes. The study area concerns Pan-Europe, as defined in section 1.1. The increasing deterioration of many European landscapes, habitats and landscape elements has created the awareness that they need to be protected and monitored in more comprehensive ways. However, there are currently no quantitative figures about the extent and trends of European habitats and landscapes. To achieve this objective, the following specific research questions have been formulated:

A. What is the added value of remote sensing for landscape ecology in Europe, with special emphasis on mapping and monitoring of habitats and landscapes? And more specific: do uses of remote sensing provide principles for classification within European landscape ecology?

B. Is it possible to model the spatial distribution of European landscapes using remote sensing and additional spatial information?

C. Is it possible to model the spatial distribution of European habitats using remote sensing and additional spatial information?

D. Since land cover information plays a crucial role in the spatial modelling of European landscapes and habitats, can we monitor Europe's land cover?

E. If it is possible to monitor European habitats using standardized procedures for field surveillance, can this be integrated with remote sensing to mitigate the latter's limitations?

1.5 Outline

The central chapters of this thesis (Chapter 2 to 6) were designed to answer the research questions mentioned in the previous section. These chapters have been published as peer reviewed articles in four scientific journals, namely *Landscape Ecology*, *Landscape and Urban Planning*, *Ecological Indicators* and *International Journal of Remote Sensing*. Every chapter focuses on Europe and includes an introduction related to one of the specific research questions, followed in principle by materials, methods, results, discussion and conclusions.

The use of remote sensing within European landscape ecology provides a rich range of examples of the interface between methods. Chapter 2 gives an overview of this and relates to experiences and perspectives in a European context, with seven examples of the application of image data, including some of the latest satellite imagery, and examination of associated classification issues.

Chapter 3 concerns the geo-spatial modelling of European landscapes, resulting in a new European landscape classification, called LANMAP. It concerns a transparent, flexible and user-friendly methodology to categorise landscapes. Because there are many regional differences in landscape properties, it is crucial to strike the right balance between reducing the inherent complexity and maintaining an adequate level of detail. Against this background, LANMAP has been established, making use of available segmentation and classification techniques using high resolution Pan-European environmental data sets.

Chapter 4 concerns the geo-spatial modelling of European habitats. The methodology identifies the spatial distribution of habitats across Europe, so that their actual extent can be determined. Spatial distribution models were derived for 27 Natura 2000 habitats representing the most significant European ecosystems, but can easily be extended to other habitats.

While Chapters 3 and 4 concentrate on the geo-spatial modelling of European landscapes and habitats, leading to quantitative figures of their spatial extent, Chapters 5 and 6 deal with monitoring issues of habitats and associated land cover across European landscapes, using both remote sensing and field surveying techniques.

Chapter 5 concerns European land cover characterization and change detection, using low resolution satellite imagery. A methodology was designed that resulted in the establishment of a Pan-European land cover database, called PELCOM, with a 1 km spatial resolution. Since the proposed methodology for land cover mapping has limitations for monitoring changes, due to the low spatial resolution and limited classification accuracies, a change-detection methodology is proposed on the basis of linear unmixing techniques.

Chapter 6 concerns standardized field surveys for the monitoring of European habitats and the provision of spatial data. Rigorous survey rules are needed to provide consistent data on changes in European habitats. Field surveys can only be implemented on a sample basis, and a good sampling framework is a prerequisite, as discussed in Appendix I.

Chapter 7 concludes this thesis with the results and main findings of all previous chapters and discusses the future outlook. At the end summaries are given in English, Dutch and Spanish, next to the acknowledgements, glossary, curriculum vitae and list of the author's publications.

References

Arino, O., Bicheron, P., Achard, F., Latham, J., Witt, R., Weber, J.L., 2008. GlobCover: The most detailed portrait of Earth. European Space Agency Bulletin 2008 (136), 24-31.

Anderson, J.R., Hardy, E.E., Roach, J.T., Witmer, R.E., 1976. Land use and land cover classification system for use with remote sensor data. U.S. Geological Survey professional paper (964).

Austin, M.P., 2002. Spatial prediction of species distribution: An interface between ecological theory and statistical modelling. Ecol. Model. 157 (2-3), 101-118.

Bartholomé, E., Belward, A.S., 2005. GLC2000: A new approach to global land cover mapping from earth observation data. Int. J. Remote Sens. 26 (9), 1959-1977.

Battrick, B. (Ed.), 2005. Global Earth Observation System of Systems GEOSS. 10-Year Implementation Plan Reference Document. Group on Earth Observations. GEO 1000R / ESA SP – 1284, ESA Publication Division, ESTEC, Noordwijk, the Netherlands, pp. 209.

Battrick, B. (Ed.), 2006. The Changing Earth. New Scientific Challenges for ESA's Living Planet Programme. SP-1304, ESA Publication Division, ESTEC, Noordwijk, the Netherlands, pp. 83.

Blaschke, T., 2006. The role of the spatial dimension within the framework of sustainable landscapes and natural capital. Landscape Urban Plan. 75 (3-4), 198-226.

Brown, I., 2006. Modelling future landscape change on coastal floodplains using a rule-based GIS. Environ. Modell. Softw. 21 (10), 1479-1490.

Bugden, J. L., Andrey, J., Howarth, P. J., 2004. A SAR process model for land-cover mapping. Can. J. Remote Sens. 30 (2), 195-204.

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 Ecol. 23 (1), 11-25.

CBD, 1992. The United Nations Convention on Biological Diversity. Reprinted in International Legal Materials 31 (5 June 1992): 818. http://www.cbd.int/. (Entered into force 29 December 1993).

CBD, 2002. The United Nations Convention on Biological Diversity. 2010 Biodiversity Target. http://www.cbd.int/2010-target/.

Council of Europe, UNEP, ECNC, 1996. The Pan-European Biological and Landscape Diversity Strategy: a vision for Europe's natural heritage. Strasbourg, Council of Europe Publishing.

Burnett, C., Blaschke, T., 2003. A multi-scale segmentation/object relationship modelling methodology for landscape analysis. Ecol. Model. 168 (3), 233-249.

Burrough, P.A., McDonnell, R.A., 1998. Principles of Geographical Information Systems. Oxford University Press, 333 p.

Büttner, G., Maucha, G., 2006. The thematic accuracy of CORINE Land Cover 2000. Assessment using LUCAS (land use/cover area frame statistical survey). EEA Technical report no.7/2006. Copenhagen, Denmark.

CEC, 1994. CORINE Land Cover Technical Guide. European Union, Directorate-General Environment, Nuclear Safety and Civil Protection, Office for Official Publications of the European Communities, Luxembourg. EUR, ISSN 1018-5593, ISBN 92-826-2578-8.

Chen, J. M., Liu, J., Leblanc, S. G., Lacaze, R., Roujean, J. L., 2003. Multi-angular optical remote sensing for assessing vegetation structure and carbon absorption. Remote Sens. Environ. 84 (4), 516-525.

Council of Europe, UNEP, ECNC, 1996. The Pan-European Biological and Landscape Diversity Strategy: a vision for Europe's natural heritage. Submitted by the Council of Europe at the

Ministerial Conference "Environment for Europe", Sofia, Bulgaria, 23-25 October 1995 and approved by the Ministers of the Environment of the 55 states present at the Conference. Nature and Environment, No. 74. Council of Europe Press, Strasbourg, 69 pp.

De Aranzabal, I., Schmitz, M.F., Aguilera, P., Pineda, F.D., 2008. Modelling of landscape changes derived from the dynamics of socio-ecological systems. A case of study in a semiarid Mediterranean landscape. Ecological Indicators 8 (5), 672-685.

Defourny, P., Schouten, L., Bartalev, S., Bontemps, S., Cacetta P., de Wit, A.J.W., et al., 2009. Accuracy Assessment of a 300 m Global Land Cover Map: the GlobCover Experience. Submitted to 33rd International Symposium on Remote Sensing of Environment (ISRSE), May 4-8.2009, Stresa, Italy.

Dullinger, S., Kleinbauer, I., Peterseil, J., Smolik, M., Essl, F., 2009. Niche based distribution modelling of an invasive alien plant: effects of population status, propagule pressure and invasion history. Biol. Invasions 1-14.

Duro, D.C., Coops, N.C., Wulder, M.A., Han, T., 2007. Development of a large area biodiversity monitoring system driven by remote sensing. Prog. Phys. Geog. 31(3), 235-260.

ECNC, IUCN and Council of Europe, 2004. Pan-European Biological and Landscape Diversity Strategy. Council for the European Biological and Landscape Diversity Strategy. Third Intergovernmental Conference 'Biodiversity in Europe'. Follow up of the Kyiv Biodiversity Resolution: Pan-European Ecological Network Action Plan Proposal. STRA-CO (2004) 3c rev, 12 pp (http://www.peblds.org).

EEA, 2005. The European Environment - State and Outlook 2005. Copenhagen.

EEA, 2007. Halting the loss of biodiversity by 2010: proposal for a first set of indicators to monitor progress in Europe. EEA Technical report No 11/2007, ISSN 1725–2237, EEA, Copenhagen, pp 186.

EU Council Directive, 1992. Natura 2000 Network on the conservation of natural habitats and of wild fauna. COUNCIL DIRECTIVE 92/43/EEC (1) of 21 May 1992. The Council of the European Communities.

Foody, G. M., Sargent, I. M. J., Atkinson, P. M., Williams, J. W., 2004. Thematic labelling from hyperspectral remotely sensed imagery: Trade-offs in image properties. Int. J. Remote Sens. 25 (12), 2337-2363.

Förster, M., Frick, A., Walentowski, H., Kleinschmit, B., 2008. Approaches to utilising QuickBird data for the monitoring of NATURA 2000 habitats. Community Ecol. 9 (2), 155-168.

Guisan, A., Zimmermann, N. E., 2000. Predictive habitat distribution models in ecology. Ecol. Model. 135 (2-3), 147-186.

Guisan, A., Thuiller, W., 2005. Predicting species distribution: Offering more than simple habitat models. Ecol. Lett. 8 (9), 993-1009.

Groom, G., 2005. Methodological review of existing classifications, in: Wascher, D.M. (Ed.), European Landscape Character Areas – Typology, Cartography and Indicators for the Assessment of Sustainable Landscapes. Final ELCAI project report, Landscape Europe, pp. 32-45.

Groom G., Mücher, C.A., Ihse M., Wrbka T., 2006. Remote Sensing in landscape ecology: experiences and perspectives in a European context. Landscape Ecol. 21, 391-408.

Hall, R. K., Watkins, R.L., Heggem, D.T., Jones, K.B., Kaufmann, P.R., Moore, S.B., Gregory, S.J., 2009. Quantifying structural physical habitat attributes using LIDAR and hyperspectral imagery. Environ. Monit. Assess. 1-21.

Hansen, A.J., deFries, R.S., Turner, W., 2004. Land Use Change and Biodiversity: A Synthesis of Rates Consequences during the Period of Satellite Imagery, in: Gutman, G., Janetos, A.C., Justice, C.O., Moran, E.F., et al. (Eds.), Land Change Science: Observing, Monitoring and Understanding Trajectories of Change on the Earth's Surface. Series title Remote sensing and digital image processing (vol. 6) Publisher Kluwer Academic Publishers, pp. 277-300.

Hay, G. J., Dubé, P., Bouchard, A., Marceau, D. J., 2002. A scale-space primer for exploring and quantifying complex landscapes. Ecological Modelling 153 (1-2), 27-49.

Herold, M., Woodcock, C.E., Loveland, T.R., Townshend, J., Brady, M., Steenmans, C., Schmullius, C.C., 2008. Land-cover observations as part of a global earth observation system of systems (GEOSS): Progress, activities, and prospects. IEEE Systems Journal 2 (3), 414-423.

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.

Jones-Walters, L., 2007. Pan-European Ecological Networks. J. Nat. Conserv. 15(4), 262-264.

Jongman, R. H.G. (Ed.), 1996. Ecological and Landscape consequences of land use Change in Europe. Proceedings of the First ECNC Seminar on L and Use Change and its Ecological Consequences, Tilburg, the Netherlands, 16–18 February 1995. ECNC Publication Series on Man and Nature, Volume 2, November 1996. ISBN 90-802482-1-5.

Jongman, R.H.G., Bunce, R.G.H., 2000. Landscape classification, scales ad biodiversity in Europe, in Mander, Ü., Jongman, R.H.G. (Eds.), Consequences of Land use change in Europe pp. 11-38.

Köhler, R., Olschofsky, K., Gerard, F. (Eds.), 2006. Land Cover Change in Europe from the 1950'ies to 2000. Aerial photo interpretation and derived statistics from 59 samples distributed across Europe. Published by University of Hamburg, World Forestry Institute, Germany. ISBN 80-89088-46-5, 364 pp.

Keramitsoglou, I., Kontoes, C., Sifakis, N., Mitchley, J., Xofis, P., 2005. Kernel based re-classification of Earth observation data for fine scale habitat mapping. J. Nat. Conserv. 13 (2-3), 91-99.

Klein Goldewijk, K., Ramankutty, N., 2004. Land cover change over the last three centuries due to human activities: The availability of new global data sets. GeoJournal 61 (4), 335-344.

Kobler, A., Džeroski, S., Keramitsoglou, I., 2006. Habitat mapping using machine learning-extended kernel-based reclassification of an Ikonos satellite image. Ecol. Model. 191 (1), 83-95.

Küchler, M., Ecker, K., Feldmeyer-Christe, E., Graf, U., Küchler, H., Waser, L. T., 2004. Combining remotely sensed spectral data and digital surface models for fine-scale modelling of mire ecosystems. Community Ecol. 5 (1), 55-68.

Lillesand, T. M., Kiefer, R.W.,. Chipman J.W., 2008. Remote sensing and image interpretation (6th edition). Publisher Wiley, New York, , 756 p.

Loveland, T. R., Reed, B. C., Brown, J. F., Ohlen, D. O., Zhu, Z., Yang, L., Merchant, J. W., 2000. Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data. Int. J. Remote Sens. 21 (6-7), 1303-1330.

Mander, Ü., Mitchley, J., Xofis, P., Keramitsoglou, I., Bock, M., 2005. Earth observation methods for habitat mapping and spatial indicators for nature conservation in Europe. J. Nat. Conserv. 13 (2-3), 69-73.

Mayaux, P., Eva, H., Gallego, J., Strahler, A. H., Herold, M., Agrawal, S., Naumov, S., De Miranda, E. E., Di Bella, C. M., Ordoyne, C., Kopin, Y., Roy, P. S., 2006. Validation of the global land cover 2000 map. IEEE T. Geosci. Remote 44 (7), 1728-1737.

Meeus, J.H.A., 1995. Pan-European landscapes. Landscape Urban Plan. 31 (1-3), 57-79.

Milanova, E.V., Kushlin, A.V. (Eds.), 1993. World map of present day landscapes. An explanatory note. Department of World Physical Geography and Geoecology, Moscow State University, in collaboration with UNEP, 25 pp plus annexes.

Moran, E.F., Skole, D.L., Turner II, B.L., 2004. The Development of the International Land Use and Land Cover Change (LCLUC) Initiative., in: Gutman, G., Janetos, A.C., Justice, C.O., Moran, E.F., et al. (Eds.), Land Change Science: Observing, Monitoring and Understanding Trajectories of Change on the Earth's Surface. Series title Remote sensing and digital image processing (vol. 6) Publisher Kluwer Academic Publishers. pp 1-16.

Mücher, C.A., Steinnocher, K., Kressler, F, Heunks, C., 2000, Land cover characterization and change detection for environmental monitoring of pan-Europe. Int. J. remote Sens. 21 (2000), 6/7: 1159-1181.

Mücher, C.A., Champeaux, J.L., Steinnocher, K.T., Griguolo, S., Wester, K., Heunks, C., et al., 2001. Development of a consistent methodology to derive land cover information on a European scale from Remote Sensing for environmental monitoring; The PELCOM report. Alterra Report 178, CGI report 6, 178 pp., Wageningen, the Netherlands.

Mücher, C.A., Hennekens, S.M., Bunce, R.G.H., Schaminée, J.H.J., 2005. Spatial identification of European habitats to support the design and implementation of a Pan-European Ecological Network, in: McCollin, D., Jackson, J.I.(Eds.), Planning, People and Practice. The landscape ecology of sustainable landscapes. Proceeding of the 13th Annual IALE(UK) Conference, held at the University of Northampton, 2005, pp. 217-225.

Mücher, C.A., Hennekens, S.M., Bunce, R.G.H., Schaminée, J.H.J., Schaepman, M.E., 2009a. Modelling the Spatial Distribution of Natura 2000 Habitats across Europe. Landscape Urban Plan. 92 (2), 148-159.

Mücher, C.A., Klijn, J.A., Wascher, D.M., Schaminée, J.H.J., 2009b. A new European Landscape Classification (LANMAP): A transparent, flexible and user-oriented methodology to distinguish landscapes. Ecol. Indicat., doi:10.1016/j.ecolind.2009.03.018. In Press.

Nagendra, H., 2001. Review article. Using remote sensing to assess biodiversity. Int. J. Remote Sens. 22 (12), 2377-2400.

Noss, R.F., 1990. Indicators for monitoring biodiversity: a hierarchical approach. Conservation Biology 4 (4), 355-364.

Opdam, P., Verboom, J., Pouwels, R., 2003. Landscape cohesion: an index for the conservation potential of landscapes for biodiversity. Landscape ecol. 18, 113-126.

Opstal, A. van, 1999. The Architecture of the Pan-European Ecological Network: Suggestions for Concept and Criteria. Discussion report on behalf of the committee of experts of the Pan European Ecological Network. Report IKC Natuurbeheer Nr.37, Wageningen, The Netherlands.

Ostermann, O. P., 1998. The need for management of nature conservation sites designated under Natura 2000. J. Appl. Ecol. 35 (6), 968-973.

Papadimitriou, F., 2009. Modelling spatial landscape complexity using the Levenshtein algorithm. Ecological Informatics 4 (1), 48-55.

Pearson, R.G., Dawson, T.P., Liu, C., 2004. Modelling species distributions in Britain: A hierarchical integration of climate and land-cover data. Ecography 27 (3), 285-298.

Perry, G.L.W., Enright, N.J., 2002. Spatial modelling of landscape composition and pattern in a maquis-forest complex, Mont Do, New Caledonia. Ecol. Model. 152 (2-3), 279-302.

Potschin, M.B., Haines-Young, R.H., 2006. Landscapes and sustainability. Landscape Urban Plan. 75 (3-4), 155-161.

Runhaar, J., De Haes, H.A., 1994. The use of site factors as ecosystem classification characteristics, in: F. Klijn (Ed.) Ecosystem Classification for Environmental Management. Kluwer, Dordrecht, pp 139-172.

Scepan, J., Menz, G., Hansen, M. C., 1999. The DISCover validation image interpretation process. Photogramm. Eng. Rem. S. 65 (9), 1075-1081.

Schaepman-Strub, G., Limpens, J., Menken, M., Bartholomeus, H.M., Schaepman, M.E., 2009. Towards spatial assessment of carbon sequestration in peatlands: Spectroscopy based estimation of fractional cover of three plant functional types. Biogeosciences 6 (2), 275-284.

Secretariat of the Convention on Biological Diversity, 2006. Global Biodiversity Outlook 2. Montreal, 81 + vii pages.

Sommer, M., Gerke, H. H., Deumlich, D., 2008. Modelling soil landscape genesis - A "time split" approach for hummocky agricultural landscapes. Geoderma 145 (3-4), 480-493.

Spellenberg, I.F., 2005. Monitoring Ecological Change. Second Edition. Cambridge University Press, Cambridge, UK, 391 pp.

Stanners, D., Bordeaux, P. (Eds.), 1995. Europe’s Environment; The Dobříš Assessment. European Environmental Agency, Copenhagen. 676 pp. Office for Official Publications of the European Communities, Luxembourg.

Steinmann, K., Linder, H.P., Zimmermann, N.E., 2009. Modelling plant species richness using functional groups. Ecol. Model. 220 (7), 962-967.

Stomph, T.J., C.A. Mücher and L.O. Fresco, 1997. Environmental Impact of Land Use: A New Basis for Analysis. The Land, 1997, Vol 1.2, pp 129-142.

Strand, H., Höft, R., Strittholt, J., Miles, L., Horning, N., Fosnight, E., Turner, W., (Eds.), 2007. Sourcebook on Remote Sensing and Biodiversity Indicators. Secretariat of the Convention on Biological Diversity, Montreal, Technical Series no. 32, pp. 203.

Su, L., Chopping, M.J., Rango, A., Martonchik, J. V., Peters, D.P.C., 2007. Differentiation of semi-arid vegetation types based on multi-angular observations from MISR and MODIS. Int. J. Remote Sens. 28 (6), 1419-1424.

Theobald, M.R., Dragosits, U., Place, C.J., Smith, J.U., Sozanska, M., Brown, L., et al., 2004. Modelling nitrogen fluxes at the landscape scale. Water, Air, and Soil Pollution: Focus 4 (6), 135-142.

Thuiller, W. Araujo, M.B., Lavorel, S., 2004. Do we need land-cover data to model species distributions in Europe ? J. Biogeogr., 31, 353-361.

Van Duuren, L., Eggink, G.J., Kalkhovan, J., Notenboom, J., Strien, A.J. van, Wortelboer, R. (Eds.), 2003. Natuurcompendium 2003. Natuur in cijfers. CBS (Voorburg), MNP (Bilthoven en Wageningen),http://www.pbl.nl/nl/publicaties/mnp/2003/Natuurcompendium_2003.html, ISBN 906960101X., 494 pp.

Vos, W., Stortelder, A.H.F., 1992. Vanishing Tuscan landscapes: landscape ecology of a Submediterranean-Montane area (Solano Basin, Tuscany, Italy). Pudoc Scientific Publishers, ISBN 9022009645, Wageningen, the Netherlands. 403 p. + 1 map.

Wu, J., David, J.L., 2002. A spatially explicit hierarchical approach to modeling complex ecological systems: Theory and applications. Ecol. Model. 153 (1-2), 7-26.

Wu, J., Marceau, D., 2002. Modeling complex ecological systems: An introduction. Ecol. Model. 153 (1-2), 1-6.

Zimmermann, N.E., Kienast, F., 1999. Predictive mapping of alpine grasslands in Switzerland: Species versus community approach. J. Veg. Sci. 10 (4), 469-482.

Zimmermann, N.E., Edwards Jr, T.C., Moisen, G.G., Frescino, T.S., Blackard, J.A., 2007. Remote sensing-based predictors improve distribution models of rare, early successional and broadleaf tree species in Utah. J. Appl. Ecol. 44 (5), 1057-1067.

Photo: A flock of Mergelland sheep near a drinking pool in the valley of Gerendal, Limburg, The Netherlands.

CHAPTER 2

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

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Groom, G., Mücher, C.A., Ihse, M., Wrbka, T., 2006. Remote sensing in landscape ecology: experiences and perspectives in a European context. *Landscape Ecol.*, 21, 391-408. The contribution of C.A. Mücher to this work is: 35% design and methodology, 30% of the case studies, and 30% writing.

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

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.

Keywords: classification, landscape ecology, landscape information, remote sensing

2.1 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.

2.2 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.

2.2.1 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.

2.2.2 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.

2.2.3 Abstraction-free landscape information

To function as a science landscape ecology requires landscape information. Two important data collection methods are field data collection and use of existing data such as topographic maps. Notwithstanding their significance, both these methods also 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 preparing the field work and makes it more efficient; this is especially true when mapping and/or sampling is part of the field work.

2.2.4 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.

2.3 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.

2.3.1 Medium spatial resolution satellite 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).

2.3.2 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 2.1) 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 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.

2.3.3 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.

Table 2.1 The currently operating very high spatial resolution satellite remote sensing systems for civil applications.

Satellite	began operating	spatial resolution[a]	swath (km) [1]	spectral bands (nm)	repeat time (days) [1]
IRS 1C, 1D	1C – Dec.95 1D – Sept.97	5.8 m	70	500 - 750	24 (min 5)
IKONOS 1, 2	1 – Apr.99 2 – Sept.99	1 m (Pan) 4 m (Multispectral)	11.3	Pan: 450 – 900 Multispectral: 450 – 520, 520 – 600, 630 – 690, 760 – 900	as ordered (min 1.5)
EROS 1A	Dec.2000	1.8 m	13.5	500 – 900	1.8
Quickbird	Oct. 01	0.6 m (Pan) 2.5 m (Multispec.)	16.5	Pan: 450 – 900 Multispectral: 450 – 520, 520 – 600, 630 – 690, 760 – 890	1 - 3.5
SPOT 5a	May 02	2.5 m (Pan) 5.0 m (Pan)	60	510 – 730	26 (min 3)
ORBView-3	June 03	1 m (Pan) 4 m (Multispectral)	8	Pan: 450 – 900 Multispectral: 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.

2.3.4 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).

2.3.5 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.

2.4 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 2.2 the set covers a range of scales and scopes/purposes.

Table 2.2 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).

Scope / scale	Local	National / Regional	Supranational / European
Extraction of descriptors of Vegetation Structure	1 (DK)		
Monitoring of Vegetation Degradation		3 (SE)	
Classification / Delineation of biotopes/ habitats	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)	

2.4.1 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:

- 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 and 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 x 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 AIS (Area Information System) vector 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 (Fig. 2.1). 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 2.3a); 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 2.3a). Application of the classifiers followed rule-based state definition and combination (Table 2.3b).

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 areas (broad-leaved forest, needle-leaved forest, mixed forest, scrub, young plantation, grassland, wet areas and bare ground).

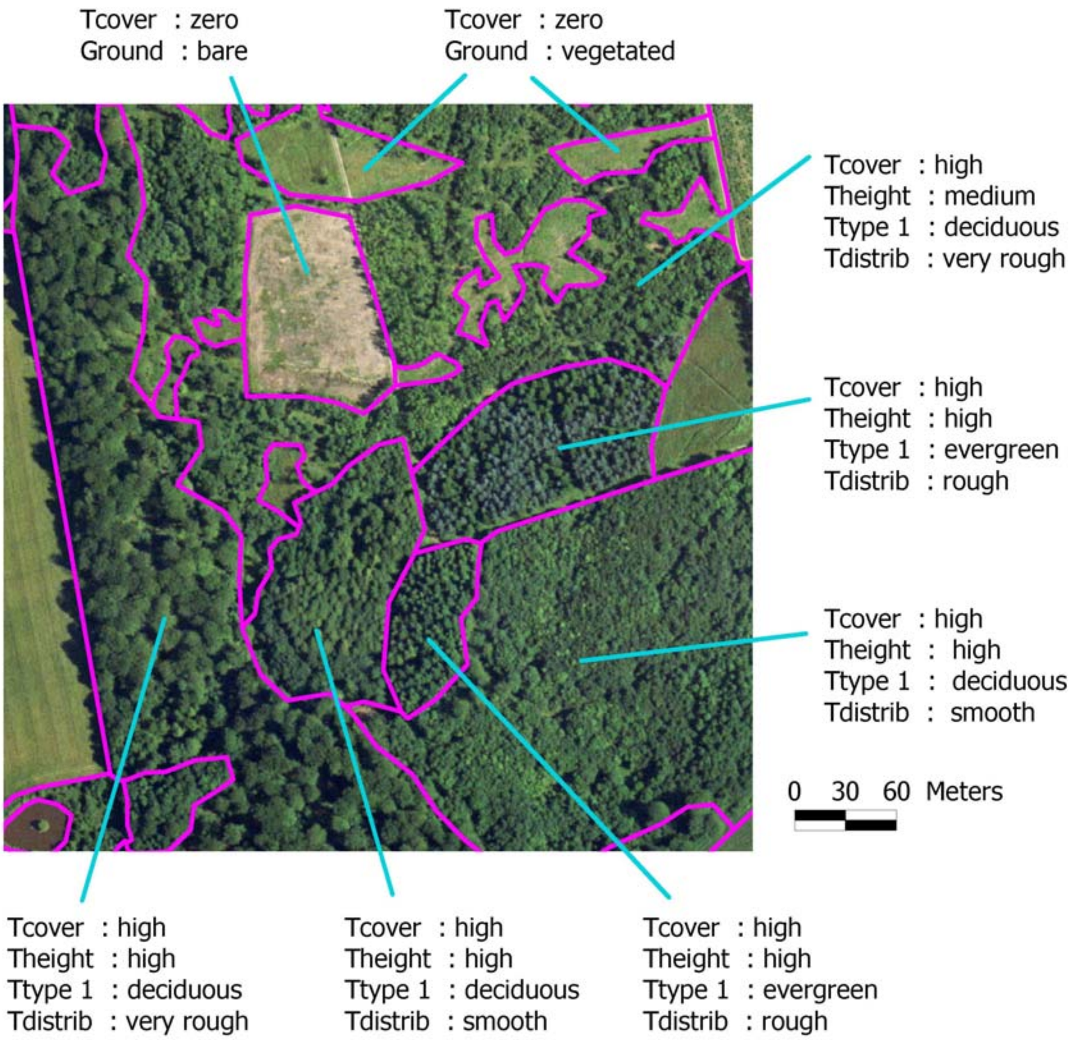


Fig. 2.1 An example of the interpretation of digital orthophotos (0.4 meter pixels) for mapping of forest characteristics for generation of a landscape map for the ALMaSS wildlife modelling.

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.

Table 2.3 (a) Modelled relationships between requirements of the ALMaSS Landscape Map for forest information to classifers interpretable from orthophoto images. (b) The states and combinations of states for the classifiers used for forest character mapping for the ALMaSS Landscape Map. 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 ortho-photos
(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

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 broadleaved deciduous forest the accuracy is 72–75%.

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

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 ErdasTM 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 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 mountain 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 x 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 (Fig. 2.2). 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 x 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.

2.4.2 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 an individual 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 satellite derived land cover data that has been developed as the Pan-European Habitat 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.

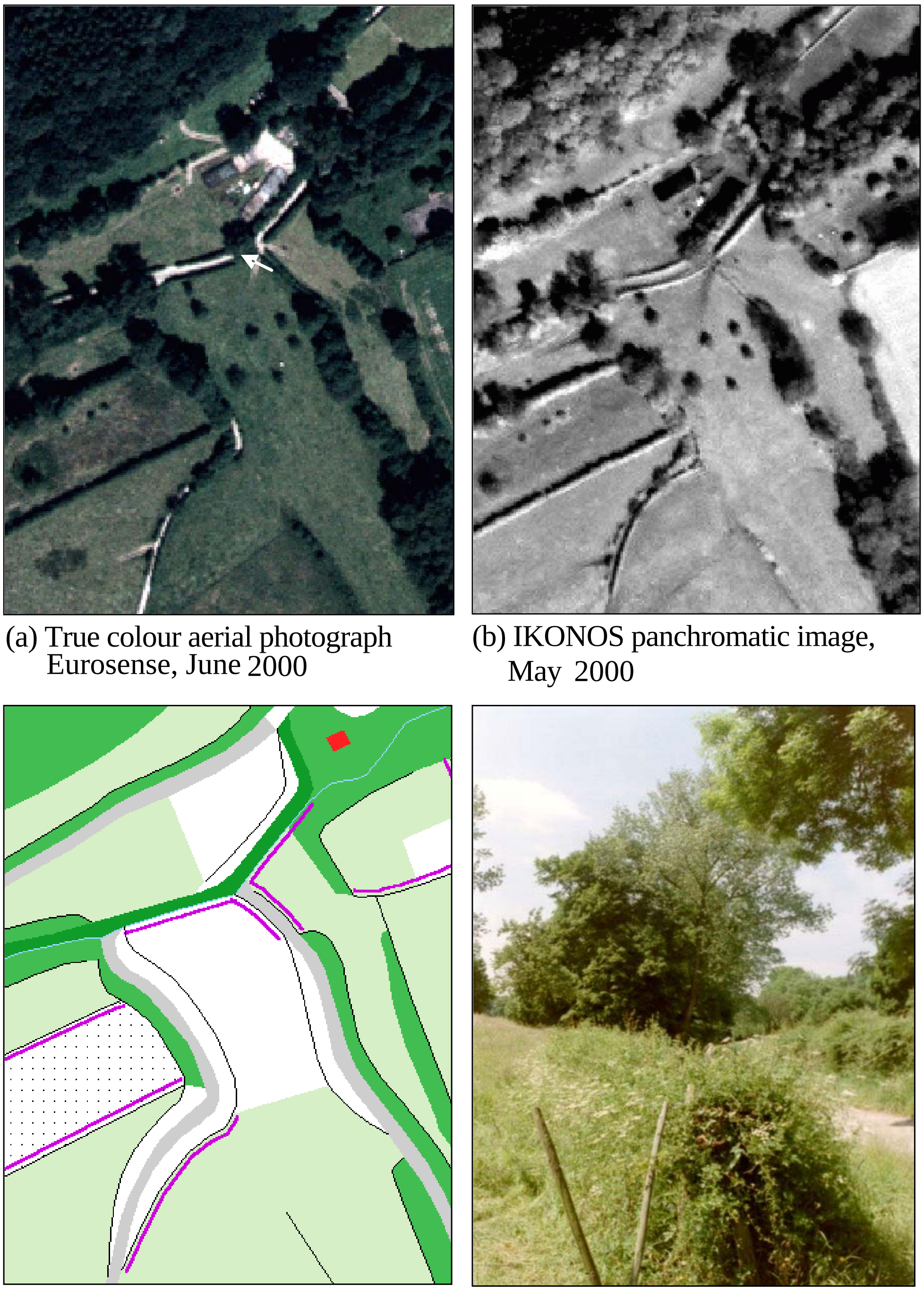
Example 5. Extraction of habitat information from European databases and remote sensing data

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 Europapeae, 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, releve´ s 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).



(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)

Fig. 2.2 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).

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).

2.4.3 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).

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

Burnett, C., 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., 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., 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., 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 Gregório, A., 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., 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., 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., 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., 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., 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., Ejrns, R., 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., Oddersk r 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., Lam, K.W.K., 2003. Effects of JPEG compression on image classification. Int. J. Remote Sens. 24: 1535–1544.

Lofvenhaft, K., Bjorn, C., 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., 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., 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. 407.

Mücher, C.A., Steinnocher, K., Kessler, F., 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., Beissmann H., 2004. Evaluating the ecological sustainability of Austrian agricultural landscapes – the SINUS approach. Land Use Policy 21: 307–320.

Rogan. J., Chen D., 2004. Remote sensing technology for mapping and monitoring land-cover and land-use change. Prog. Plann. 61: 301–325.

Sawaya, K.E., Olmanson, L.G., Heinert, N.J., Brezonik, P.L., 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., 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., 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., 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., 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., 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., 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., Oddersk 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., Scholte K., 2000. MERILAND: MERIS potential for land applications. (USP-2 Report 1999, 99-36), BCRS, Delft, The Netherlands, 113 pp.

Wagner, W., Luckman, A., Vietmeier, J., Tansey, K., Balzter, H., Schmullius, C., Davidson, M., Gaveau, D., Gluck, M., 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., 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., 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., 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., Hobbs, R., 2002. Key issues and research priorities in landscape ecology: an idiosyncratic synthesis. Landscape Ecol. 17: 355–365.

Photo: A Highland calf in a heatland of Garderen ‘Gardensche veld’, The Netherlands.

CHAPTER 3

A new European landscape classification (LANMAP): A transparent, flexible and user-oriented methodology to distinguish landscapes

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A new European Landscape Classification (LANMAP): A transparent, flexible and user-oriented methodology to distinguish landscapes

Abstract

We have developed a new hierarchical European landscape classification that can be used as a framework for e.g. indicator reporting and environmental sampling. Landscapes are ecological meaningful units where many processes and components interact. And as such, landscapes themselves have resulted from long-term interactions of natural abiotic, biotic and anthropogenic processes. A good understanding of landscapes is essential for its assessment, protection, management and planning. An internationally consistent approach is therefore obligatory and the production of landscape classifications and associated maps is an important tool in this context. Although intuitive maps are available there are no consistent quantitative maps of European landscapes. In this paper, landscapes are regarded as forming recognizable parts of the earth's surface and as showing a characteristic ordering of elements. The complex nature of the underlying scientific concepts, which sometimes overlap and conflict, requires an objective and consistent methodology, as described in the present paper. As there are many regional differences in landscape properties, it is crucial to strike the right balance between reducing the inherent complexity and maintaining an adequate level of detail. Against this background, a European Landscape Map (LANMAP) has been produced, making use of available segmentation and classification techniques on high resolution spatial data sets. LANMAP is a landscape classification of Pan-Europe with four hierarchical levels; using digital data on climate, altitude, parent material and land use as determinant factors; and has 350 landscape types at the most detailed level. At this level there are 14,000 mapping units with a minimum mapping unit of 11 km^2. Thus far, LANMAP is limited to a biophysical approach, since there is a lack of consistent and European-wide data on cultural-historical factors. This paper describes the conceptual background of LANMAP, its methodology and results, and shows its potentials and limitations.

Keywords: spatial modelling; segmentation, environmental data sets; validation; European framework indicator reporting

3.1 Introduction

Europe has a long and complex coastline and wide variations in altitude, with many mountain ranges and extensive lowlands. It also reveals contrasts in geology and soils and has a broad climatic spectrum, from the Arctic to near desert conditions in the Mediterranean. There is also a west-east gradient from Atlantic to Continental climates. Recent pollen and plant macrofossil analysis from sites in Denmark provide records of the last 7,000 years of vegetation history linked to to changing land use practices (Rasmussen, 2005). In southern Europe, the origins of land cultivation date back even further. The combination of all these environmental and cultural factors has led to a rich amalgam of landscapes in Europe, ranging from the nearly untouched landscapes of Svalbard (Norway) to the artificially constructed landscapes of the Dutch polders (Meeus, 1995; Council of Europe et al., 1996; Wascher, 2000; Klijn and Vos, 2000; Green and Vos, 2001; Aalen, 2001; Klijn, 2004).

Landscape definitions differ according to the context or type of application. In the present paper landscapes are considered to form recognizable, although often heterogeneous, parts of the earth's surface, which show a characteristic ordering of elements. Landscapes are ecological meaningful units where many processes and components interact. And as such, landscapes themselves have resulted from the long-term interactions of natural abiotic, biotic and anthropogenic processes and are complex systems in which many components are interdependent. The outstanding richness and diversity of Europe's landscapes is widely recognised, as these form a unique natural and cultural heritage containing high ecological, aesthetic, archaeological and historical values. These are sometimes linked to economic values such as recreation and tourism, craft and art work as well as attractive environments for housing and business. They contribute to the character of landscapes to which the history and culture of its people is strongly connected. Landscapes are changing, though at different rates and time scales. And nowadays resulting in a loss of landscape character that alarms citizens and policymakers alike. The question is how to safeguard or even restore values whereas a host of changes affect these landscape now and in the future.

The changes are manifold and related to driving forces such as climate change, drainage, demography (e.g., population increase, land abandonment, urbanisation), economic development, and technology driving for instance urbanisation and traffic, and man's lifestyle (consumption patterns, leisure). All these forces affect land use and through them landscapes (Meeus et al., 1990; Delbaere, 1998; Klijn, 2004, Antrop, 2005). What can be observed and predicted is a widespread loss of characteristic differences between landscapes; in other words homogenisation, invoking a loss of identity and deterioration of quality.

These concerns have been addressed in recent policy documents, such as the Pan-European Biological and Landscape Diversity Strategy (Council of Europe et al., 1996) and more recently by the European Landscape Convention. This convention (Council of Europe, 2000; Déjeant-Pons, 2006) states amongst others: “believing that landscape is a key element of individual and social well-being and that its protection, management and planning entail rights and responsibilities for everyone”. Identification and assessment of landscapes are mentioned as a specific measure in Article 6 (Council of Europe, 2000). From discussions at the Sofia conference in 1995, eleven action-themes were defined. Action-theme 4 included the objective to establish of a Pan-European Landscape Map, next to the development of landscape assessment criteria, and a Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis of European landscapes (Council of Europe, 1996; Vervloet and Spek, 2003). Maps are tools to distinguish essentially different landscapes and indicate their distribution, extent, and often their exposure to major influences. Maps are efficient at communicating otherwise abstract matters. Among physical planners the saying goes: ‘When maps are shown, emotions run high’. Once printed, maps are a static cartographic product whose aim is to serve as many goals as possible, but they are usually based on a transitory approach and can be considered as just one statement. It is now possible to profit from modern GIS techniques in data gathering, processing, analysis, storage, and advanced classification methods. These techniques provide opportunities to combine various data layers and produce tailor made classifications that can readily be updated. After the first attempts of Milanova and Kushlin (1993) and Meeus (1995), a landscape map of Europe should utilize these new techniques and environmental data sets with a high spatial resolution.

An initiative to produce a Pan-European landscape classification using state-of-the-art technology was set-up in 2002 and, after various test-procedures, resulted in the present paper. The European landscape map is designed to provide a practical and easy tool for communication between interested partners involved in European landscapes and associated policy implementation. Moreover, such a classification provides an excellent tool for indicator reporting or environmental assessments and can be used as a sampling framework for monitoring activities. As stated in the Dobříš report of the European Environment Agency (EEA) on the state of Europe’s Environment (Stanners and Bordeaux, 1995), there is still substantial disparity in the wide variety of European landscapes and an internationally harmonised and accepted approach to characterise and identify them is still lacking. The maps of Milanova and Kushlin (1993) and Meeus (1995) were a first attempt to produce a European landscape map, but they were rather inaccurate, partly due to a lack of systematic digital information with a high spatial accuracy and computer supported data processing. These studies nevertheless provide examples of European-wide information on the character, locations and properties of landscapes. The essential shortcoming in landscape information in the European Union (EU) was repeated on various occasions (e.g., Wascher, 1999) but did not yet lead to a co-ordinated action towards a European Landscape classification.

Having this in mind, a new user-oriented Pan-European Landscape Map – LANMAP – has been produced, based on digital data sets with a high spatial accuracy and a high degree of flexibility to enable adaptations and extensions. The LANMAP methodology and resulting classification and database and its applications are explained below.

3.2 Materials and Methods

3.2.1 Conceptual framework

During the last ten years, data availability and quality and conceptual understanding in the field of the terrestrial environment has advanced substantially. For example the use of Google Earth has advanced the availability of spatial information to the general public, which helps, but does not solve the conceptual problems of how to design a robust and widely accepted landscape classification. The absence of a common conceptual framework for European environmental and landscape classifications is felt by ecologists, historical geographers, landscape planners, and also those involved in policy making. Extensive discussions were held on the shortcomings of earlier attempts and the need to deliver a more widely accepted data supported landscape and environmental classification that could serve EU policy development (Bunce et al. 1996, Jongman and Bunce, 2000, Klijn, 2000, Wascher 1998, Wascher 2000,Vervloet and Spek, 2003). From these discussions and evaluations the following requirements were formulated:

- A commonly shared conceptual framework.
- Explicit end-user orientation at an international level.
- Flexibility to be guaranteed by a well structured GIS which contains the necessary information layers and can be approached easily to deliver tailor-made products at various

scales, as well as easy updates and improvements, flexibility in data interpretation, and/or aggregation/generalisation of results.

- Methodological transparency: i.e., which data sets are used, what information is qualitative (nominal) and what is quantitative (rank order, ratio), what is the spatial accuracy ?
- Sufficient support from scientists and policy-makers in order to guarantee that data are really accepted and are being used.
- Moving away from a subjective, intuitive and qualitative approach towards a more formal, objective and quantitative standardised system.

Landscapes are complex, spatially heterogeneous systems with many properties and values: this makes classification and mapping difficult, especially at continental scales. The conceptual framework used (Mücher et al., 2003) is based upon a hierarchical approach of various landscape components: abiotic, biotic and cultural factors. Landscape components are often interrelated in their origin and evolution, in actual functioning and in spatial distribution. Spatial and temporal and causal (inter)relationships, if analyzed, interpreted, simplified, ordered and ranked properly can form the basis of a classification. Relationships are often asymmetric; i.e., some (relatively) independent components and processes clearly determine the behaviour of (relatively) dependent components and processes, the latter expressing the influence of the former.

By the process known as pair-wise comparison, it is possible to order and rank landscape components according to their respective mutual independence/dependence statuses. This is called hierarchic ordering (Klijn, 1995). Some landscape components emerge as relatively stable and independent, while other components are relatively dependent; with the pattern of the former variables being largely responsible for that of the latter. Likewise, a change in independent variables inevitably evokes a reaction in the dependent ones. To illustrate this: it is accepted that relatively independent abiotic phenomena (e.g., climate and geology) determine the presence and nature of relatively dependent biotic phenomena, such as vegetation. Changes in these abiotic characteristics generally lead to changes in biotic components (shift in position, shift in composition). Landscapes are entities where many components and processes interact. As given in Eq. 3.1, it is possible to rank and order the various phenomena accordingly (Klijn, 1995; Bunce et al., 1996). This equation is in line with the work of Jenny (1941) who reassessed the significance of the five soil forming factors as described by the Dukuchaev school of soil science; i.e., climate, organisms, topography, parent material and time. The interpretation of soil properties as functions of state factors lead to the equation of Jenny (Vos and Stortelder, 1992). This approach has its parallels in our approach to landscapes.

Eq. 3.1 $\text{Landscape} = f(C_{(t)}, G_{(t)}, H_{(t)}, S_{(t)}, V_{(t)}, F_{(t)}, LU_{(t)}, STR_{(t)})$

C = Climate, G = Geology and Geomorphology, H = Hydrology, S = Soils, V= Vegetation, F= Fauna and LU = Land Use, STR = Landscape Structure, (t) = Time).

The sequence of state factors in Eq. 3.1 is ordered by increasing dependency and grouped according to abiotic (C, G, H, S), biotic (V, F) and cultural aspects (LU, STR). Groom (2005) showed that these factors had an important role in most of the 49 national and regional landscape classifications analysed. Hierarchies are helpful for understanding natural landscapes and processes, but human factors act at many levels. Man's influence has progressively increased in importance since prehistoric times. Nowadays it is possible to observe major impacts even on seemingly independent natural components, such as atmospheric and oceanic systems (e.g., climate change and sea-level rise). This makes it necessary to identify and specify man's position and his influences within the various levels of a landscape hierarchy. Human influences can thereafter be ordered and ranked according to their specific impacts or their degree of interference with the ecosystem, where they affect components on the various hierarchical levels (e.g., Mücher, 1992; Klijn, 1995; Stomph et al. 1997). The above summarized procedure for ranking landscape components, their natural processes and man's interference at various levels has practical uses. It can be used to order and rank various processes and their impact on dependent variables and it can support classification and mapping by: i) in the selection of data that are considered important, ii) by ranking these according to the hierarchy shown and therefore, iii) can contribute to the architecture of a classification from which, iv) a legend of a map can be derived. This procedure is not dictated solely by scientific criteria, the quality and detail of classifications and maps also depend on user requirements.

Although LANMAP is limited to an eco-physical approach, the perceived character of landscapes is strongly linked to past and present cultural influences. Generally, it is found that these are only partly determined by physical phenomena, e.g., climate, geology, geomorphology and soil conditions. Demography, cultural and political history also act as independent factors that explain certain former land use types, or occupation patterns. However, some cultural phenomena do reflect physical conditions quite clearly; for example, the distribution of vineyards and buildings connected with cultivation and wine production. These are historically conditioned by climate and soil types. Often cultural phenomena are too complex to categorise in a simple, comprehensive and internationally accepted way. This may be due to that fact, in comparison with abiotic or biotic data, discussions on how to interpret and classify cultural data have not yet achieved sufficient international consensus and digital data sets are rare.

3.2.2 Data

A critical review of the availability of appropriate data sets was needed, which led to a confrontation between the ideal and the attainable. Unfortunately, in most cases, several data sources had to be integrated to obtain a full European coverage for a selected theme. A pragmatic approach was taken, which led to the selection of the following differentiating criteria and associated key data sources for identifying and delineating landscape units (Mücher et al., 2006):

1. **Climate (C)**. Data layer obtained by integration of the European Environmental Zones (EnZ) by Metzger et al., (2005) and by the EEA adopted Biogeographical Regions Map of Europe (BRME) by Roekaerts (2002).
2. **Altitude (A)**. Data layer directly obtained from the Digital Elevation Model GTOPO30 (http://edcdaac.usgs.gov/gtopo30/gtopo30.asp)
3. **Parent material (P)**. Data layer obtained by integration of the European Soil Database (ESDB; CEC, 1985), which has a parent material attribute, and the FAO Soil Map of the World (FAO, 1991).
4. **Land cover / Land use (LC)**. Data layer obtained by integration of the following land cover databases CORINE (CEC, 1994, Nuñes de Lima, 2005), GLC2000 global land cover database (Bartholomé and Belward, 2005.) and PELCOM (Mücher et al., 2000; Mücher et al., 2001).

Fig. 3.1 shows these data layers. In an ideal case systematic data on geology and geomorphology would be preferable, as mentioned in Eq. 3.1. However, a high-resolution geomorphology map of Europe is not available, although Embleton (1984) describes the Geomorphology of Europe in 20 chapters, presenting many figures on aspects of geology and geomorphology for most regions in Europe. However, in general, these maps have a very low accuracy, have no co-ordinates, no information about the projection, and differ considerably in their contents and the legends used, which makes it impossible to transform all this information into one consistent geomorphology map of Europe.

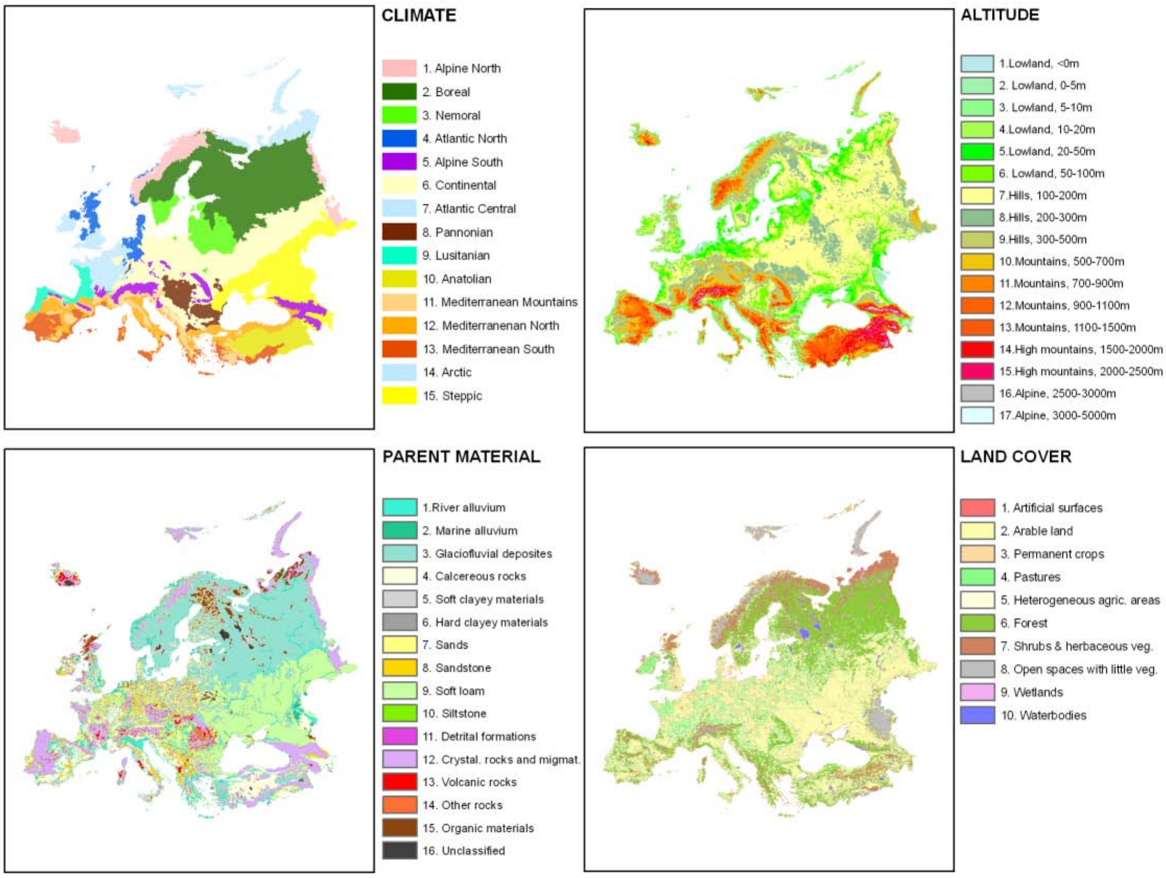

Fig. 3.1 Fig. 3.1a shows the first data layer Climate (C), which was obtained by integration of the European Environmental Stratification (Metzger et al. 2005) and the Biogeographical Regions Map of Europe (Roekaerts, 2002). Fig. 3.1b, above right, shows the second data layer Altitude (A) derived from the Digital Elevation Model GTOPO30. Fig. 3.1c, below left, shows the third data layer Parent material (P), which was obtained by integration of the European Soil Database (CEC, 1985), and the FAO Soil Map of the World (FAO, 1991). Fig. 3.1d, below right, shows the fourth data layer Land cover (LC) , which was obtained by integration of the following land cover databases CORINE (CEC, 1994), GLC2000 global land cover database (Fritz et al., 2003) and PELCOM (Mücher, 2001).

Therefore, information on parent material and topography (altitude) has been used as an adequate substitute. The parent material is derived from the state-of-the-art soil databases which are available in digital format based upon detailed and systematic soil classifications, though they are primarily structured for agricultural application. In part, land use and land cover can be seen as the interactive result of cultural and biophysical phenomena, and a high spatial resolution is available for a large part of Europe. Land use and land cover information is derived from databases that have been obtained by the interpretation of satellite imagery and other ancillary data sources (e.g., topographic maps). An example of this is the CORINE land cover database which, although it still contains some inconsistencies, is the most detailed for Europe. It has a spatial scale of 1:100,000 and has been used to its widest extent. CORINE roughly applies only the EU countries and so the remaining Pan-European countries had to be covered by GLC2000 (Bartholomé and Belward, 2005.) and, for a few exceptions, by PELCOM (Mücher et al., 2000; 2001). Apart from altitude, it was a demanding task to integrate all sources for each thematic data layer to obtain full Pan-European coverage. Unfortunately, cultural aspects of the European landscapes; e.g., parcellation, occupation patterns, and periods of original cultivation; could not be covered, due to the extreme scarcity of appropriate spatial data.

3.2.3 Method

Different data sources had to be integrated for each thematic layer to obtain Pan-European coverage (Mücher et al., 2003, 2006). The spatial data sets used were the most accurate and detailed available at the time of the processing. The above mentioned four core data sets formed the foundation for the identification of the landscape units and typology. Intelligent and user-oriented combination of the data was needed, in addition to judicious use of modern techniques in automatic data processing. Therefore, segmentation techniques (Burnett and Blaschke, 2003; Lucas et al., 2007) were used for the spatial identification of the landscape units. Segmentation (object recognition, based on spatial characteristics), is the process of identifying spatial units, which are mostly derived from satellite imagery. The segmentation itself was implemented with the software eCognition (now called Definiens Developer) which is an object-oriented image segmentation and classification software for multi-scale analysis of Earth Observation data of all kinds (Definiens Imaging, 2005). Before the segmentation process was started, the data layers were prepared to a standard nomenclature with a limited number of classes that were meaningful for the spatial identification of European landscapes (approximately 15 classes for each thematic layer). In addition, it was often necessary to generalise the original data sources to enable integration of sources for each thematic layer. After the thematic generalisation the data layers were re-sampled to a 1 km spatial resolution, using a majority rule for the spatial generalisation. Segmentation was only used to identify the landscape units. For their classification or labelling, a simplification of each thematic layer was needed to create a landscape typology with a limited number of types. From an operational perspective and on the basis of existing national typologies, the authors considered a considered a total number of 500 landscape types to be a maximum for keeping the typology user-friendly and informative. Therefore the diagnostic criteria used for the identification of units had to be further generalised to limit typology to an acceptable number of classes. A full overview of the diagnostic criteria and typology for each of the four data layers can be found in Annex 3.1. Fig. 3.2 shows a flowchart of the methodology.

Segmentation

The segmentation is based on the thematic data layers; parent material, altitude and land cover which were aggregated to a 1 kilometre spatial resolution. The climate layer has a lower spatial resolution and was therefore used for the typology but not for the delineation of the landscape units. For the segmentation, the three data layers, Altitude (A) with 17 classes, Parent material (P) with 16 classes, and Land cover (LC) with 10 classes, were transformed into one RGB colour composite, which gives the impression of dealing with a satellite image, and was used as the input file for the segmentation process. In eCognition (Definiens Imaging, 2005) several parameters had to be set; e.g., scale, shape and colour factors. The colour factor was set to one and implied directly a shape factor of zero. This was done because the segmentation needed to be based purely on the values of the data layers and not on certain degree of compactness, since landscapes have no predefined shape. The parameter settings for the scale and weight factor went through an iterative process of trial and error in consultation with landscape ecologists and a geomorphologist. For example, when the scale factor is set to a low value, e.g., 15, the segmentation is very detailed. Inversely, if the scale factor is set to a high value, e.g., 100, the segmentation is very coarse (in other words very large objects).

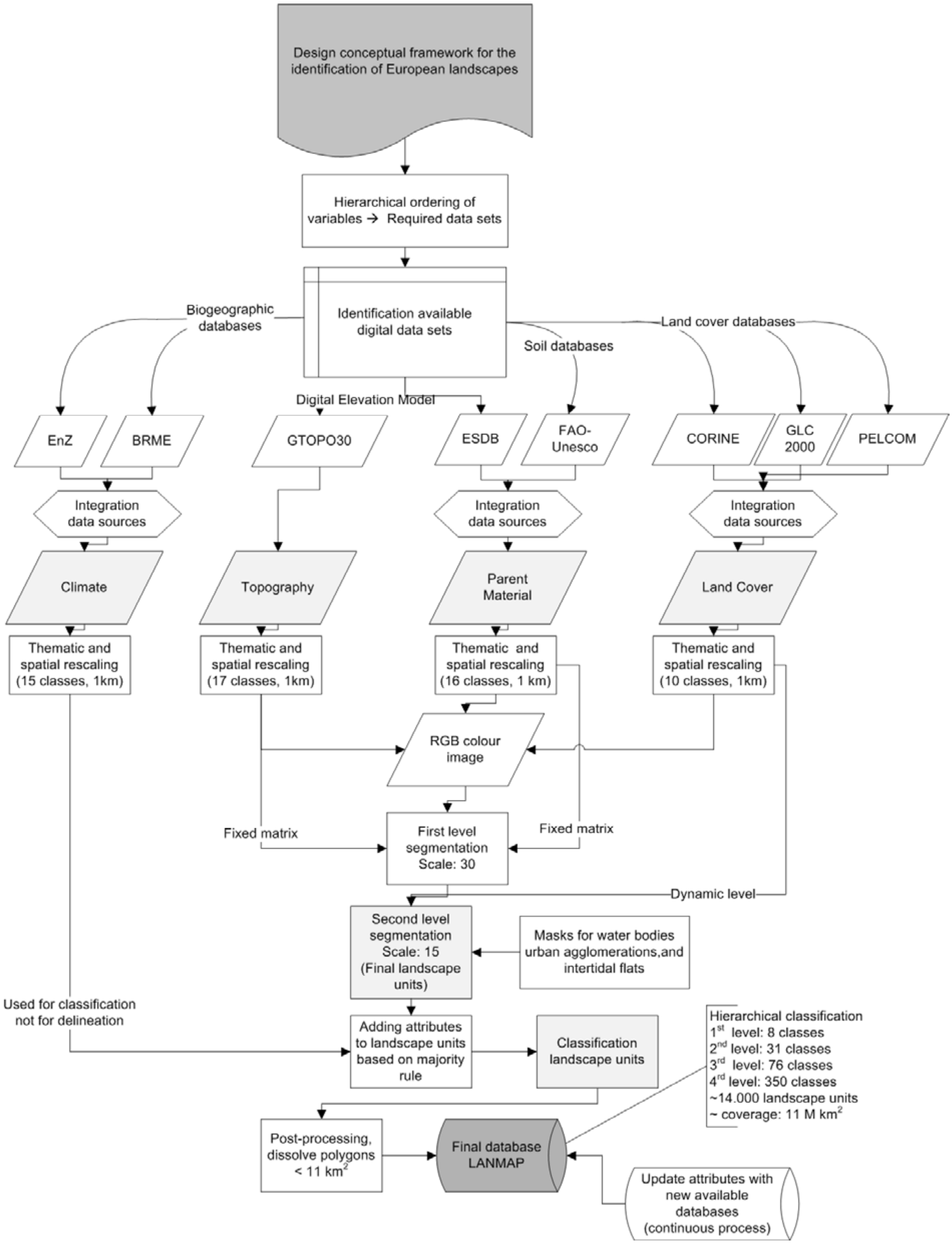

Fig. 3.2 Flowchart of the LANMAP methodology

Finally, the segmentation was implemented in a two-step approach. For the first level segmentation the scale factor was set to 30 and was based on parent material and topography only. The first level segmentation result was considered to be a fixed matrix since it is based on the relatively static physical data layers of altitude and parent material.

In a second step, the first segmentation level was further segmented based on the data layer land cover (LC). For this second level segmentation, the scale factor was to 15 and resulted in more detailed sub-segments. The second level was considered as the final segmentation result that identified the landscape units. The final result was exported from eCognition to a shape file. Climate was added afterwards as an attribute to each landscape unit. Although climate was the most important descriptor for the landscape type, it did not determine the delineation of the landscape unit. In other words, although the most important factor in determining the type of a landscape unit was climate, it did not determine the shape of the landscape unit. The determinant factors and the general descriptions for the landscape typology were also attached as attributes to each landscape unit in the database.

Landscape Typology

The landscape typology is a hierarchical nomenclature with four levels. The nomenclature is made of simple combinations of climate, altitude, parent material and land cover. Fig. 3.3 and Table 3.1 demonstrate that at the highest level climate is the principal determinant, followed by climate and topography at the second level. Since the typology is derived from eight climate types, five altitude classes, three parent material classes and ten land cover types (see Fig. 3.3), in principle 1200 European landscape types (8 x 5 x 3 x 10) could be obtained. Fortunately, and as expected, not all combinations are possible in reality. Existing combinations resulted in 350 European landscape types at level 4.

An example of a landscape type in Fig. 3.4 is the Mediterranean (M) lowland (l) dominated by sediments (s) and arable land (al), indicated by the symbol '*Mls_al*'. This is very characteristic of the highly productive Po valley which is situated roughly between Milan, Bologna and Venice.

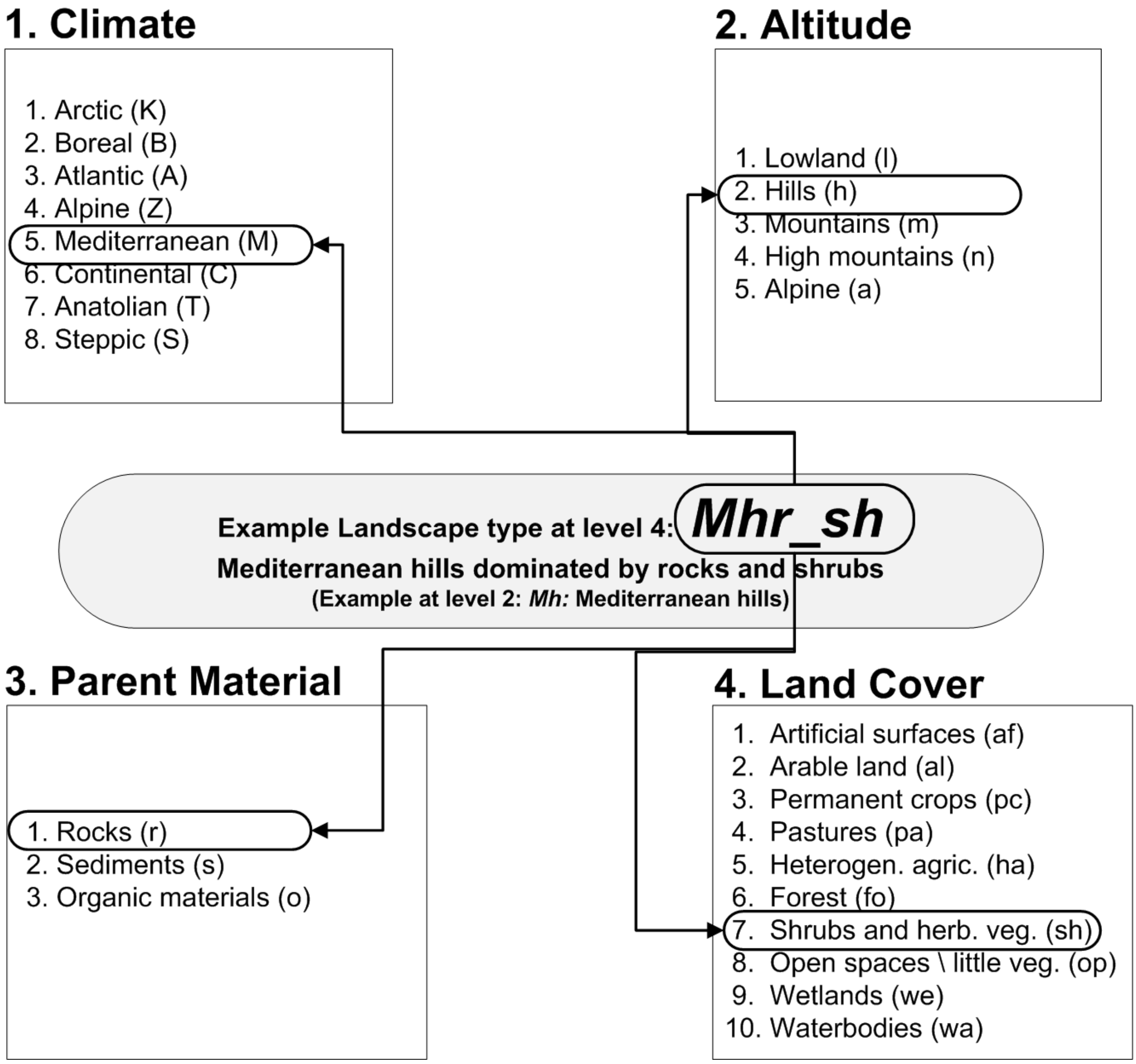

Fig. 3.3 Flowchart of the LANMAP typology

In the post-processing phase, some masks were created that were superimposed over the classification, namely for urban agglomerations (URBAN), water bodies (WABOD) and intertidal flats (FLATS). These masks cover areas for which the soil databases often did not contain any information. The mask for major urban agglomerations was based on a 5km majority filter on all urban areas in the land cover database. All larger regions that were dominated by urban agglomerations were seen as a specific landscape type. The mask for inter-tidal flats, outside the current extent of the database, was derived directly from the integrated land cover database and superimposed on the European Landscape database. These inter-tidal flats are an important landscape type which is very characteristic of areas such as the Wadden Sea. A last step in the post-processing was the removal of polygons smaller than 11 km^2, which were integrated with the (smallest) adjacent polygon.

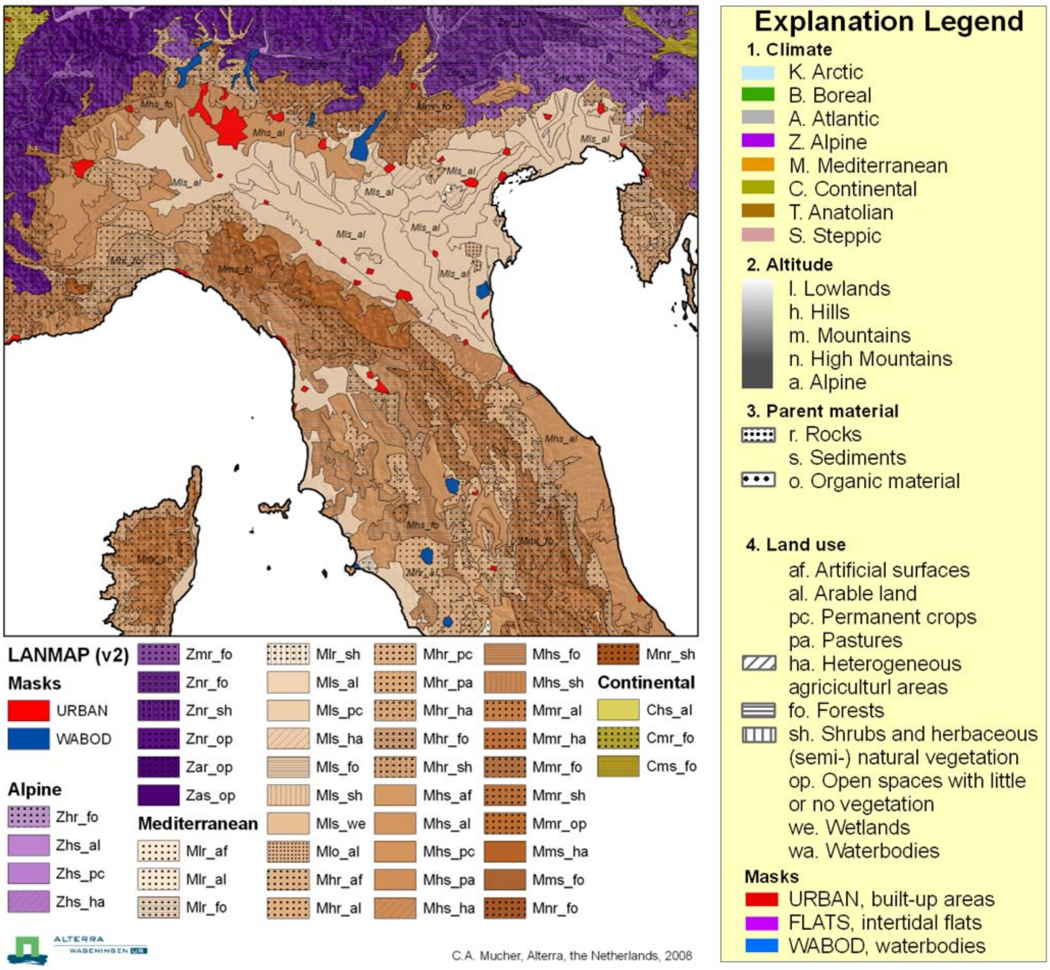

Fig. 3.4 Detail of the European Landscape Classification for Northern Italy and direct surroundings.

3.3 Results

3.3.1 Established European Classification

The final result is the European Landscape Map, LANMAP, a Pan-European Landscape database at a scale of ~ 1:2M. The European landscape classification covers Pan-Europe entirely from Iceland in the Northwest to Azerbaijan in the Southeast and from Gibraltar in the Southwest to Nova Zembla in the Northeast. LANMAP covers an area of approximately 11 million km^2 (Mücher et al., 2006), as shown in Fig. 3.5. The European Landscape

Classification has four hierarchical levels. Level 1 is based on climate only and has eight classes. The largest class is the Boreal region (*B*) with 3 million km^2 (27.8% of pan-Europe) and the smallest class is Anatolian region (*T*) with 0.4 million km^2 (3.9% of pan-Europe), see also Table 3.1. Level 2 is based on climate and altitude and has 31 classes. The largest class here is the Boreal hills (*Bh*) with 2.2 million km^2 (20.3%) and the smallest class is Continental high mountains (*Cn*) with 1946 km^2 and covering less than 0.02%. Level 3 is based on climate, altitude and parent material and has 76 classes. Level 4 is based on all four layers and has 350 landscape types. At this level the database has 14,000 landscape units.

Table 3.1 LANMAP hierarchical typology

Level 1 (8 classes)	Area (km^2)	%	Level 2 (31 classes)	Area (km^2)	%	Level 3 (Area in km^2)* (76 classes)
Arctic (K)	445273	4.1	Arctic lowlands (Kl) Arctic hills (Kh) Arctic mountains (Km)	125719 278676 38101	28.4 63.0 8.6	Klo (46852), Klr (50687), Kls (28180), Kho (15589), Khr (188942), Khs (74146), Kmr (38101)
					100.0	
Boreal (B)	3018460	27.8	Boreal lowlands (Bl) Boreal hills (Bh) Boreal moutains (Bm)	653316 2203017 66806	22.3 75.4 2.3	Blo (39054), Blr(16746), Bls (597516), Bho (144696), Bhr (21359), Bhs (2036962), Bmo(294), Bmr(5853), Bms (60660)
					100.0	
Atlantic (A)	995179	9.2	Atlantic lowlands (Al) Atlantic hills (Ah) Atlantic mountains (Am)	370168 539620 53888	38.4 56.0 5.6	Alo (17731), Alr (117498), Als (234939), Aho(32467), Ahr (337794), Ahs (169359), Amo(1199), Amr(50281), Ams (2408)
					100.0	
Alpine (Z)	977477	9.0	Alpine lowlands (Zl) Alpine hills Zh Alpine mountains (Zm) Alpine hign mountains (Zn) Alpine alpine (Za)	19647 342788 443100 142350 25045	2.0 35.2 45.5 14.6 2.6	Zlr (7199), Zls (10504), Zho (4822), Zhr (131457) , Zhs (206510) , Zlo (1944), Zmo (335), Zmr (366370), Zms (76396), Znr (140658), Zns (1692), Zar (24797), Zas (248)
					100.0	
Mediterr. (M)	1493710	13.8	Mediterranean hills (Mh) Mediterranean lowlands (Ml) Mediterranean mountains (Mm) Mediterranean high mountains (Mn) Mediterranean alpine (Ma)	614075 145915 667412 46766 3799	41.5 9.9 45.2 3.2 0.3	Mlo (1279), Mlr (31254), Mls (113381), Mhr (385189), Mhs (228886), Mmo (111), Mmr (555614), Mms (111688), Mnr (39491), Mns (7275), Mar (3799)
					100.0	
Continent. (C)	2353780	21.7	Continental lowlands (Cl) Continental hills (Ch) Continental mountains (Cm) Continental high mountains (Cn)	330911 1737594 251530 1946	14.3 74.8 10.8 0.1	Clo (11759), Clr (660), Cls (318493), Cho (22101) , Chr (194869), Chs (1520624), Cmo (387), Cmr (182877), Cms (68266), Cnr (1946)
					100.0	
Anatolian (T)	428137	3.9	Anatolian hills (Th) Anatolian mountains (Tm) Anatolian high mountains (Tn) Anatolian alpine (Ta)	8609 247341 153129 11061	2.0 58.9 36.4 2.6	Thr (7549), Ths (1060), Tmr (192522), Tms (54819), Tnr (98174), Tns (54955) Tar (10215), Tas (846),
					100.0	
Steppic (S)	1131430	10.4	Steppic lowlands (Sl) Steppic hills (Sh) Steppic mountains (Sm) Steppic high mountains(Sn)	510988 565442 24161 8471	46.1 51.0 2.2 0.8	Slr (76935), Sls (428979), Shr (31836), Shs (533606), Slo (5073), Smr (11876), Sms (12284), Snr (7420) , Sns (1050)
		100.0			100.0	

Each landscape unit, stored as a record in the database, has a now long list of attributes, approximately 70, which helps in describing the landscape units. Next to the most important attributes as described in Table 3.2, there are additional attributes for e.g.: climate (mean monthly values of precipitation, sunshine and temperatures), altitude (minimum, maximum, mean, deviation and slope), geomorphology, potential natural vegetation, and population density. For each landscape type an extensive description is given by Rick van der Heijden (2007) based on these attributes.

The mean landscape size, at the lowest hierarchical level, is 774 km^2. However, large variations in landscape size do exist. The smallest landscape unit is 11 km^2 and the largest landscape unit is 739,000 km^2. The largest landscape units can be found in the western part of Russia, Ukraine and Scandinavia. Natural soil and climate conditions are more extreme in eastern Europe but also more homogeneous than in the west (Meeus,1995). The average landscape unit is also much smaller in Western and Central Europe due to high population densities and intensive land use over a long period of time. Another reason is that the spatial scale of information is in general lower in Eastern Europe.

In the final version of LANMAP (version 2) the first hierarchical level has eight classes, the second hierarchical has 31 classes and the third hierarchical level has 76 classes, and the fourth level has 350 classes (Mücher et al., 2006).

Table 3.2 Most important attributes for each landscape unit in the LANMAP database

Attribute	*Description*
CLIM_NR	Climate class (15 classes)
DEM_NR	Elevation class on which the segmentation is based (17 classes)
PM_NR	Parent material class on which the segmentation is based (16 classes)
LC_NR	Land cover class on which the segmentation is based (10 classes)
T_CLIM	One character for the climate class which determines the final typology (8 classes)
T_DEM	One character for the elevation class which determines the final typology (5 classes)
T_PM	One character for the parent material class in the final typology (3 classes)
T_LC	One character for the land cover class which determines the final typology (10 classes)
LSTYPE	Landscapetype (as a 5 character set) concatenated on basis on the 4 above mentioned attributes
LS_NR	Landscape type number calculated as follows: 1000000*[Clim_nr] +10000*[Dem_nr]+ 100*[Pm_nr]+[Lc_nr]
LAND	Attached land-sea mask: 1=land, 2= sea
LS-COD	Unique code in sequential order for each landscape type (numer 10-381) and numbers: 1:URBAN mask, 2 intertidal flats mask, 3 waterbody mask, 999 no data
LEVEL 1	Landscape type at hierarchical level 1 (8 classes)
LEVEL 2	Landscape type at hierarchical level 2 (31 classes)
LEVEL 3	Landscape type at hierarchical level 3 (76 classes)
LEVEL 4	Landscape type at hierarchical level 4 (350 classes)

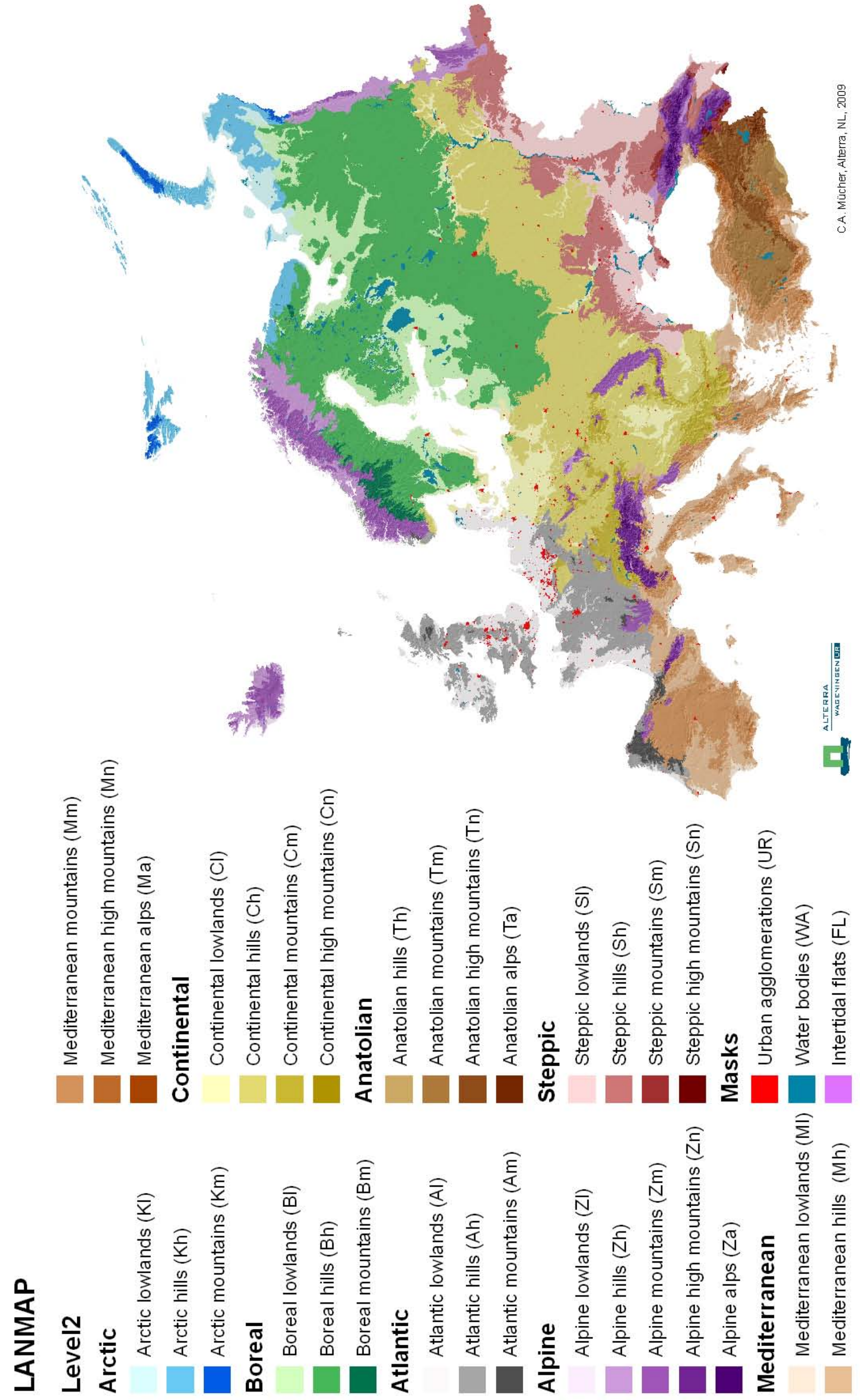

Fig. 3.5 LANMAP, a newly established European Landscape Classification based on high-resolution spatial-explicit digital information. Level 2 of LANMAP is shown in this figure.

3.3.2 Validation

In the test phase some cross-validations were made for the Netherlands and Germany. For the Netherlands the resemblances to the Dutch national landscape map were clear (Mücher et al., 2003). But Fig. 3.5 shows also clear differences between the final version of LANMAP and the National Landscape Map (Nota Landschap, Ministerie van LNV, 1992). The differences in Fig. 3.5 resulted mainly after the extension to Pan-Europe, partly because the final typology had to be simplified to limit the number of European landscape types. This implied that the LANMAP typology made no longer a distinction between the origin of the sediments (sand or marine or river alluvium), which is an important criterion in the Dutch landscape typology. Nevertheless, these differences in origin of sediments are still present as an attribute in the LANMAP database and anyway determined the delineation of the landscape units as reflected in the diagnostic factors (see also Annex 3.1). Since differences in parent material often caused differences in land use the LANMAP typology still emphasizes these differences. For example, LANMAP does not distinguish lowland peat areas from exploited peat bogs. Nevertheless, the former were converted mainly into pastures and the latter mainly into arable land (*Alo_al* and *Alo_pa*, see Fig. 3.6). Another clear difference is that LANMAP clearly shows the urban agglomerations in the Netherlands as a specific landscape type, while this type is absent in the Dutch landscape typology. The Dutch National Landscape classification is the result of a long consultation process that reflects the views of most landscape ecologists and physical geographers, but it is not based on semi-automatic classification methods as used in many other countries to create their national landscape classifications.

For Germany the validation results were less good, but the general patterns were to a large extent the same (Mücher et al., 2003). For Spain a comparison can be made with the Atlas de los Paisajes de España (Mata Olmo and Sanz Herraiz, 2003). The Spanish Landscape Typology comprised three levels: 1) landscapes, 2) landscape types and 3) landscape associates. Fig. 3.7 shows the Spanish landscape types (top left), which were based on Spanish expert interpretations. More detailed information about this classification can also be found in Wascher et al. (2005). Fig. 3.7 shows that there are clear resemblances in the general patterns between LANMAP and the Spanish Landscape Typology, but in greater detail there are significant differences. Fig. 3.7 also shows a MODIS satellite image of the region, taken on the 20th of April 2002, with the LANMAP landscape units superimposed. It shows clear resemblances in the surface reflectance and LANMAP landscape units. Both are strongly related to the land cover.

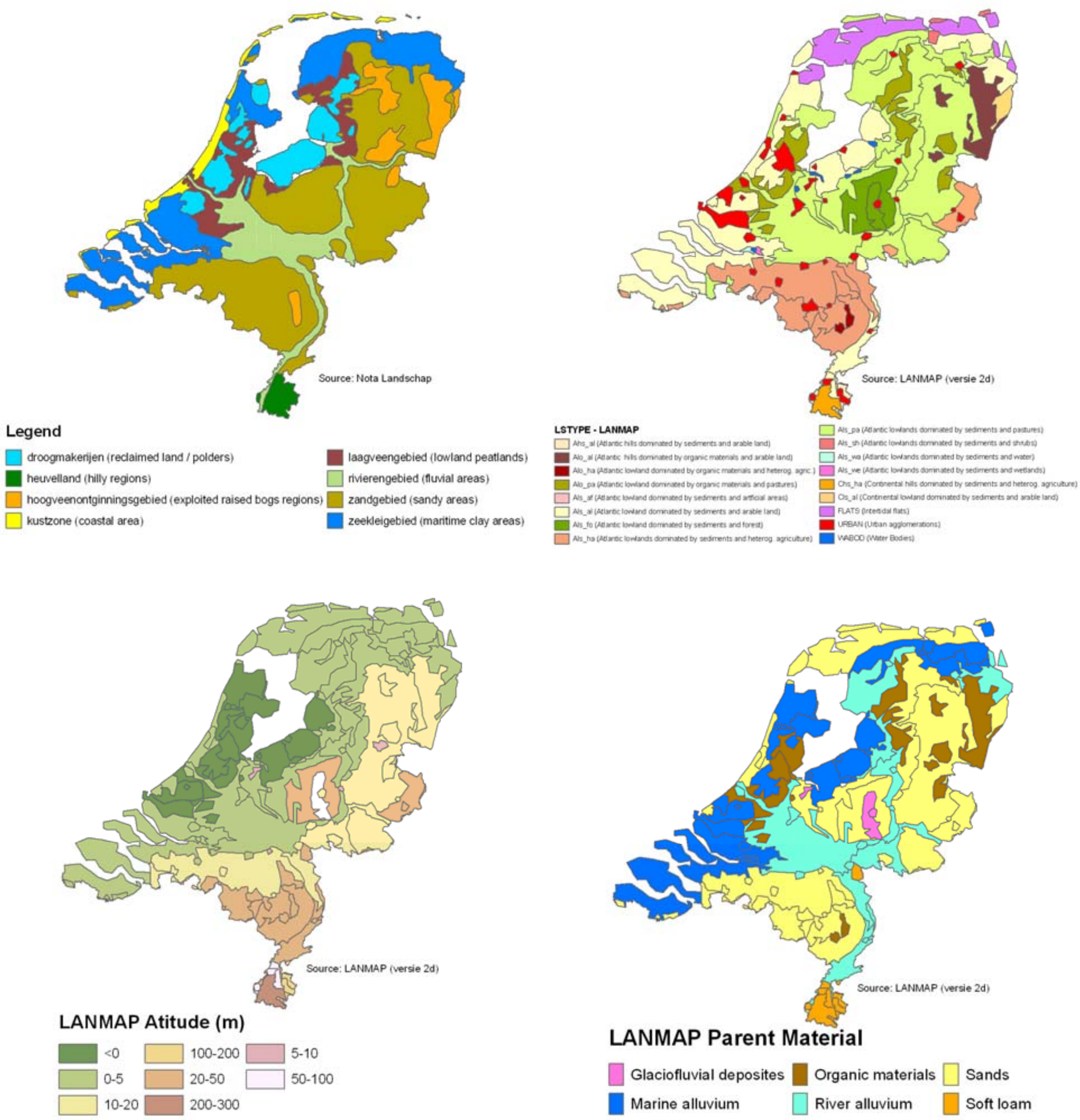

Fig. 3.6 Comparison of LANMAP (top right) with the Dutch National Landscape Classification (Nota Landschap) on the top left. Below LANMAP is shown with the diagnostic criterion altitude (below left) and parent material (below right). These diagnostic factors, next to land cover, determined the landscape units but were generalized in the landscape typology.

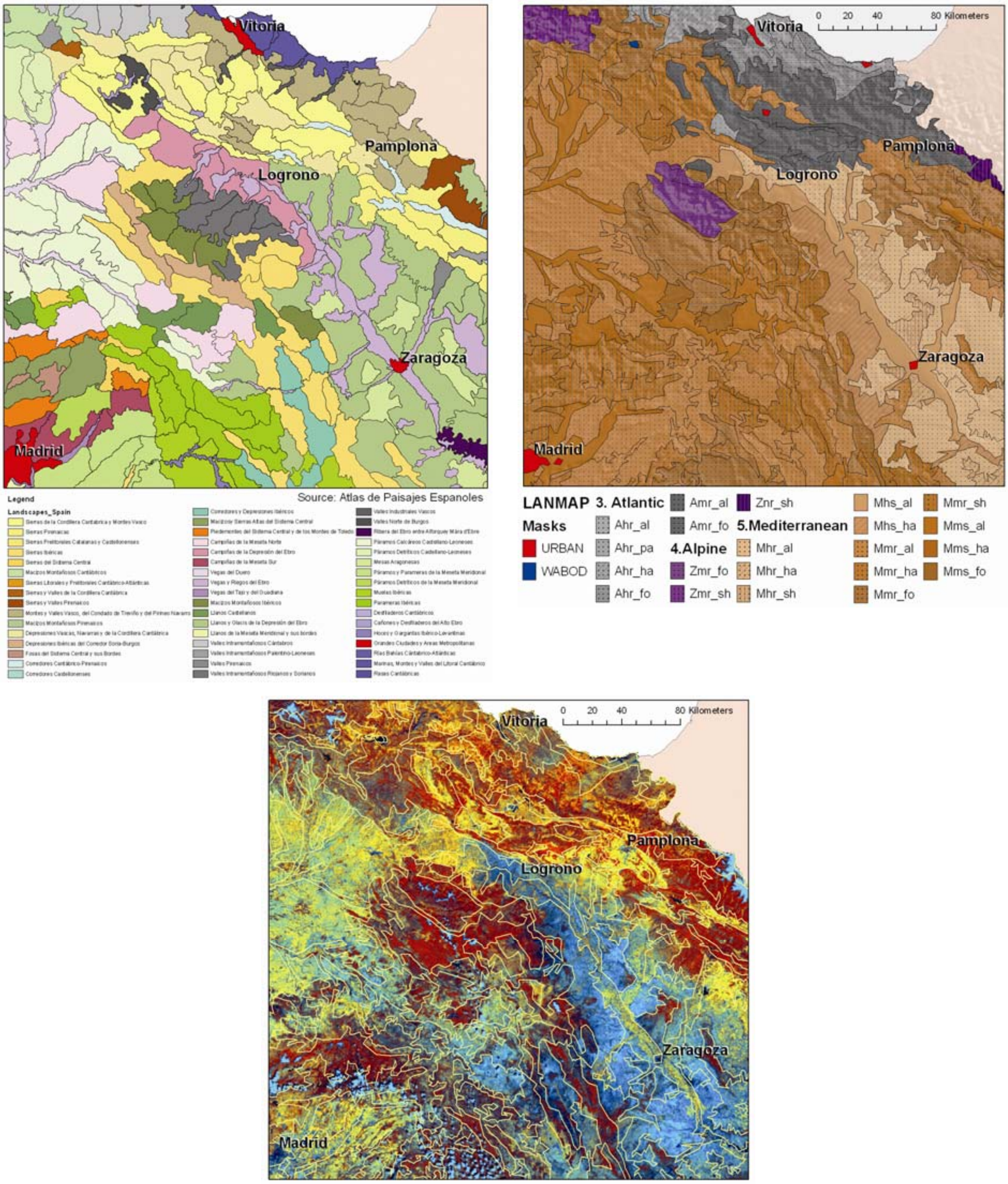

Fig. 3.7 Comparison of LANMAP (top right) with the Spanish National Landscape Classification from the Atlas de Paisajes Españoles (top left) and a MODIS satellite image of 20 April 2002 overlaid with LANMAP.

A more thorough comparison between LANMAP and ten other national landscape typologies was made in the European Landscape Character Assessment Initiative (ELCAI project, Wascher, 2005). Within this project, Groom (2005) presented the state-of-the-art of national and regional landscape classifications with their typologies, spatial properties, criteria used, and methods. Kindler (2005) presented the geo-spatial cross-analysis of LANMAP with ten of these national landscape classifications. Table 3.3 summarizes the cross-analysis of Kindler (2005) in an adjusted format. A general assumption was that LANMAP would present a stronger generalisation and simplification than the national classifications. Nevertheless, this was not the case for Switzerland, Germany, the Netherlands, Spain and Norway (Kindler, 2005).

Table 3.3 Table 3 Comparison between LANMAP and the national landscape classifications. Adjusted from (Kindler, 2005).

Code	Title	National Classifications					European Classification (LANMAP)				
		Min. Area [km^2]	Max. Area [km^2]	Mean Area [km^2]	Nr. of polygons	Nr. of landscape types	Min. Area [km^2]	Max. Area [km^2]	Mean Area [km^2]	Nr. of polygons	Nr. of landscape types
AT2 (Austria)	SINUS – cultural landscapes	0,002	1239,3	4,2	20128	42	11, 0	6893,7	308,7	272[1]	35
BE7 (Belgium)	Landscape Characters of Belgium	0,999	1578,1	4,3	7320	48	11, 0	4154,5	176,3	174[1]	20
CH4 (Switzerland)	Landscape quality of mobilité spatiale regions	0,018	1470,6	276,8	147	6	11, 0	11432,0	122,8	336[1]	32
DE7 (Germany)	Landscape types of Germany	0,006	3861,7	332,2	1094	24	11, 0	10066,0	212,6	1681[1]	67
ES1 (Spain)	Atlas of Spanish Landscapes	0,001	3499,8	265,3	1879	94	11, 0	10395,0	242,7	2053[2]	65
GB1 (England)	Countryside Character	0,392	2493,1	71,4	1831	75	11, 0	7402	102	1274[2]	23
HU2 (Hungary)	Landscape types of Hungary	0,025	2311,7	97,8	951	48	11, 0	8580,7	360,8	258[2]	25
NL2 (Netherlands)	Landscape types of the Netherlands	0,157	4645,4	336,8	112	9	11, 0	3416,7	53,5	658[2]	19
NO1 (Norway)	The Norwegian landscape reference system	0,020	13554,8	292,1	1100	45	11, 0	16430,2	39,5	8264[2]	67
PT1 (Portugal)	Landscape characterisation in Portugal	0,004	3413,4	386,5	230	128	11, 0	8662,8	186,7	476[2]	34

Results varied greatly, and a major conclusion was that the national landscape typologies differ so much in spatial and thematic scale, methods and techniques used that it was difficult to make meaningful comparisons (Kindler, 2005). LANMAP is intended to complement the national classifications and overcome the lack of coherence that exists, especially in trans-frontier landscapes. The ELCAI questionnaire on LANMAP concluded that LANMAP gives a consistent view across Europe and provides a common language and classification system, but cannot replace any of the national landscape classifications. Furthermore, there was a clear case for integrating further components into the LANMAP classification; e.g., slope, climate variables, information about landscape history, visual, cultural and aesthetic components (Kindler, 2005).

3.4 Discussions and Conclusions

It is widely recognized that, as shown in the introduction, there has been an urgent need for a common and geo-referenced classification system of landscapes for Europe. Within the ELCAI project (Wascher, 2005) it was shown that many countries have developed their own landscape typology or classification, and even within countries there exist various different landscape classifications, e.g., in Belgium and The Netherlands. However, these landscape typologies and classifications differ widely in their methodological approach, the data sources used, the scale of application and nomenclatures (Groom, 2005). For that reason the national and regional classifications are difficult to compare, emphasizing the need for a common classification system of European landscapes. LANMAP fulfilled these needs but the ELCAI project also showed that the validation of LANMAP was hampered by the amalgam of national and regional landscape classifications (Kindler, 2005). As the Spanish landscape classification (Mata Olmo and Sanz Herriaz, 2003) used a more similar approach as LANMAP, the landscape patterns are more in general agreement in comparison with the English landscape character map (Groom, 2005) which uses a different approach where every region is considered to be unique. Some stakeholders are therefore more satisfied with the results of LANMAP than others, as shown by the ELCAI enquiry (Kindler, 2005).

Ten years after the landscape typology of Meeus (1995), used in the report ‘Europe’s Environment: the Dobríš assessment’ (Stanners and Bourdeau, 1995) the development of LANMAP was initiated (Mücher et al. 2006), as described in the present paper. So far, LANMAP is limited to a biophysical factors, since there is a lack of consistent data on cultural-historical aspects.

Integration of LANMAP with socio-economic data has been implemented within the EU project SENSOR resulting in a new Spatial Regional Reference Framework (SRRF) with 27 broad cluster regions for environmental impact assessment (Renetzeder et al., 2008). However, LANMAP is a major breakthrough because a consistent framework is used to integrate the various thematic data sources described above. The ELCAI project (Wascher, 2005) showed that LANMAP gives a consistent view across Europe and provides a common language and classification system. However, LANMAP still lacks much information at the regional level about cultural-historical and socio-economic aspects that are indispensible for many regional applications. There is also a tendency for stakeholders to overemphasize the uniqueness of each individual site, which hinders the identification of features that are in common. In contrast, LANMAP may underestimate regional identity and might therewith infer a pitfall. In that sense there is tension between “lumpers” and “splitters”, but underestimation of local identity is also due to lack of consistent regional information on socio-cultural aspects. LANMAP cannot replace any of the national landscape classifications but does provide a European framework for the widely different national classifications. LANMAP has already led to the re-evaluation of some national approaches. Similar approaches have been used now to construct two newly established national landscape classifications: the landscape characterisation of Belgium (Van Eetvelde and Antrop, 2007; Van Eetvelde and Antrop, 2009) and the landscape classification of Italy (Blasi et al., 2007)

Although LANMAP has its limitations, it can be used in a wide range of applications, ranging from indicator reporting to frameworks for environmental monitoring. It can be used as the ecological entity (holistic approach) to integrate various disciplines and to identify spatial-functional relationships in biophysical and socio-economic domains at European scales. In the development of a stratification for European sampling, the first hierarchical level of LANMAP has been used to divide Europe into relatively homogeneous zones (Jongman et al., 2006). But depending on the number of samples that can be acquired lower levels of the LANMAP hierarchy can be used for stratification. LANMAP and its associated methodology can now be downloaded from the following website: (http://www.alterra.wur.nl/UK/research/Specialisation+Geo-Information/Projects/lanmap2) and has therefore increasingly been used for educational purposes. The database has also been requested and downloaded from 20 European countries, including Turkey and Russia. In the research domain, different requests have been in addition to those described above, for example in studies related of visualisation, soils, habitats, spatial economics, epidemiology, leisure and bio-fuels. Within the EU FP6-IP project

ECOCHANGE LANMAP has been used not only to study the relationships between land cover changes and landscapes with their associated habitats (Mücher et al, 2008) but also to study trends in phenology over the period 1981-2003 within European landscapes (De Wit and Mücher, 2009). In several desktop studies LANMAP has been used in the initial phase of a Landscape Character Assessment, in order to facilitate the analyses of the structure and pattern of landscapes. For example, it has been applied in a comparative study of the trans-frontier National Parks of Arribes del Duero (Salamanca, Spain) and Douro Internacional (Portugal). The landscape types of LANMAP were used to examine the landscape composition, which allowed the stratification of the territory into landscape types and consequent selection of homogeneous sampling units (Mücher et al., 2005). LANMAP is also being used to provide a framework for biodiversity in the province of Noord-Brabant in the Netherlands, where an e-conference http://www.biodiversitybrabant.nl/) has been set up in order to develop an effective policy and pragmatic programme for conservation. More recently, LANMAP has been used within the LUCAS project of Eurostat to identify specific landscapes for their changes in land use, and in a new project of the Dutch Ministry of Agriculture, Nature and Food Quality to establish a European Leisure Map. Currently, LANMAP is being used in the EURURALIS project (www.eururalis.eu) to analyse the impact of future land use changes on European landscapes.

LANMAP also requires improvements and we investigated already within the framework of the EU FP6-IP project SENSOR the use of high-resolution satellite imagery to derive the landscape structure by segmentation procedures (Mucher et al, 2007). If successful and resources are available, information on landscape pattern can be added as an attribute though various landscape metrics to the LANMAP database. Moreover, improvements are also needed in terms of spatial identification of certain landscape types e.g., coastal dunes. Descriptions are also needed of the LANMAP landscape types. All these factors are considered to be of significance in the identification of commonly recognisable landscape types. It is also important that national concepts should be ‘nested’ within a hierarchy of scales that build upon each other. Regional, national, and European units should therefore be part of the same methodological system and LANMAP is designed to provide such a framework at the highest level.

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References

Aalen, F.H., 2001. Landscape development and change. In: Green, B.H., Vos, W. (Eds.), 2001, Threatened landscapes: conserving cultural environments. Span Press, London: p.3-20.

Antrop, M., 2005. Why landscapes of the past are important for the future. Landscape Urban Plan. 70 (1-2), 21-34.

Bartholomé, E., Belward, A.S., 2005. GLC2000: A new approach to global land cover mapping from earth observation data. Int. J. Remote Sens. 26 (9), 1959-1977.

Blasi, C., Guida, D., Siervo, V., Paolanti, M., Michetti, L., Capotorti, G., Smiraglia, D., 2007. Defining and mapping the landscapes of Italy. Proceedings of the 7th IALE World Congress – Part I, July 2007, Wageningen, the Netherlands, p. 572-573.

Bunce, R.G.H., Barr, C.J., Clarke, R.T., Howard, D.C., Lane, A.M.J., 1996. Land classification for strategic ecological survey. J. Environ. Manage. 47:37–60.

Burnett, C., Blaschke, T., 2003. A multi-scale segmentation/object relationship modelling methodology for landscape analysis. Ecol. Model. 168 (3), 233-249.

CEC, 1985. Soil map of the European Communities 1:100.0000 (Tavernier cs). Commission of the European Communities, Luxembourg. 124 pp.

CEC, 1994. CORINE land cover. Technical guide. Office for Official Publications of European Communities, Luxembourg.

Council of Europe, UNEP, ECNC, 1996. The Pan-European Biological and Landscape Diversity Strategy: a vision for Europe's natural heritage. Strasbourg, Council of Europe Publishing.

Council of Europe, 2000. European Landscape Convention. Florence, 20 October 2000. European Treaty Series – No. 176, 9 pp.

Definiens Imaging, 2005. eCognition version 5 Object Oriented Image Analysis User Guide. Definiens Imaging GmbH, Munich.

Déjeant-Pons, M., 2006. The European landscape convention. Landscape Res. 31 (4), 363-384.

Delbaere, B.C.W, 1998. Facts and figures on Europe's biodiversity; state and trends. ECNC, Tilburg, 115 pp.

De Wit, A., Mücher, C.A., 2009. Satellite-derived trends in phenology over Europe: real trends or algorithmic effects. Geophysical Research Abstracts, Vol. 11, EGU2009-4837, 2009. EGU General Assembly 2009 from 19 – 24 April 2009, Vienna, Austria.

Embleton, C., 1984. Geomorphology of Europe. Published by The Macmillan Press Ltd, London. ISBN 0-333-37963-2, 465 pp.

FAO, 1991. The Digitized Soil Map of the World (Release 1.0), Rep. No. 67/1. Food and Agriculture Organization of the United Nations, Rome.

Green, B.H., Vos, W. (Eds.), 2001. Threatened landscapes: conserving cultural environments. Spon Press, London: 168 pp.

Groom, G., 2005. Methodological review of existing classifications, in: Wascher, D.M. (Ed.), European Landscape Character Areas – Typology, Cartography and Indicators for the Assessment of Sustainable Landscapes. Final ELCAI project report, Landscape Europe, pp. 32-45.

Jenny, H., 1941. Factors of soil formation: a system of quantitative pedology. McGraw-Hill publications in the agricultural sciences, McGraw-Hill, New York. Description , 281 pp.

Jongman, R.H.G., Bunce, R.G.H., 2000. Landscape classification, scales ad biodiversity in Europe, in Mander, Ü., Jongman, R.H.G. (Eds.), Consequences of Land use change in Europe pp. 11-38.

Jongman, R.H.G., Bunce, R.G.H., Metzger, M.J., Mücher, C.A., Howard, D.C., Mateus, V. L., 2006. Objectives and applications of a statistical environmental stratification of Europe. Landsc. Ecol. 21 (3 SPEC. ISS.), 409-419.

Kindler, A., 2005. Geo-spatial Cross-Analysis of LANMAP and National Approaches, in: Wascher, D.M. (Ed.), European Landscape Character Areas – Typology, Cartography and Indicators for the Assessment of Sustainable Landscapes. Final ELCAI project report, Landscape Europe, pp. 46-87.

Klijn, J.A., 1995. Hierarchical concepts in landscape ecology and its underlying disciplines; the unbearable lightness of a theory? Wageningen, SC-DLO, 1995. Report 100, 144 pp.

Klijn, J.A., 2000. Developments in European landscape assessment. In: D.M. Wascher (Ed.), Landscapes and suitability; proceedings of the Eruopean workshop on landscape assessment as a policy tool, 25th-26th March '99, Strasbourg, France. Tilburg, ECNC, 2000, pp. 58-61,

Klijn, J.A., Vos, W., 2000. From landscape ecology to landscape science: proceedings of the European congres "Landscape ecology: things to do - proactive thoughts for the 21st century", organised in 1997 by the Dutch Association for Landscape Ecology (WLO) on the occasion of its 25th anniversary. Kluwer Dordrecht, ISBN 0792369211, 163 pp.

Klijn, J.A., 2004. Driving forces behind landscape transformation in Europe, from a conceptual approach to policy options, in: Jongman. R.H.G. (Ed.), The new dimensions of the European landscape. Wageningen UR Frontis series: 4, Dordrecht, Springer, pp. 201-218.

Lucas, R., Rowlands, A., Brown, A., Keyworth, S., Bunting, P., 2007. Rule-based classification of multi-temporal satellite imagery for habitat and agricultural land cover mapping. ISPRS J. Photogramm. 62 (3), 165-185.

Mata Olmo, R., Sanz Herraiz, C. (Eds.), 2003. Atlas de los Paisajes de España. Ministério de Médio Ambiente de España, Madrid. 683 pp.

Meeus, J.H.A., Wijermans, M.P., Vroom, M.J., 1990. Agricultural landscapes in Europe and their transformation. Landscape Urban Plan. 18 (3-4), 289-352.

Meeus, J.H.A., 1995. Pan-European landscapes. Landscape Urban Plan. 31 (1-3), 57-79.

Metzger, M.J., Bunce, R.G.H., Jongman, R.H.G., Mücher, C.A., Watkins, J.W., 2005. A climatic stratification of the environment of Europe. Global Ecol. Biogeogr. 14 (6), 549-563.

Milanova, E.V., Kushlin, A.V. (Eds.), 1993. World map of present day landscapes. An explanatory note. Department of World Physical Geography and Geoecology, Moscow State University, in collaboration with UNEP, 25 pp plus annexes.

Ministerie van Landbouw, Natuurbeheer en Visserij, 1992. Nota Landschap: Regeringsbeslissing visie landschap. Min. van LNV, Den Haag, the Netherlands, 21 p.

Mücher, C.A., 1992. A discussion on land use classifications. An amalgam of methods. Internal report, Department of Tropical Crop Science, Wageningen Agricultural University, The Netherlands.

Mücher, C.A., Steinnocher, K.T., Kressler, F.P., Heunks, C., 2000. Land cover characterization and change detection for environmental monitoring of Pan-Europe. Int. J. Remote Sens. 21 (2000), 6/7: 1159-1181.

Mücher, C.A., Champeaux, J.L., Steinnocher, K.T., Griguolo, S., Wester, K., Heunks, C., Winiwater, W., Kressler, F.P., Goutorbe, J.P., ten Brink, B., van Katwijk, V.F., Furberg, O., Perdigao, V., Nieuwenhuis, G.J.A.,2001. Development of a consistent methodology to derive land cover information on a European scale from remote sensing for environmental monitoring; the PELCOM report. Alterra-rapport 178 / CGI-report 6, Alterra, Wageningen, the Netherlands, 178 pp.

Mücher, C.A., Bunce, R.G.H., Jongman, R.H.G, Klijn, J.A., Koomen, A.J.M., Metzger, M.J., Wascher, D.M., 2003. Identification and Characterisation of Environments and Landscapes in Europe. Alterra rapport 832, Alterra, Wageningen, 119 pp.

Mücher, C.A., Garcia-Feced, C., Perez-Soba, M. , Wascher, D.M., 2005. Landscapes of Europe, in: Perez-Soba, M, Wascher, D. M. (Eds.), Landscape Character Areas – Places for building sustainable Europe. Policy Brochure as deliverable from EU's Accompanying measure project European Landscape Character Assessment Initiative (ELCAI), funded under the 5th Framework Programme on Energy, Environment and Sustainable Development. Printed by Information Press, Oxford, United Kingdom, pp. 6-8.

Mücher, C.A., Wascher, D.M, Klijn, J.A. Koomen A.J.M., Jongman, R.H.G., 2006. A new European Landscape Map as an integrative framework for landscape character assessment, in Bunce, R.G.H, Jongman, R.H.G. (Eds.), Landscape Ecology in the Mediterranean: inside and outside approaches. Proceedings of the European IALE Conference 29 March – 2 April 2005 Faro, Portugal. IALE Publication Series 3, pp. 233-243.

Mücher, C.A , Vos, C.C., Renetzeder, C., Wrbka, T., Kiers, M., van Eupen, M., Bugter, R., 2007. The application of satellite imagery to identify landscape structure. In: Proceedings of the IALE 2007 World Congress July 8th – 12th , Wageningen, the Netherlands, pp. 590 – 591.

Mücher, C.A., Hazeu. G., Swetnam, R. Pino J., Halada L., and Gerard F., 2008. Historic land cover changes at Natura 2000 sites and their associated landscapes across Europe. In: Proceedings 28th EARSeL Symposium: Remote Sensing for a Changing Europe, Istanbul, Turkey on 2-7 June 2008. p. 146.

Nuñes de Lima, M.V. (Ed.), 2005. IMAGE2000 and CLC2000 : products and methods. European Commission, Joint Research Centre, Ispra, Italy. Published by the European Communities, EUR 21757 EN, ISBN-92-894-9862-5, Italy, 150p.

Renetzeder, C., van Eupen, M., Mücher, C.A., Wrbka, T., 2008. A Spatial Regional Reference Framework for Sustainability Assessment in Europe, in: Helming, K., Perez-Soba, M., Tabbush, P. (Eds.), Sustainability Impact Assessment of Land Use Changes. Springer, Berlin Heidelberg New York, ISBN 978-3-540-78647-4, pp 249- 268.

Roekaerts, M., 2002. The biogeographical regions map of Europe. Basic principles of its creation and overview of its development. European Environment Agency, Copenhagen.

Rasmussen, P., 2005. Mid- to late-Holocene land sue change and lake development at Dallund, Denmark: vegetation and land-use history inferred from pollen data. The Holocene, 15 (8), 1116-1129.

Stanners, D., Bordeaux, P. (Eds.), 1995. Europe’s Environment; The Dobříš Assessment. European Environmental Agency, Copenhagen. 676 pp. Office for Official Publications of the European Communities, Luxembourg.

Stomph, T.J.; Mücher, C.A., Fresco, L.O., 1997. Environmental Impact of Land Use: A New Basis for Analysis. The Land, 1997, 1.2, 129-142.

Van der Heijden, R.B.J., 2007. Characterization of European Landscapes and analysis of their dynamics. Internal CGI Report, Alterra, Wageningen, the Netherlands, pp 1370.

Van Eetvelde, V., Antrop, M., 2007. Landscape characterisation in Belgium: integration of different scale levels and analysing temporal differences. Proceedings of the 7th IALE World Congress – Part I, July 2007, Wageningen, the Netherlands, pp. 580-581.

Van Eetvelde, V., Antrop, M., 2009. A stepwise multi-scaled landscape typology and characterisation for trans-regional integration, applied on the federal state of Belgium. Landscape Urban Plan., In Press.

Vervloet, J. A. J., Spek, T., 2003. Towards a Pan-European landscape map - a mid-term review. European landscapes: from mountain to sea, Tallinn (Estonia), Huma, 9-19.

Vos, W., Stortelder, A.H.F., 1992. Vanishing Tuscan landscapes: landscape ecology of a Submediterranean-Montane area (Solano Basin, Tuscany, Italy). Pudoc Scientific Publishers, ISBN 9022009645, Wageningen, the Netherlands. 403 p. + 1 map.

Wascher, D.M.(Ed.), 1998. Landscapes and Sustainability. Proceedings of the European Workshop on landscape assessment as policy tool; 25th-26th March 1999 Strasbourg, organised by the European Centre for Nature Conservation and the Countryside Agency of England, United Kingdom, Tilburg, 94 pp.

Wascher, D.M. (Ed.), 1999. Landscapes and sustainability. Proceedings of the European Workshop on landscape assessment as a policy tool. ECNC/Countryside Agency, Strassbourg.

Wascher, D.M. (Ed.), 2000. “The Face of Europe – Policy Perspectives for European Landscapes”. Report on the implementation of the PEBLDS Action Theme 4 on European Landscapes, published under the auspices of the Council of Europe. ECNC, Tilburg, 60 pages.

Wascher, D.M. (Ed.), 2005. European Landscape Character Areas – Typologies, Cartography and Indicators for the Assessment of Sustainable Landscapes. Final ELCAI project report, Landscape Europe,160 pp.

Wascher, D. M., Groom, G., Mücher, C.A., Kindler, A., 2005. Recent developments in mapping Europe’s landscapes, in: Wascher, D.M. (Ed.), European Landscape Character Areas – Typologies, Cartography and Indicators for the Assessment of Sustainable Landscapes. Final ELCAI project report, Landscape Europe, pp. 5-3.

Annex 3.1 Diagnostic criteria used for the identification of the landscape units and descriptors for the typology

FIRST LEVEL	**1. CLIMATE**				
	DIAGNOSTIC CRITERIA	GENERALISA-TION			TYPOLOGY
Clim_nr	**Climate**		**Nr**	**Symbol**	**Name**
1	Alpine North	Alpine	1	**K**	Arctic
2	Boreal	Boreal	2	**B**	Boreal
3	Nemoral	Boreal	3	**A**	Atlantic
4	Atlantic North	Atlantic	4	**Z**	Alpine
5	Alpine South	Alpine	5	**M**	Mediterranean
6	Continental	Continental	6	**C**	Continental
7	Atlantic Central	Atalantic	7	**T**	Anatolian
8	Pannonian	Continental	8	**S**	Steppic
9	Lusitanian	Atlantic			
10	Anatolian	Anatolian			
11	Mediterranean Mountains	Mediterranean			
12	Mediterranean North	Mediterranean			
13	Mediterranean South	Mediterranean			
14	Arctic	Arctic			
15	Steppic	Steppic			

SECOND LEVEL	**2. ALTITUDE**				
	DIAGNOSTIC CRITERIA	GENERALISA-TION			TYPOLOGY
Dem_nr	**Altitude (meters)**		**Nr**	**Symbol**	**Name**
1	<0	Lowland	1	**l**	Lowland
2	0-5	Lowland	2	**h**	Hills
3	5-10	Lowland	3	**m**	Mountains
4	10-20	Lowland	4	**n**	High mountains
5	20-50	Lowland	5	**a**	Alpine
6	50-100	Lowland			
7	100-200	Hills			
8	200-300	Hills			
9	300-500	Hills			
10	500-700	Mountains			
11	700-900	Mountains			
12	900-1100	Mountains			
13	1100-1500	Mountains			
14	1500-2000	High mountains			
15	2000-2500	High mountains			
16	2500-3000	Alpine			
17	3000-5000	Alpine			

THIRD LEVEL	**3. PARENT MATERIAL** DIAGNOSTIC CRITERIA	GENERALISA-TION			TYPOLOGY
Pm_nr	**Parent material**	**T_PM**	**Nr**	**Symbol**	**Name**
1	River alluvium	Sediments	1	**r**	Rocks
2	Marine alluvium	Sediments	2	**s**	Sediments
3	Glaciofluvial deposites	Sediments	3	**o**	Organic materials
4	Calcereous rocks	Rocks			
5	Soft clayey materials	Sediments			
6	Hard clayey materials	Rocks			
7	Sands	Sediments			
8	Sandstone	Rocks			
9	Soft loam	Sediments			
10	Siltstone	Rocks			
11	Detrital formations	Rocks			
12	Crystalline rocks and migmatites	Rocks			
13	Volcanic rocks	Rocks			
14	Other rocks	Rocks			
15	Organic materials	Organic			
16	Unclassified (urban/water/ice)	-			

FOURTH LEVEL	**4. LAND COVER / LAND USE** DIAGNOSTIC CRITERIA	GENERALISA-TION			TYPOLOGY
Lc_nr	**Land cover**	**T_LC**	**Nr**	**Symbol**	**Name**
1	Artificial surfaces	Artificial surfaces	1	**af**	Artificial surfaces
2	Arable land	Arable land	2	**al**	Arable land
3	Permanent crops	Permanent crops	3	**pc**	Permanent crops
4	Pastures	Pastures	4	**pa**	Pastures
5	Heterogeneous agric. areas	Heterogeneous agric. Areas	5	**ha**	Heterogeneous agric. Areas
6	Forest	Forest	6	**fo**	Forest
7	Shrubs & herbaceous vegetation	Shrubs & herbaceous vegetation	7	**sh**	Shrubs & herbaceous vegetation
8	Open spaces with little or no ve	Open spaces with little or no ve	8	**op**	Open spaces with little or no ve
9	Wetlands	Wetlands	9	**we**	Wetlands
10	Waterbodies	Waterbodies	10	**wa**	Waterbodies

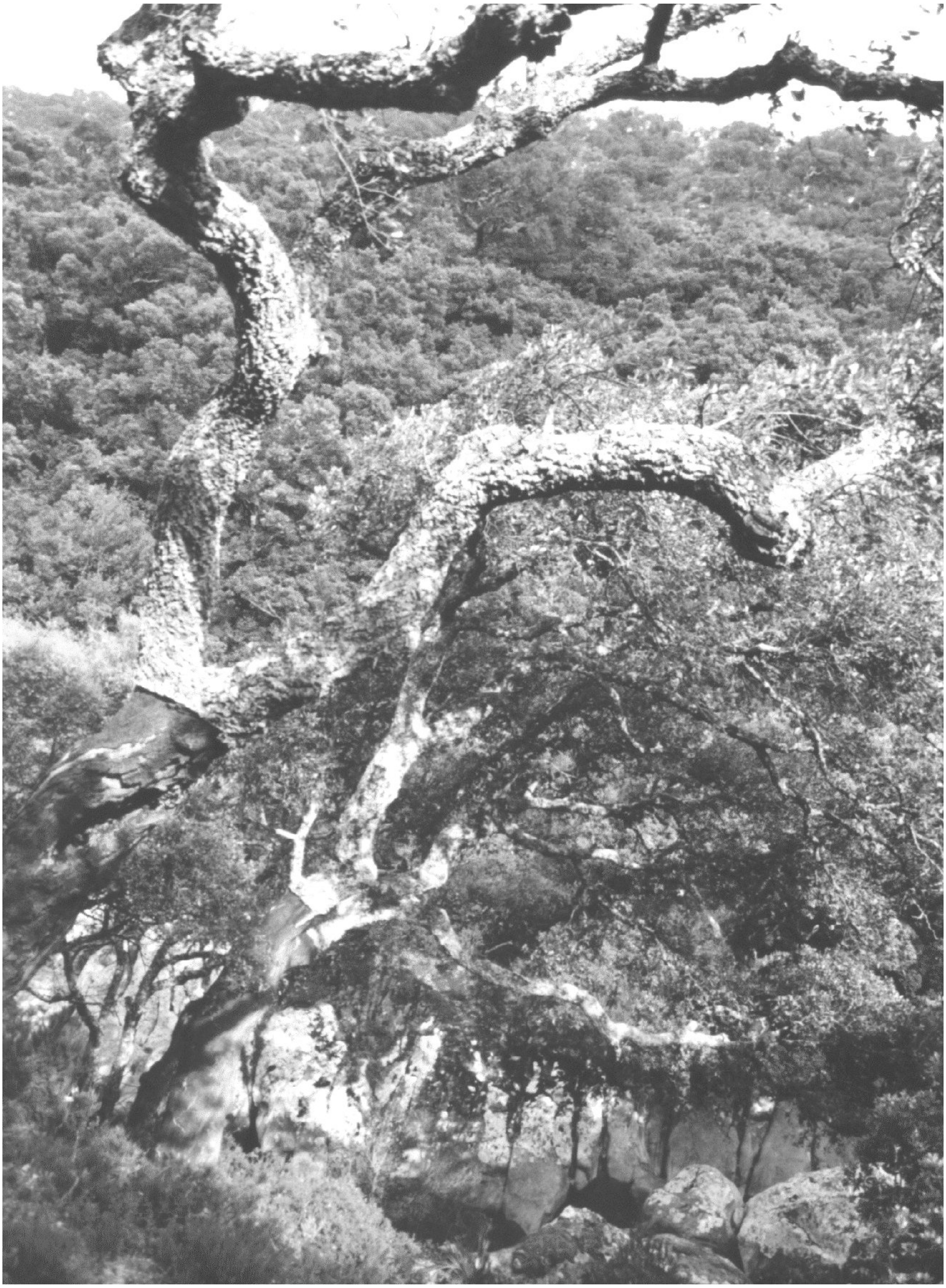

Photo: Quercus suber forest in Los Alcornocales Natural Park in Spain (Photo M. Romero).

CHAPTER 4

Modelling the spatial distribution of Natura 2000 habitats across Europe

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Modelling the spatial distribution of Natura 2000 habitats across Europe

Abstract

The development of a Pan-European Ecological Network is now widely recognised as an important policy initiative in support of protected Natura 2000 sites. The site selection is based on habitats as defined in the Annex I of the Habitats Directive. Whilst there is information about the presence of these habitats in Natura 2000 sites, there is no detail of their distribution elsewhere in Europe. The present paper describes a methodology that identifies the spatial distribution of habitats across Europe so that their actual extent can be determined. Five methodological steps are involved starting with selection of appropriate spatial data sets, defining knowledge rules from the descriptions of Annex I habitats, continuing with additional ecological expert knowledge when needed, implementation of the models, and finally the validation. Spatial distribution models were derived for 27 habitats representing the most significant ecosystems. This spatial modelling approach is illustrated with one detailed example. Validation showed that mapping accuracy depends on the habitat description available but also upon its spatial character. Thus widespread habitats such as forests were accurately assessed whereas dispersed classes such as freshwater systems were more difficult to assess. Possible methodological improvements are suggested, such as inclusion of vegetation relevés to improve the knowledge rules. Extension of the methodology to other habitats would require a moderate effort since data collection and processing has now been completed and it is this which is the most time consuming part of the process. We conclude that our method maps widespread European habitats with unprecedented accuracy.

Keywords: spatial modelling; knowledge rules; land cover; disaggregation; environmental data sets; remote sensing

4.1 Introduction

Human population has expanded rapidly, especially in the last two centuries, with associated expansion in industrialisation and urbanisation (Stanners and Bordeaux, 1995; Moran et al., 2004; EEA, 2005). Modern management techniques in agriculture and forestry have also caused dramatic declines in the quality and extent of habitats (Hansen et al., 2004; Reidsma et al., 2006; Reger et al., 2007). Habitat degradation and loss, resulting from changes in land use remain significant drivers of biodiversity loss (Hansen et al., 2004). These trends are widely recognised and have forced national and international agencies to identify protected sites for natural areas with high biodiversity value (Convention of Bern, 1979). The Habitats (Directive 92/43/CEE) and Birds Directive (Directive 79/409/CEE) are two of the most important European Union (EU) policy initiatives to conserve biodiversity across Europe. Provision of quantitative figures on fragmentation and extent of habitats and biodiversity is fundamental for general policy formulation for the maintenance and enhancement of biodiversity across Europe (Young et al., 2004; Ewers and Didham 2005; Weiers et al., 2004; Keramitsogloua et al., 2005). The Habitats Directive on the conservation of natural habitats and of wild fauna and flora (Commission of the European Communities, 2003) requires member states of the European Union to establish a network of Special Areas for Conservation (SAC) to protect species and habitats considered to be of 'Community Interest' and listed in the Annexes of the Directive (Evans, 2006). For the protection of primary nature conservation areas, the development of the series of Natura 2000 sites based on the above mentioned Directives is the major initiative (EU Council Directive, 1992; Ostermann, 1998). However at the same time, these sites do not guarantee the maintenance of biodiversity in the wider countryside because inevitably many habitats and species are outside protected areas (Brandt et al., 2001; Hansen et al., 2004).

Therefore, there is a need to develop additional policy instruments for nature conservation outside protected areas, that are equally appropriate to those applied in the protected areas. An important policy instrument is the Pan-European Biological and Landscape Diversity Strategy (PEBLDS) which was approved by the 3rd Conference of Ministers "An Environment for Europe", in Sofia, on 25th of October 1995. The PEBLDS Strategy (Council of Europe, 1996) aims to ensure the conservation of habitats and species, maintain genetic diversity and preserve important European landscapes. The development of the Pan-European Ecological Network (PEEN) is the most significant tool in the implementation of PEBLDS. The PEEN concept (van Opstal, 1998, 1999; Jongman et al., 2004; Opdam et al., 2006, Jones-Walters,

2007) is designed to strengthen the ecological coherence of Europe as a whole with a common set of criteria consisting of core areas, corridors, buffer zones and nature development areas (see also http://countdown2010.net/archive/paneuropean.html). One of the major goals of PEEN is to develop an indicative map of the Pan-European Ecological Network for the whole of Europe (Council of Europe, 1999; van Opstal, 1999; Bouwma et al., 2002). The design of such an indicative map requires information about the spatial distribution of habitats and species in Europe, both inside and outside protected areas. Moreover, to determine the spatial cohesion of habitat networks for viable populations in the landscape (Opdam et al., 2003, 2006) it is also necessary to obtain information about the exact extent and spatial distributions of habitats. Information about the spatial distribution of species is being collected by many international organisations (e.g., Birdlife International). However, there are currently no pan-European habitat maps available. Such data are needed for the further development of a coherent ecological network (Mücher et al., 2004, 2005a). In response to this need, we present a methodology for the assessment and mapping of the distribution of habitats at pan-European scales.

4.1.1 Habitat classifications

Many concepts and definitions of habitats exist, reflected in the wide range of regional, national and European habitat classifications. The main European classifications are; CORINE Biotopes (CEC, 1991; Moss and Wyatt, 1994), the Palaearctic habitat classification (Devillers and Devillers – Terschuren, 1996), the Annex I of the Habitats Directive (European Commission, 2007), the EUNIS habitat classification (Davies and Moss, 2002), the Phytosociological alliances of the European Vegetation Survey (Rodwell et al., 1995, 2002), the Natural Vegetation of Europe (Bohn et al., 2003; Bohn and Gollub, 2006), and the recently established BioHab General Habitat Categories (Bunce et al., 2008). Although the EUNIS habitat classification and the Natura 2000 habitats were both based on experience from the CORINE biotopes project and Palaearctic habitat classification (Mücher et al., 2004), the classifications still differ in nomenclature, criteria and approach which makes it often difficult to link and compare them directly. Within European conservation agencies, two habitat classifications are now central, namely the EUNIS habitat classification and the Annex I of the Habitats Directive. The main reason for using the latter in the present project is that these form the legal framework for habitat protection in Europe through their link with the

Natura 2000 sites. Evans (2006) describes the way these habitats have been developed and their role in nature conservation policies. The expansion of the EU to the current 27 Member States has also led to progressive refining of the habitat definitions. The habitat definitions as given in Annex I of the Habitats Directive (European Commission, 2007) were therefore used as the basis for the present methodology. Annex I currently lists 231 Natura 2000 habitat types, of which 71 are priority habitats. These 231 types cover a range of marine and terrestrial habitats, both natural and semi-natural with both biotic and abiotic features (Evans, 2006). They have been used as the basis for the identification of the Natura 2000 sites which form the framework for nature conservation in Europe. Each habitat belongs to one of nine major categories: (1) coastal and halophytic habitats, (2) coastal sand dunes and inland dunes, (3) freshwater habitats, (4) temperate heath and scrub, (5) sclerophyllous scrub, (6) natural and semi-natural grassland formations, (7) raised bogs, mires and fens, (8) rocky habitats and caves, and (9) forests. They are described in the Interpretation Manual of European Union Habitats (European Commission, 2007), and in a more extended version at the EUNIS website (http://eunis.eea.europa.eu/habitats-books.jsp), by:

(i.) Natura 2000 code (a four digit code);

(ii.) Explicit name of the habitat;

(iii.) Definition (this is a general description in terms of vegetation, syntaxa, abiotic features and origin);

(iv.) Characteristic species (listing of animal and plant key species including details of their occurrence on Annexes II and IV);

(v.) Geographic distribution (descriptive);

(vi.) Correspondence with other classification systems; and

(vii.) Bibliographic references.

The Annex I habitat descriptions as described in the Interpretation Manual of European Habitats (European Commission, 2007) have been used in this study as the reference not only for pragmatic reasons but also for the reason that the Natura 2000 sites and associated habitats will form the backbone of any European ecological network. However, in principle, the proposed methodology could also be applied to other classifications such as the phytosociological alliances of Rodwell et al. (2002).

4.2 Materials and methods

The study area is Pan-Europe and covers an area of approximately 11 million square kilometres. Pan- Europe is defined here as the area ranging from Iceland in the north-western corner to Turkey in the south-eastern corner. The most eastern border is defined by the Ural mountains and the most western border by the Atlantic ocean. This is the area considered for the construction of a Pan-European Ecological Network.

4.2.1 Selection of data sources

The first step of this study was to identify appropriate available data sets, as summarized in Table 4.1. Their potential for integration to obtain a pan-European coverage is discussed below.

Ecoregions

The Environmental Stratification of Europe (EnS) by Metzger et al. (2005) is considered to be the most reliable biogeographic division of Europe since it is based on statistical clustering of the most comprehensive high-resolution climate data set (CRU_TS1.2), developed by the Climatic Research Unit (CRU) at the University of East Anglia (Mitchell and Jones, 2005). The EnS are divided hierarchically into 13 Environmental Zones (EnZ). Unfortunately, the Environmental Zones did not cover pan-Europe (Mücher et al., 2003, 2004; Metzger et al., 2005). This made it necessary to integrate the EnZ with the Biogeographical Regions Map of Europe (BRME). The BRME of the EEA (Roekaerts, 2002) is also the official map being used by the Habitats Directive, but is the product of committee discussions rather than a scientific output. Whereas the EnS was produced by statistical analysis of climate data. The integration of both databases was carried out by using the EnZ as the basis, but integrating the BRME according to the boundaries and classes of EnZ. The result is shown in Fig. 4.1 and contains 15 ecoregions. This is two classes more than the EnZ, namely the Arctic and Steppic zones.

Table 4.1 Summary of selected data sets used to assess the spatial distribution of European habitats.

Theme	Core data sets	Scale / spatial resolution	Extent	Number of hierarchical classes	Reference (Source)
Ecoregions	Biogeographical Regions Map of Europe (BRME)	1: 2,500,000	Pan-Europe	11	Roekaerts (2002) (EEA)
	The European Environmental Zones (EnZ)	1km	Europe	13 (level 1) 84 (level 2)	Metzger et al. (2005) (WUR)
Land cover	CORINE land cover	1:100,000	EU28+	5 (level 1) 15 (level 2) 44 (level 3)	CEC (1994) (EEA)
	GLC2000	1km	Global	23 (level 1)	Bartholomé & Belward (2005) (JRC)
	PELCOM	1km	Pan-Europe	16	Mücher et al. (2000)(Alterra)
Elevation	GTOPO30	30-arc seconds (~ 1 km)	Global	Continuous (altitude in meters)	USGS
Soil	European Soil Database (ESDB)	1:1,000,000	EU28		CEC (1985) (ESDB)
	FAO / Unesco Soil Database	1: 5,000	Global	26 (level 1) 106 (level 2)	FAO (1991)
Indicator species	Atlas Florae Europaeae (AFE)	50 km	Pan-Europe	3270 species	Jalas et al. (1972-1999)
	Database of the Map of the Natural Vegetation of Europe (PNV)	1: 2,500,000	Pan-Europe	19 (level 1) 60 (level 2) 699 (level 3)	Bohn et al. (2003) (BfN)

Land cover

The CORINE land cover database is considered by the authors to be the most detailed land cover database for the European Union. CORINE is a hierarchical land cover classification with 44 classes at level 3. It is based on the visual interpretation of high-resolution satellite images at a scale of 1:100.000 (CEC, 1994; Feranec et al. 2007). The minimum mapping unit is 25 ha which is still larger than most habitat patches. The CORINE land cover database covers only part of pan-Europe (see Fig. 4.2), but continues to expand its coverage up to present. Therefore, CORINE had to be integrated with other land cover data sources such as PELCOM and GLC2000. PELCOM is a pan-European land cover database based on the classification of NDVI monthly maximum value composites of NOAA-AVHRR satellite imagery for the year 1997 (Mücher et al., 2000; Champeaux et al., 2000). This database contains 16 thematic classes with a 1 km spatial resolution. The GLC2000 is a global land cover database with a 1 km spatial resolution based on regional classifications of SPOT-VEGETATION monthly mosaics and resulted in 23 thematic classes (Bartholomé and

Belward, 2005). GLC2000 is considered to be more accurate than PELCOM, since SPOT-VEGETATION satellite imagery are a technically a better product than NOAA-AVHRR data. Integration was carried out by selecting the best data source for each country, see Fig. 4.2. For several countries, such as Iceland, Norway, Moldava, Croatia, Serbia and Montenegro PELCOM was preferred above GLC2000 due to an underestimation of wetlands (Iceland, Norway and Balkan), urban areas and rivers (Moldava) and forests (Balkan region). Note that meanwhile CORINE land cover information has become available for some of these countries e.g., Croatia, Serbia and Montenegro. Fig. 4.2 shows that 41% of the pan-European land cover database has been derived from CORINE, 53% from GLC2000 and only 6% from PELCOM. Before the three land cover databases could be integrated it was necessary to revise the CORINE legend and to harmonise the legends according to the CORINE land cover typology (CEC, 1994; Feranec et al. 2007) based on expert knowledge and visual comparisons of the databases (Mücher et al., 2004). As an example transitional wood-land scrub (CORINE class 3.2.4) was recoded to sclerophyllous vegetation (class 3.2.3) in the Mediterranean region due to different interpretations of the same class (Mücher et al., 2004). After recoding all databases to the same nomenclature, they were resampled to a spatial resolution of 250 m. The newly established pan-European land cover database covers pan-Europe with an area of 11 million km^2.

Elevation

Elevation data plays a crucial role in many species, habitat and niche suitability modelling studies (Zimmermann and Kienast 1999; Luoto et al., 2001; Palo et al., 2005; Guisan and Thuiller, 2005; Gutiérrez et al., 2005; Acevedo et al., 2007; Lira-Noriega et al., 2007). However, most of these studies concentrate on smaller regions than the whole of Europe. For this reason the GTOPO30 was used in this study. GTOPO30 is a global Digital Elevation Model (DEM) resulting from a collaborative effort led by the U.S. Geological Survey's EROS Data Center in Sioux Falls, South Dakota (see also http://edc.usgs.gov/products/elevation/gtopo30/gtopo30.html). The elevations are given in meters and are regularly spaced at 30-arc seconds (approximately 1 km). GTOPO30 was developed to meet the needs of the geospatial data user community for regional and continental scale topographic data.

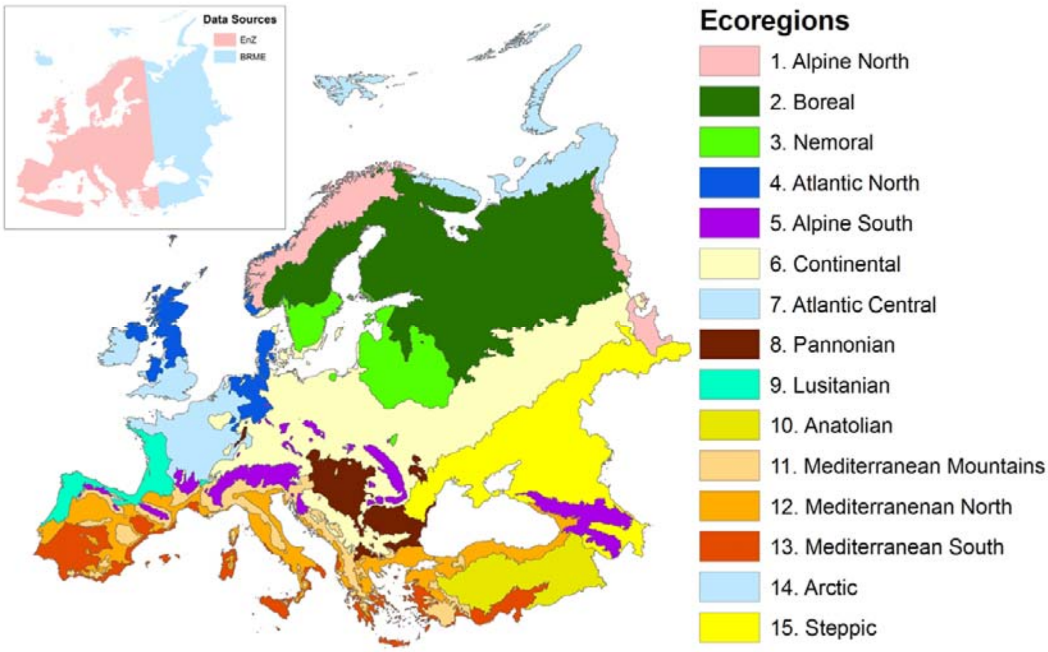

Fig. 4.1 Ecoregions of Europe based on the integration of the Environmental Zones (source: Wageningen UR) and the Biogeographical Regions Map of Europe (source: EEA)

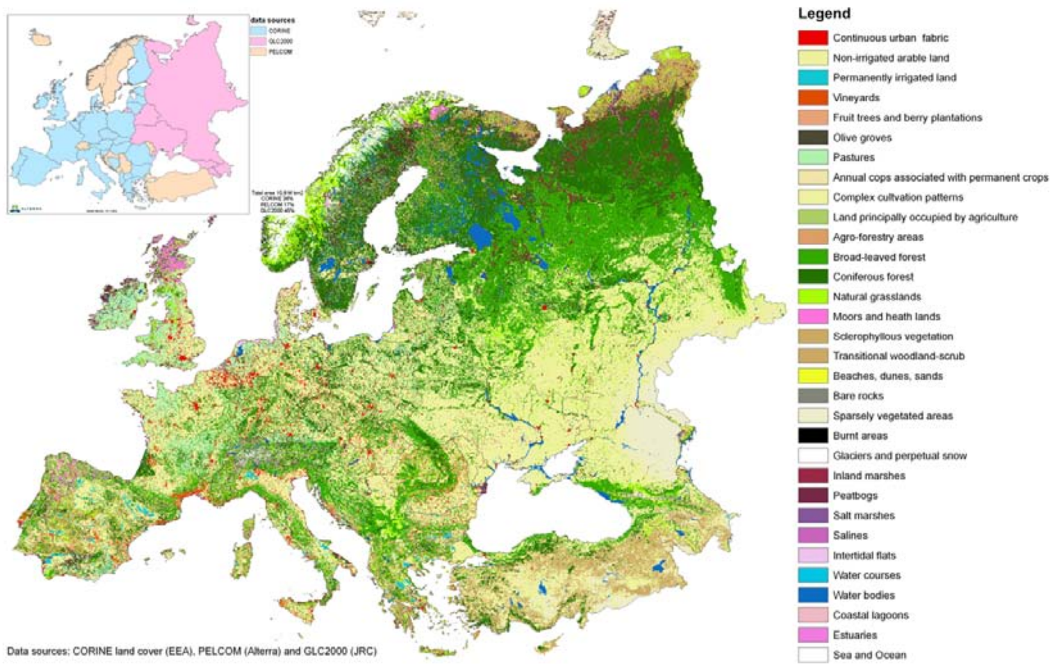

Fig. 4.2 Pan-European land cover database with a spatial resolution of 250 m based on integration of CORINE land cover (source: EEA), GLC2000 (source: JRC) and PELCOM (source: Alterra).

Meanwhile the SRTM global elevation data has become a more accurate database (Chen, 2005). However, information above latitudes of 60 degrees North are not available and distortions in and between European tiles do exist.

Soils

Much information about site conditions can de derived from soil databases. For Europe, the European Soil Database at a scale of 1:1,000,000 (CEC, 1985) is considered to be the most accurate soil database. Unfortunately, the European Soil Database (ESDB) did not cover the whole of pan-Europe. Therefore, it was necessary to integrate the ESDB with the FAO-Unesco Soil Map of the World (FAO, 1988; FAO 1991) available at a scale of 1:5,000,000. ESDB is the resulting product of a collaborative project involving all the European Union and neighbouring countries (CEC, 1985). It is a simplified representation of the diversity and spatial variability of soil profiles. The methodology used to differentiate and name the main soil types is based on the terminology of the FAO legend for the Soil Map of the World. The FAO-UNESCO Soil Map of the World was published between 1974 and 1978 at 1:5,000,000 scale (FAO, 1991) and has 106 soil units (from Af to Zt) aggregated in 26 major soil groupings. Integration of the two soil databases was done according to the 1974 (modified in 1985) FAO-Unesco soil legend. The integration concentrated on map production of the following four ecological site factors: calcareous, wet, organic and saline soils. One obstacle to the successful integration of the ESDB with the FAO soil database was the fact that the ESDB attributes were not consistently available, with some only available for certain countries. This meant that the integration of the two databases had to be implemented separately for each site condition separately (Mücher et al., 2004). Fig. 4.3 shows an example of the integration of the two soil databases for the site condition calcareous soils. Concerning the ESDB (CEC, 1985), calcareous soils were derived from the soil attribute parent material, wet soils from the attribute water regime, and the saline and organic soils by the soil type (Mücher et al., 2004).

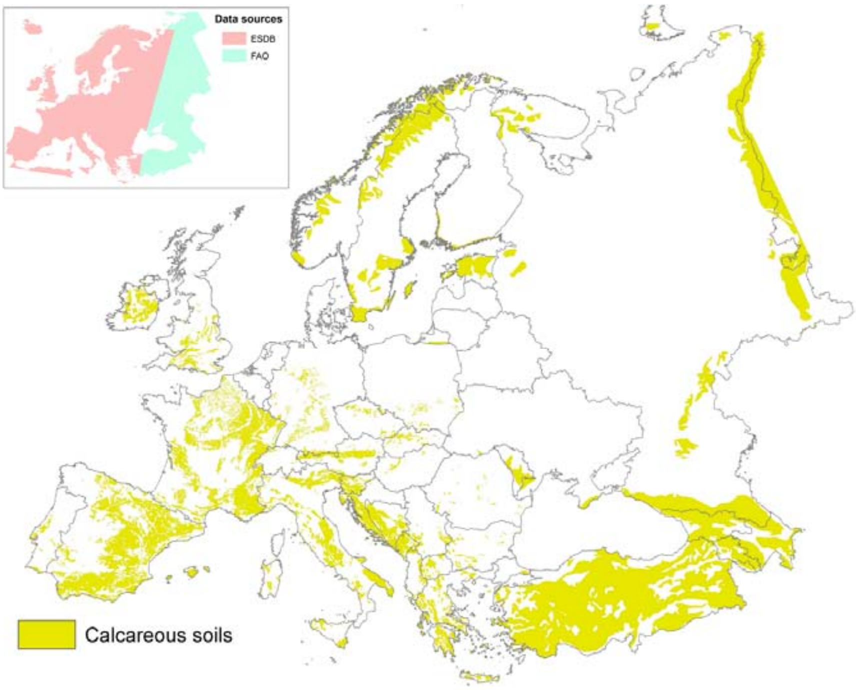

Fig. 4.3 Calcareous soils in Europe based on the integration of the European Soil Database (source :ESDB/JRC) and the FAO-Unesco Soil Map of the World (source: FAO).

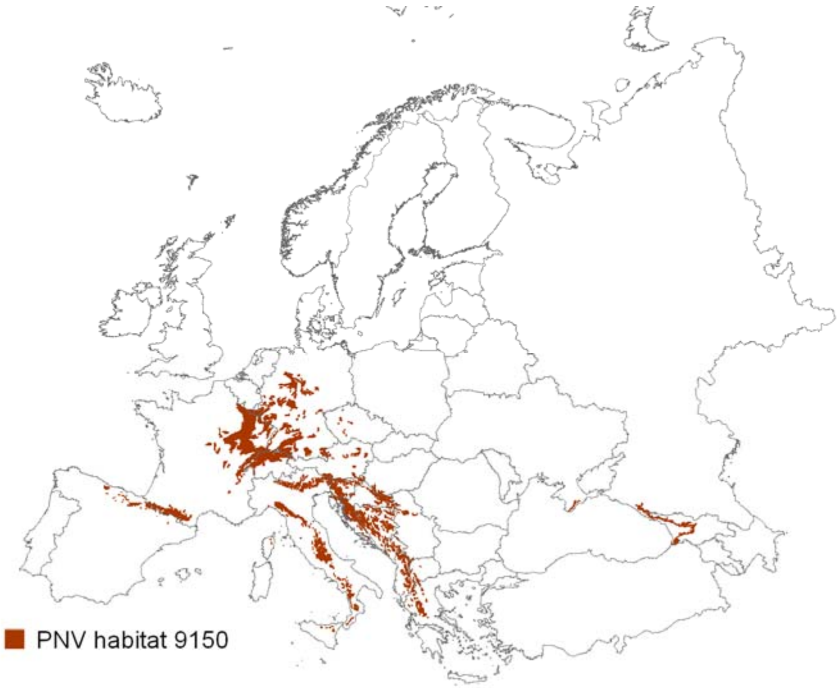

Fig. 4.4 Identification of the Habitat 9150 " Medio-European limestone beech forests of the Cephalanthero-Fagion" based on the selection of specific attributes from the database of the Map of the Natural Vegetation of Europe (PNV, source: BfN)

Indicator plant species

The characteristic plant species for each habitat type are listed in the Interpretation Manual of European Habitats (European Commission, 2007). If distribution maps of the characteristic plant species are available it is possible to improve the spatial identification of the Natura 2000 habitat types. The spatial distribution of characteristic plant species was extracted from two data sources; the Atlas Flora Europapaeae (Jalas et al., 1972-1999) and the Map of the Natural Vegetation of Europe (Bohn et al., 2003; Bohn and Gollub, 2006). The Atlas Florae Europaeae (AFE) has been designed to map the distribution of vascular plants in Europe based upon a 50 km grid (Jalas et al., 1972-1999). The project was launched in 1965 as a collaborative effort of European botanists. The Botanical department of the Finnish Museum of Natural History in Helsinki functions as the secretariat (www.fmnh.helsinki.fi/map/afe). So far the Committee and Societas Biologica Fennica Vanamo have published 12 volumes of the Atlas, including 2039 pages and 3270 distribution maps of individual plant species (Jalas et al., 1972-1999). Unfortunately, this means that not more than approximately one quarter of all European plant species have currently been mapped.

The production of the Map of the Natural Vegetation of Europe, further referred to as PNV (Potential Natural Vegetation) map, was co-ordinated by the Institute für Bundesamt für Naturschutz (BfN) in Germany (Bohn et al., 2003; Bohn and Gollub, 2006). The database defines the distribution of plant communities and their complexes, excluding, as far as possible, human impact. The 699 vegetation classes are organised into a hierarchical classification with 19 vegetation formations at the highest level. The map was designed for defining the potential natural vegetation and does not necessarily describe the actual vegetation at a given location. However, there are associated database attributes with comprehensive text descriptions of the actual situation for each mapping unit. Fig. 4.4 shows the result for Habitat 9150 “Medio-European limestone beech forests of the *Cephalanthero-Fagion*” based on the selection of specific key words (beech and chalk) from the text attributes in the PNV database (Bohn et al., 2003). The result below gives already a realistic overview of the potential distribution of the habitat type. However, it does not include yet the land cover currently present at a given location.

4.2.2 Spatial distribution modelling

Predictive models were developed to assess the actual spatial distribution of European habitats using the best available digital environmental data sets implemented in decision-tree classifications that contained decision rules based on their relevant parameters derived from the class descriptions (e.g., within the Annex I of the Habitats Directive) and additional ecological knowledge of experts (knowledge rules). In data mining and machine learning, a decision tree is a predictive model; that is, mapping from observations about an item to conclusions about its target value. In principle, the methodology therefore constitutes a disaggregation of land cover information, obtained from the interpretation of satellite imagery, based on biotic and abiotic site conditions. Each data set (e.g., land cover, altitude and species distribution maps) contributed to an improved spatial identification of the actual habitat (Fig. 5). However, each data set has a particular accuracy which is rarely specified in the meta-information and is often unknown but has a large influence on the end-result. The methodology starts with land cover information derived from satellite imagery and uses a series of progressive steps to disaggregate the initial map and finally predicts the actual spatial distribution of the selected habitat type. For this purpose, a flexible spatial data infrastructure was developed to exploit existing, revised and new spatial datasets in combination with explicitly defined decision rules in the following steps defined below:

1) Identification, processing and integration of important and available environmental data sets with the highest possible accuracy for Europe.
2) Establishment of knowledge rules for each habitat derived from the descriptions in the Annex I.
3) Incorporation of additional ecological knowledge from experts, especially, where the availability of information from the Annex I was limited.
4) Construction of the spatial distribution models as graphic decision-tree models within a GIS for the specific habitat type in which the decision rules were integrated on basis of the integrated spatial data sets and knowledge rules.
5) Validation of the results.

Step 1

The most important data sets and their integration were summarized in section 2.1 above.

Step 2

The knowledge rules consisted of a combination of decision rules derived from the Annex I habitat descriptions, additional expert knowledge and selected spatial data sets. Mücher et al. (2004) provides Annexes of these knowledge rules. The knowledge or decision rules were formalised within a spatial model for each habitat type and can be easily modified when new data sets or improved knowledge rule become available. The methodology was implemented for 27 habitat types of the Habitats Directive representing all major ecosystems and was published as an interactive CDROM (Mücher et al. 2005b), which enabled visual exploration of the results and associated environmental data sets and knowledge rules. The methodology is demonstrated here for Annex I habitat type 9150 "Medio-European limestone beech forest of the Cephalanthero-Fagion". Although it is not a priority habitat it is an important European ecosystem, sensitive to climate and land use change, and is widely distributed across pan-Europe.

Step 3

Expert knowledge was gained from the experience from the authors, but could be expanded by further consultation.

Step 4

Annex I habitat type 9150 was selected as an example in the present paper and is a representative of broad-leaved forests.

In the first branch of the predictive distribution model, the land cover information was combined with the AFE indicator species map for *Fagus sylvatica* (see section 2.1.2) to limit the extent of broad-leaved forests with the occurrence of *Fagus sylvatica*. Mücher et al. (2004) give indicator species for each habitat type. The species were in principle selected from those given in the Interpretation Manual of European Habitats (European Commission, 2007) as the most characteristic species of that habitat. The selected species for habitat 9150 were as follows: *Fagus sylvatica*, *Cephelanthera* spp., *Neottia nidus-avis* and *Carex digitata*. Currently, the Atlas Florae Europaeae (AFE) contains only *Fagus sylvatica* from this list, because not all species yet have been completed. Abiotic site conditions were then introduced to further refine the distribution. The Interpretation Manual states that habitat 9150 is present on calcareous, often superficial, soils, usually on steep slopes. Therefore, calcareous soils were added as a further decision rule and since steep slopes are rare in the lowlands, the DEM (see section 2.1.3) was used to exclude altitudes below 200 m. In some cases additional expert knowledge was used to refine the distribution, e.g., for habitat type 91C0, to refine the distribution.

The second branch of each graphic model started with the PNV extracted potential habitat map (Bohn et al., 2003). Specific PNV database attributes played a crucial role in the habitat identification process (e.g., explanatory text in ‘dominant and most frequent species’, ‘diagnostically important species’ and ‘site conditions’). Because it was not likely that all characteristic species for one habitat type were present in a PNV mapping unit, a threshold was defined for the minimum number of species that should be present in each PNV mapping unit. For example, two as a threshold meant that at least two species from the total list of characteristic species as mentioned in Annex I had to be present in a mapping unit. For habitat type 9150, the PNV mapping units were selected that contained the attributes “beech” and “limestone” as a site condition. A next step was the intersection of the selected PNV mapping units with the actual land cover to further enhance the spatial identification. All spatial models were implemented as graphic models in ERDAS Imagine. When a decision rule needed to be adjusted or revised or new input data became available, it was easy to adapt the graphic model and run it again. The intermediate results were finally combined to assess the spatial distribution of a specific habitat type in three probability classes; low, medium and high. A high probability meant that a specific pixel was both identified by the first branch of the spatial model (land cover with associated indicator species and abiotic site conditions) and the second branch (the PNV corrected for the actual land cover). In case of a low probability the pixel was not identified by any part of the model. In case of a medium probability the pixel was identified by one of the two main branches of the model.

Step 5

The validation is discussed in section 4.3.2.

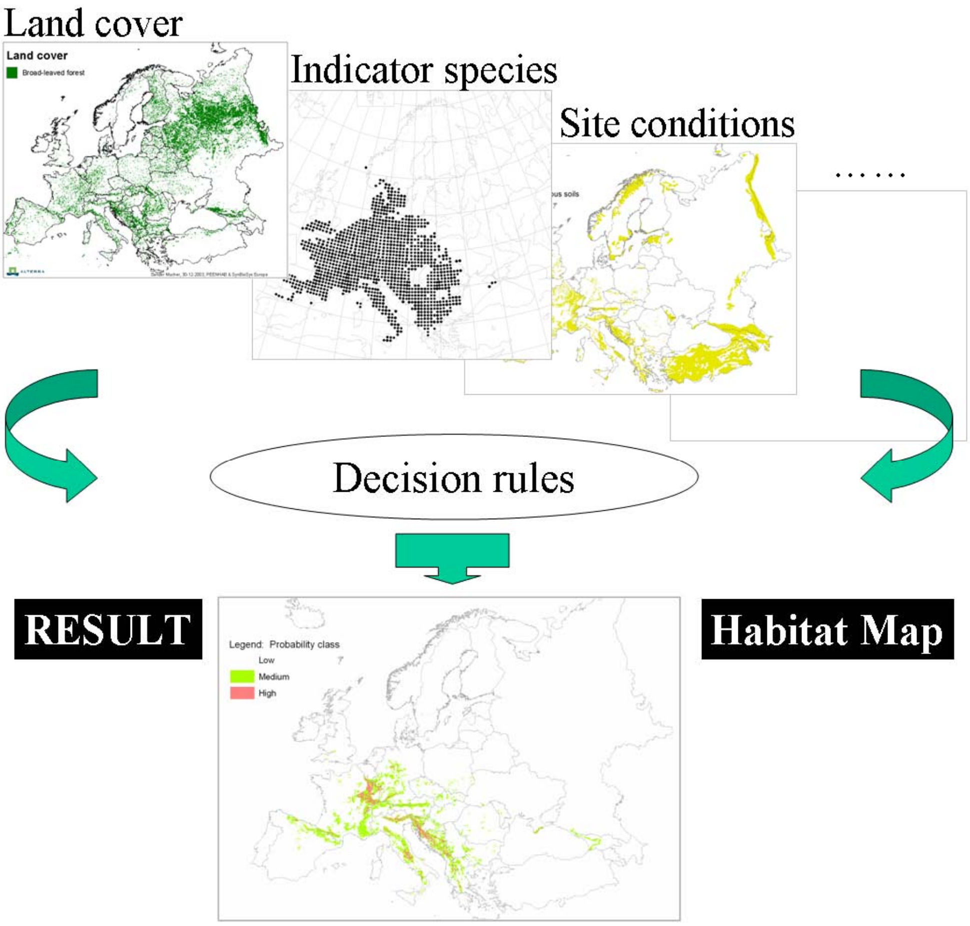

Fig. 4.5 Methodological flowchart with decision rules based on expert knowledge that combines European data sets with a high spatial resolution to assess the spatial distribution of habitat 9150 "limestone beech forests" ranked into various probability classes on a 250 m grid basis.

4.3 Results

4.3.1 Spatial distribution maps

Mücher et al. (2004) showed that by using a pan-European land cover database it is possible to provide provisional estimates of the spatial distribution of the nine major ecosystems of the Annex I Habitats Directive. It was estimated that approximately 78% of the total surface of European natural and semi-natural habitats was provided by the broad land cover categories forest and grassland, see Table 4.2. These figures strongly contrast with the estimates of restricted ecosystems such as "coastal and halophytic habitats", "coastal sand dunes and inland dunes" and "rocky habitat and caves" that contribute together only 1% to the total surface of European habitats. Further disaggregation of these rare ecosystems or habitat groups is not feasible at the European scale. The estimates are also partly reflected by the figures given by Evans (2006) as declared by the Member States. As would be expected the actual area that is proposed as designated for the relevant habitat group (sent by the 25 Member states to the European Commission by June 2005) is relatively larger for rare groups and smaller for widespread groups (see Table 4.2).

To test the proposed methodology 27 Natura 2000 habitat types were selected from all major ecosystems, except for 'coastal sand dunes and inland dunes' and 'rocky habitats and caves' for reasons mentioned above (see Table 4.3). The selection was further based on a mixture of priority and non-priority habitats, adequate descriptions in the Interpretation Manual of European Habitats (European Commission, 2007) and different degrees of spatial distribution. In total, 13 Priority Habitats were included which are indicated in Table 4.3 with an asterisk. Once the basic data sets had been assembled and the decision rules determined about half a day is required to produce a distribution map. Modification of the decision rules can be rapidly incorporated, so that distribution maps can be updated as required.

Table 4.2 First estimation of the contribution of Natura 2000 habitats in Europe at level one of the Annex I of the Habitats Directive, based on information from the compiled pan-European land cover database. The third column (Evans, 2006) gives the area in percentages as proposed or designated by the 25 Member states (sent in to the European Commission by June 2005)

Annex I habitat (Natura2000), level 1	Estimates in percentages based on land cover only	Area in percentages Declared by Member states (Evans, 2006)
1. Coastal and halophytic habitats	0.4	16.5
2. Coastal sand dunes and inland dunes	0.1	1.6
3. Freshwater habitats	4.1	6.8
4. Temperate heath and scrub	5.2	12.6
5. Sclerophyllous scrub	7.8	4.4
6. Natural and semi-natural grasslands[a]	23.7	12.7
7. Raised bogs, mires and fens	4.2	8.6
8. Rocky habitats and caves	0.5	4.5
9. Forests	54.0	32.3
Total	100.0	100.0

[a] An important remark here is that pastures (CORINE class 2.3.1) has been included within the major habitat type "Natural and semi-natural grasslands (6)", since many countries did not distinguish well the classes natural grassland (3.2.1) and pastures (2.3.1). And therefore this habitat is still overestimated in the table above.

Table 4.3 Selected Annex I habitats in this study

1.	Coastal and halophytic habitats 1330 Atlantic salt meadows (Glauco-Puccinellietalia)
2.	Coastal sand dunes and inland dunes -
3.	Freshwater habitats 3130 Oligotrophic to mesotrophic standing waters with vegetation of the Littorelletea uniflorae and/or of the Isoëto-Nanojuncetea 3210 Fennoscandian natural rivers
4.	Temperate heath and scrubs 4020 * Temperate Atlantic wet heaths with Erica ciliaris and Erica tetralix 4030 European dry heaths 4060 Alpine and Boreal heaths 4070 * Bushes with Pinus mugo and Rhododendron hirsutum (Mugo-Rhododendretum hirsuti)
5.	Sclerophyllous scrubs 5130 Juniperus communis formations on heaths or calcareous grasslands 5210 Arborescent matorral with Juniperus spp. 5220 * Arborescent matorral with Zyziphus[a]
6.	Natural and semi-natural grassland formations 6120 * Xeric sand calcareous grasslands 6170 Alpine and subalpine calcareous grasslands 6210 Semi-natural dry grasslands and scrubland facies on calcareous substrates (Festuco-Brometalia (* important orchid sites) 6230 * Species-rich Nardus grasslands, on silicious substrates in mountain areas (and submountain areas in Continental Europe) 6260 * Pannonic sand steppes[a] 6280 * Nordic alvar and precambrian calcareous flatrocks
7.	Raised bogs and mires and fens 7110* Active raised bogs 7210 * Calcareous fens with Cladium mariscus and species of the Caricion davallianae
8.	Rocky habitats and caves -
9.	Forests 9020 * Fennoscandian hemiboreal natural old broad-leaved deciduous forests (Quercus, Tilia, Acer, Fraxinus or Ulmus) rich in epiphytes. 9150 Medio-European limestone beech forests of the Cephalanthero-Fagion 9160 Sub-Atlantic and medio-European oak or oak-hornbeam forests of the Carpinion betuli 91C0 * Caledonian forest 91G0 * Pannonic woods with Quercus petraea and Carpinus betulus 91I0 * Euro-Siberian steppic woods with Quercus spp.[a] 9210 * Apeninne beech forests with Taxus and Ilex 92C0 Platanus orientalis and Liquidambar orientalis woods (Platanion orientalis)[a] 9330 Quercus suber forests[a]

[a] These 5 habitat types have not been validated. The habitats indicated with asterisk are priority habitats.

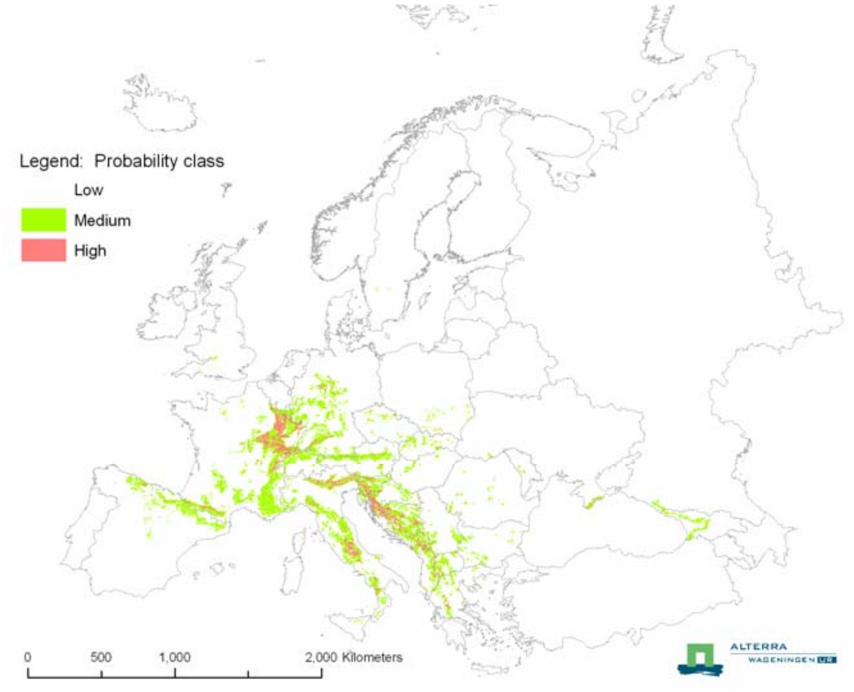

Fig. 4.6 Final result of the proposed methodology. This example concerns Annex I Habitat Type 9150 “Medio-European limestone beech forest of the Cephalanthero-Fagion”. The resulting habitat map has a spatial resolution of 250 m and is divided into three probability classes.

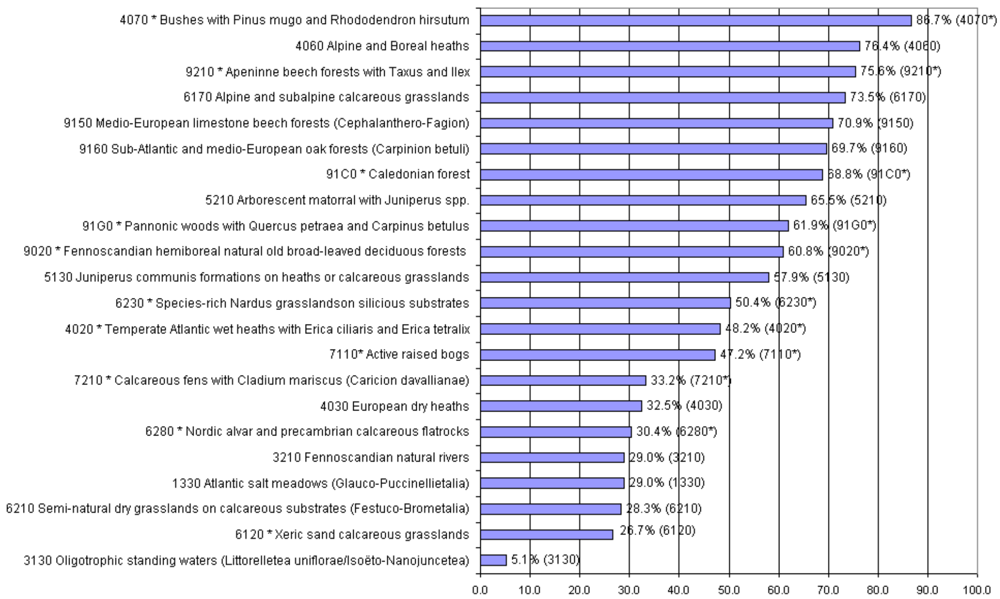

Fig. 4.7 Accuracy assessment of the methodology by calculating the percentage of the total number of Natura 2000 sites with more than 10 ha of a specific habitat that have been identified by the methodology.

The 27 habitat distribution maps derived from our predictive models have a spatial resolution of 250 m and have three probability classes. Although a spatial resolution of 250 m is quite detailed at the pan-European scale it is still quite coarse for actual habitat patches in many regions. In Fig. 4.6 the result is shown for the Annex I habitat type 9150 “Medio-European limestone beech forest of the *Cephalanthero-Fagion*”. Validation of habitat maps is presented in the next paragraphs.

4.3.2 Validation

The Natura 2000 database was obtained in 2005 for 13,405 sites in a restricted area of the European Union (approximately EU12, excluding central and southern parts of Italy and Spain) and it was then possible to validate the current methodology. The database did not contain the exact boundaries of such sites, but only the centre co-ordinates together with their surface area. The extent of each site was therefore estimated as a circle derived from the actual area. The validation below only relates to the reliability of the methodology but does not relate to the accuracy, since no spatial information is available about the presence of the habitats outside the Natura 2000 sites. Furthermore, the figures are only an indication of the overlap.

The coverage of the Natura 2000 database disabled the validation of 5 of the 27 selected habitat types (habitat types: 5220, 6260, 91I0, 92C0 and 9330), see Fig 4.7. and Table 4.3. Next, only Natura 2000 sites with an area of at least 10 ha of a specific habitat type were included. The habitat maps have a spatial resolution of 250 m (see for example Fig. 4.6), with 1 pixel being 6.25 ha. Habitats smaller than 10 ha will therefore normally not be detected. The relevant Natura 2000 sites were then intersected with the habitat distribution maps, using high and medium probability as one lumped class. The number of Natura 2000 sites identified by distribution mapping was then divided by the total number of Natura 2000 sites that contained the specific habitat type. Fig. 4.7 gives the percentage of the total amount of relevant Natura 2000 sites that were identified but provides only an indication of the reliability of the habitat maps.

Of the 22 validated habitat maps, 10 had a reliability of over 60%. Priority habitat 4070 “Bushes with *Pinus mugo* and *Rhododendron hirsuta*” had the highest reliability with 86.7%. The second highest score was given for priority habitat 9210 “Apennine beech with *Taxus* and *Ilex*” with 75.6%. Habitat 3130 “Oligotrophic standing waters” received the lowest score with

5.1%. This result is expected, since no information was available about the trophic state of European water bodies. Note also that habitat types like “Fennoscandinavian natural rivers” (3210) could have received a low reliability since it was assumed that all Natura 2000 sites had a circular surface and this is definitely not the case for rivers. The average score was 52%.

In general, the highest scores were found for forest and scrub habitats and the lowest scores for freshwater habitats. This coincides with the fact that the latter are more fragmented and occur in relatively restricted and dispersed areas. Information from geo-referenced vegetation relevés would improve the estimation of the quality of the water bodies as well as other habitats. The results for grassland habitats varied from 29% for habitat 1330 “Atlantic salt meadows” to 73.5% for habitat 6170 “Alpine and subalpine calcareous grasslands”. Habitats with a wider European distribution were therefore easier to identify than local and dispersed habitats using the proposed methodology. Habitat type 4030 “European dry heaths” has a surprising low reliability of 32.5% because the reliability on the distribution of podzols was insufficient. Currently, the soil information is often not sufficiently detailed to identify fragmented patches of dry heatlands. The combination of spatial data sets is limited by the data set with the lowest spatial accuracy. Thus in case for European dry heaths the reliability could be increased by improving, or removing, the soil information, and so, depending on the more detailed land cover information.

Habitats with a strongly restricted spatial distribution, e.g., habitat 5220 “Arborescent matorral with *Zyziphus*”, require in-situ information. For the described methodology, some in-situ information was derived from the PNV database. By using this information habitat type 5220 was reasonably well located. However, when field visits were made to this specific habitat type it was concluded that the distribution was more restricted than the habitat map indicated, because experts in Spain indicated that this habitat type was only present within a restricted area on flat sandy soils, not further than 30 km from the coast and never above an altitude of 100 m. This knowledge could be incorporated in future in the knowledge rules of the specific habitat distribution model and will result in a better spatial identification of the habitat. The quality of the knowledge rules mainly relies on the quality of the description of the habitat type in the Annex I of the Habitats Directive, which is not always adequate and needs further expert knowledge (Evans, 2006).

4.4 Discussions and conclusions

The preparation of all abiotic and biotic thematic data sources with a pan-European coverage and the highest possible spatial accuracy, ranging in most cases from 250 m to 1000 m spatial resolution, involved more than 2 man-months work, since in most cases various data sources needed to be integrated for one theme (see also Table 4.1 and Fig. 4.1, 4.2 and 4.3). In a GIS, knowledge rules were designed for each habitat type in a spatially explicit graphic model on the basis of their Annex I habitat description. Land cover information derived from high resolution satellite imagery played a crucial role in the process of spatial identification of the habitats. Although, CORINE land cover was considered as the most accurate European land cover database, it was based on visual interpretation of high resolution satellite data with a minimum mapping unit of 25 ha. Semi-automatic classification of high-resolution satellite data, such as Landsat ETM, could improve the spatial resolution to 25 m.

The PNV map is especially important for very restricted and local habitat types, e.g., Annex I habitat type 5220 “Arborescent matorral with *Zyziphus lotus*” because detailed species information is included in the database. Rare habitats often have very restricted distributions that are exactly defined in the Interpretation Manual, e.g., habitat 9590 “*Cedrus brevifolia* forests” which are confined to the western summits of the Troodos mountains in Cyprus. Land cover provides better information for habitats that have a wide distribution in Europe. The PNV map shows the potential vegetation which need to be modified as in the present study by the actual land cover. Site condition information played also an important role, but the spatial resolution should be improved in future studies, e.g., a more accurate and consistent European soil map. There is a clear trade-off between a better spatial and thematic identification of habitats at the European scale. Strictly speaking the distribution maps involve the likely occurrence of the habitat concerned, i.e. probability. The presented method provide only an indication of likely occurrence which needs to be eventually tested by in-situ data. The inclusion of vegetation relevés would provide further information to refine the distribution maps, however precise locations would be a prerequisite. The reliability of the maps above provides only an indication of likely accuracy. Expert appraisal of the maps showed few major inconsistencies of the patterns of core distributions. These inconsistencies could be further assessed by field visits and analysis of extant data.

Accessibility of vegetation relevés across Europe according to newly standardized synoptic tables by linking national vegetation databases is being initialised by SynBioSys Europe.

SynBioSys Europe, an initiative of the European Vegetation Survey (EVS), is an information system for the evaluation and management of biodiversity among plant species, vegetation types and landscapes (Schaminée et al., 2007). Further information on the Annex I habitats based on expert knowledge and consultation are currently being added. In due course new maps, incorporating these improvements, will be produced for many grassland and forest habitats.

There are other problems, e.g., CORINE land cover does not distinguish evergreen forests (e.g., *Quercus ilex*) from deciduous broadleaf forests (e.g., *Fraxinus angustifolia*). Time-series of satellite images, e.g., medium-resolution sensors as MODIS or MERIS, could help to distinguish these forest from other habitat types (Lucas et al., 2007; Zhang et al., 2006).

The present methodology integrates a top-down approach (starting with remote sensing derived information such as land cover) with a bottom-up approach (using in-situ information such as vegetation relevés) and could be applied to countries outside Europe because such information is widely available. However, many studies using very high resolution satellite imagery are limited to restricted areas (Groom et al., 2006) and therefore the use of medium resolution satellite imagery provides more opportunities at continental scales (Nagendra, 2001, Duro et al., 2007, Leyequien et al., 2007,). In order to improve the spatial cohesion of habitats amongst others through the design of ecological networks, habitat maps with a high spatial resolution are a prerequisite (Saura and Pascual-Hortal, 2007).

Uncertainties in the mapping results remain in the cases of poor habitat descriptions, spatial and thematic inaccuracies in the core data sets, and absence of spatial distribution maps of specific indicator species. The validation of the methodology indicated that the scrub and forest habitat distribution maps had the highest reliability and that freshwater habitats were less reliable. Freshwater habitats will be better identified with a better utilisation of vegetation relevés across Europe. Clear definitions and good descriptions of the habitat types will remain a prerequisite for a good spatial identification but also for an objective validation of the results. An expert system approach involving expert knowledge, thematic data sets with a high spatial accuracy and better information on the Annex I habitats has the potential for increasing the accuracy of the distribution maps. This is currently, being implemented in the EU-FP6 project ECOCHANGE and EU-FP7 project EBONE. However in situations where uncertainty in expert opinion remains researchers should be encouraged to test the range of possible uncertainties (Johnson and Gillingham, 2004).

The extension of the methodology to other habitats is feasible and should be relatively quick, because the basic environmental data sets have now been assembled. As it is now recognised that the spatial distribution and fragmentation of habitats across Europe has to be considered in the design of ecological networks and in the assessment of their spatial cohesion, the maps presented here provide a means to achieve this goal.

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References

Acevedo, P., Alzaga, V., Cassinello, J., Gortázar, C., 2007. Habitat suitability modelling reveals a strong niche overlap between two poorly known species, the broom hare and the Pyrenean grey partridge, in the north of Spain (2007) Acta Oecol. 31 (2), 174-184.

Bartholomé, E., Belward, A.S., 2005. GLC2000: a new approach to global land cover mapping from earth observation data. Int. J. Remote Sens. 26 (9), 1959-1977.

Bohn, U., Neuhäusl, R., with contributions by Gollub, G., Hettwer, C., Neuhäuslová, Z., Raus, Th., Schlüter, H., Weber, H., 2003. Karte der natürlichen Vegetation Europas (Map of the Natural Vegetation of Europe). Maßstab / Scale 1 : 2,500,000. Bundesamt für Naturschutz, Bonn, Germany.

Bohn, U., Gollub, G., 2006. The use and application of the map of the natural vegetation of Europe with particular reference to Germany. Biol. Environ. 106 (3), 199-213.

Bouwma, I.M., Jongman, R.H.G., Butovsky, R.O., 2002. Indicative map of the Pan-European Ecological Network for Central and Eastern Europe: technical background document. European Centre for Nature Conservation (ECNC), Tilburg, 166 pp. and 1 A0 map.

Brandt, J., Holmes. E., Agger, P., 2001. Integrated Monitoring on a landscape scale - lessons from Denmark, in: Groom, G.B., Reed. T.M. (Eds.), Strategic landscape monitoring for the Nordic countries. Published by the Nordic Council of Ministers TemaNord Series (TN 2001:523), pp. 31- 41.

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 Ecol. 23 (1), 11-25.

Champeaux, J.L., Mücher, C.A., Steinnocher, K., Griguolo, S., Wester, K., Goutorbe, J.P., et al., 2000. PELCOM Project: A 1-km pan-European land cover database for environmental monitoring and use in meteorological models. Int. Geosci. Remote Sens. (IGARSS), Vol. 5, 1915-1917.

Chen, J., 2005. Quality evaluation of topographic data from SRTM3 and GTOPO30. Geomat. Inform. Sci. Wuhan Univ. 30 (11), 941-944.

Commission of the European Communities, 1985. Soil map of the European Communities 1:100.0000 (Tavernier cs). Commission of the European Communities, Luxembourg.

Commission of the European Communities, 1991. CORINE biotopes manual. Habitats of the European Community. Data specification part 2, EUR 12587/3 EN, Luxembourg.

Commission of the European Communities, 1994. CORINE Land Cover. Technical Guide. Office for Official Publications of European Communities, Luxembourg.

Commission of the European Communities, 2003. Council Directive 92/43/CEE of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. As amended As amended by the Accession Act of Austria, Finland and Sweden (1995) and the Accession Act of the Czech Republic, the Republic of Estonia, the Republic of Cyprus, the Republic of Latvia, the Republic of Lithuania, the Republic of Hungary, the Republic of Malta, the Republic of Poland, the Republic of Slovenia and the Slovak Republic (2003). Official Journal of the European Union L 236 33 23.9.2003. Brussels. European Commission 1992/95/2003.

Convention of Bern, 1979. Convention on the conservation of European wildlife and natural habitats, Bern, 19-IX-1979.

Council of Europe, UNEP & European Centre for Nature Conservation, 1996. The Pan-European Biological and Landscape Diversity Strategy. A Vision for Europe’s Natural Heritage. Strasbourg/ Tilburg.

Council of Europe, 1999. General guidelines on the establishment of the Pan-European Ecological Network. Adopted on 21st of April 1999. Nature & Environment Series No. 95 of the Council of Europe.

Davies C.E., Moss, D., 2002. EUNIS Habitat Classification. Final Report to the European Topic Centre on Nature Protection and Biodiversity, European Environment Agency. February 2002. 125 pp.

Devillers, P., Devillers-Terschuren, J., 1996. A classification of Palaearctic habitats. Nature and Environment, No. 78. Strasbourg: Council of Europe Publishing. 194 p.

Duro, D.C., Coops, N.C., Wulder, M.A., Han, T., 2007. Development of a large area biodiversity monitoring system driven by remote sensing. Prog. Phys. Geog. 31(3), 235-260.

EEA, 2005. The European Environment - State and Outlook 2005. Copenhagen.

EU Council Directive, 1992. Natura 2000 Network on the Conservation of Natural Habitats and of Wild Fauna. COUNCIL DIRECTIVE 92/43/EEC (1) of 21 May 1992. The Council of the European Communities.

European Commission, 2007. Interpretation Manual of European Habitats – EUR27. Published by the European Commission, DG Environment, Nature and Biodiversity.

Evans, D., 2006. "The habitats of the European union habitats directive. Proc. Royal Irish Acad.- Section B, Biol. Environ. 106 (3): 167-173.

Ewers, R.M., Didham, R.K., 2005. Confounding factors in the detection of species responses to habitat fragmentation. Biol. Rev. 81 (1), 117-142.

FAO, 1988. Unesco Soil Map of the World. World soil Resources Report No 60, Rome.

FAO, 1991. The Digitized Soil Map of the World (Release 1.0), Rep. No. 67/1. Food and Agriculture Organization of the United Nations, Rome.

Feranec, J., Hazeu, G., Christensen, S., Jaffrain, G., 2007. Corine land cover change detection in Europe (case studies of The Netherlands and Slovakia). Land Use Policy 24 (1), 234-247.

Groom, G., Mücher, C.A., Ihse, M., Wrbka, T., 2006. Remote sensing in landscape ecology: experiences and perspectives in a European context. Landscape Ecol. 21, 391-408.

Guisan, A., Thuiller, W., 2005. Predicting species distribution: offering more than simple habitat models. Ecol. Lett. 8 (9), 993-1009.

Gutiérrez, D., Fernández, P., Seymour, A.S., Jordano, D., 2005. Habitat distribution models: are mutualist distributions good predictors of their associates? Ecol. Appl. 15 (1), 3-18.

Hansen, A.J., deFries, R.S., Turner, W., 2004. Land use change and biodiversity: a synthesis of rates consequences during the period of satellite imagery, in: Gutman, G., Janetos, A.C., Justice, C.O., Moran, E.F., et al. (Eds.), Land Change Science: Observing, Monitoring and Understanding Trajectories of Change on the Earth's Surface. Series Title Remote Sensing and Digital Image Processing, vol. 6, Publisher Kluwer Academic Publishers, pp. 277-300.

Jalas, J., Suominen, J., Lampinen, R., Kurtto, A. (Eds.), 1972-1999. Atlas Florae Europaeae. 1-12. The Committee for Mapping the Flora of Europe & Societas Biologica Fennica Vanamo, Helsinki, FI.

Johnson, C.J., Gillingham, M.P., 2004. Mapping uncertainty: sensitivity of wildlife habitat ratings to expert opinion. J. Appl. Ecol. 41 (6), 1032-1041.

Jones-Walters, L., 2007. Pan-European ecological networks. J. Nat. Conserv. 15(4), 262-264.

Jongman, R. H. G., Külvik, M., Kristiansen, I., 2004. European ecological networks and greenways. Landscape Urban Plan. 68 (2-3), 305-319.

Keramitsogloua, I., Kontoesb, C., Sifakisb, N., Mitchleyc, J., Xofisc, P., 2005. Kernel based re-classification of Earth observation data for fine scale habitat mapping. J. Nat. Conserv. 13, Issues 2-3, 91-99.

Leyequien, E., Verrelst, J., Slot, M., Schaepman-Strub, G., Heitkönig, I.M.A., Skidmore, A., 2007. Capturing the fugitive: applying remote sensing to terrestrial animal distribution and diversity. Int. J. Appl. Earth Obs. 9 (1), 1-20.

Lira-Noriega, A., Soberón, J., Navarro-Sigüenza, A.G., Nakazawa, Y., Peterson, A.T., 2007. Scale dependency of diversity components estimated from primary biodiversity data and distribution maps: biodiversity research. Divers. Distrib. 13 (2), 185-195.

Lucas, R., Rowlands, A., Brown, A., Keyworth, S., Bunting, P., 2007. Rule-based classification of multi-temporal satellite imagery for habitat and agricultural land cover mapping. ISPRS J. Photogramm. 62 (3), 165-185.

Luoto, M., Kuussaari, M., Rita, H., Salminen, J., Von Bonsdorff, T., 2001. Determinants of distribution and abundance in the clouded apollo butterfly: a landscape ecological approach. Ecography 24 (5), 601-617.

Mitchell, T.D., Jones, P.D., 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int. J. Climatol. 25 (6), 693-712.

Metzger, M.J., Bunce, R.G.H., Jongman, R.H.G., Mücher, C.A., Watkins J.W., 2005. A climatic stratification of the environment of Europe. Global Ecol. Biogeogr. 14, 549-563

Moran, E.F., Skole, D.L., Turner II, B.L., 2004. The development of the international land use and land cover change (LCLUC) initiative., in: Gutman, G., Janetos, A.C., Justice, C.O., Moran, E.F., et al. (Eds.), Land Change Science: Observing, Monitoring and Understanding Trajectories of Change on the Earth's Surface. Series Title Remote Sensing and Digital Image Processing (vol. 6) Publisher Kluwer Academic Publishers. pp 1-16.

Moss, D., Wyatt, B.K., 1994. The CORINE biotopes project: a database for conservation of nature and wildlife in the European community. Appl. Geogr. 14 (4), 327-349.

Mücher, C.A., Steinnocher, K., Kressler, F., Heunks, C., 2000. Land cover characterization and change detection for environmental monitoring of pan-Europe. Int. J. Remote Sens. 21 (6/7), 1159-1181.

Mücher, C.A., Bunce, R.G.H., Jongman, R.H.G., Klijn, J.A., Koomen, A., Metzger, M.J., et al., 2003. Identification and Characterisation of Environments and Landscapes in Europe. Alterra Report 832, Alterra, Wageningen, The Netherlands.

Mücher, C.A., Hennekens, S.M., Bunce, R.G.H., Schaminée, J.H.J., 2004. Mapping European Habitats to support the Design and Implementation of a Pan-European Ecological Network. The PEENHAB project. Alterra-report 952, ISSN 1566-7197, Wageningen, The Netherlands, pp.129.

Mücher, C.A., Hennekens, S.M., Bunce, R.G.H., Schaminée, J.H.J., 2005a. Spatial identification of European habitats to support the design and implementation of a Pan-European Ecological Network, in: McCollin, D., Jackson, J.I.(Eds.), Planning, People and Practice. The landscape ecology of sustainable landscapes. Proceeding of the 13th Annual IALE(UK) Conference, held at the University of Northampton, 2005, pp. 217-225.

Mücher, C.A., Hennekens, S.M., Bunce, R.G.H., Schaminée, J.H.J., 2005b. European Habitat Mapping – Interactive CDROM. Alterra, Wageningen, The Netherlands.

Nagendra, H., 2001. Review article. Using remote sensing to assess biodiversity. Int. J. Remote Sens. 22 (12), 2377-2400.

Opdam, P., Verboom, J., Pouwels, R., 2003. Landscape cohesion: an index for the conservation potential of landscapes for biodiversity. Landscape Ecol. 18, 113-126.

Opdam, P., Steingröver, E., van Rooij, S., 2006. Ecological networks: a spatial concept for multi-actor planning of sustainable landscapes. Landscape Urban Plan. 75(3-4), 322-332.

Opstal, A. van, 1998. Development of a Common Approach to the Development of a Pan-European Ecological Network: Concept and Criteria. Published by Council of Europe, STRA-REP(98) 20.

Opstal, A. van, 1999. The Architecture of the Pan-European Ecological Network: Suggestions for Concept and Criteria. Discussion Report on Behalf of the Committee of Experts of the Pan European Ecological Network. Report IKC Natuurbeheer Nr.37, Wageningen, The Netherlands.

Ostermann, O. P., 1998. The need for management of nature conservation sites designated under Natura 2000. J. Appl. Ecol. 35 (6), 968-973.

Palo, A., Aunap, R., Mander, Ü., 2005. Predictive vegetation mapping based on soil and topographical data: a case study from Saare County, Estonia. J. Nat. Conserv. 13 (2-3), 197-211.

Reger, B., Otte, A., Waldhart, R., 2007. Identifying patterns of land-cover change and their physical attributes in a marginal European landscape. Landscape Urban Plan. 81, 104-113. 57.1.

Reidsma, P., Tekelenburg, T., van den Berg, M., Alkemade, R., 2006. Impacts of land-use change on biodiversity: an assessment of agricultural biodiversity in the European union. Agr. Ecosyst. Environ. 114, 86-102.

Rodwell, J. S., Pignatti, S., Mucina, L., Schaminée, J. H.J, 1995. European vegetation survey: update on progress. J. Veg. Sci. 6 (5), 759-762.

Rodwell, J.S., Schaminée, J.H.J., Mucina, L., Pignati, S., Dring, J., Moss, D., 2002. The Diversity of European Vegetation. An overview of phytosociological alliances and their relationships to EUNIS habitats. EC-LNV Report nr. 2002/054. Wageningen, The Netherlands, 168 pp.

Roekaerts, M., 2002. The Biogeographical Regions Map of Europe – Basic Principles of its Creation and Overview of its Development. European Environment Agency, Copenhagen, 17 pp.

Saura, S., Pascual-Hortal, L., 2007. A new habitat availability index to integrate connectivity in landscape conservation planning: comparison with existing indices and application to a case study. Landscape Urban Plan. 83(2-3), 91-103.

Schaminée, J.H.J., Hennekens, S.M., Ozinga, W.A., 2007. Use of the ecological information system SynBioSys for the analysis of large datasets. J. Veg. Sci. 18, 463-470.

Stanners, D., P. Bordeaux (Eds.), 1995. Europe’s Environment; The Dobříš Assessment. European Environmental Agency, Copenhagen. 676 pp. Office for Official Publications of the European Communities, Luxembourg.

Weiers, S., Bock, M., Wissen, M., Rossner, G., 2004. Mapping and indicator approaches for the assessment of habitats at different scales using remote sensing and GIS methods. Landscape Urban Plan. 67, 43–65.

Young, J., Bolger, T., Kull, T., Tinch, R., Scally, L., Watt, A. D. (Eds.), 2004. Sustaining Livelihoods and Biodiversity – Attaining the 2010 Target in the European Biodiversity Strategy. Report of an Electronic Conference.

Zhang, Q., Xiao, X., Braswell, B., Linder, E., Ollinger, S., Smith, M.-L., et al., 2006. Characterization of seasonal variation of forest canopy in a temperate deciduous broadleaf forest, using daily MODIS data. Remote Sens. Environ. 105 (3), 189-203.

Zimmermann, N.E., Kienast, F., 1999. Predictive mapping of alpine grasslands in Switzerland: species versus community approach. J. Veg. Sci. 10 (4), 469-482.

Photo: Fertilization of a pasture in the valley of Ransdalerveld, Limburg, The Netherlands.

1159-1181.

CHAPTER 5

Land cover characterization and change detection for environmental monitoring of pan-Europe

Mücher, C.A., Steinnocher, K., Kressler, F., Heunks, C., 2000. Land cover characterization and change detection for environmental monitoring of pan-Europe. *Int. J. Remote Sens.* 21 6/7: 1159-1181.

Land cover characterization and change detection for environmental monitoring of pan-Europe

Abstract

Environmental studies need up-to-date and reliable information on land use and land cover. Such databases, which can be characterized by a high spatial accuracy and that can be updated easily, are currently not available for Europe as a whole. We investigated the applicability of satellite data for Pan-European Land Cover Monitoring (PELCOM). The main objective was to develop a method by which to obtain a 1 km spatial resolution pan-European land cover database that can be updated easily using National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer (NOAA AVHRR) satellite data. The database will be used as input for environmental impact studies and climate research. The study takes full advantage of both multi-spectral and multi-temporal 1 km AVHRR data. The proposed methodology for land cover mapping has its limitations in monitoring changes due to the spatial resolution and the limited accuracy of AVHRR-derived land cover data. Therefore, a change detection technique based on the use of thematic fraction images highlights those areas where the proportions of the various land cover types have changed.

Keywords: NOAA-AVHRR satellite data; multi-spectral and multi-temporal; supervised and unsupervised classification; land cover; environmental impact and climate research; change detection: linear unmixing

5.1 Introduction

During the past century, land cover has been changing at an increasing rate in space and time, causing increasing pressure on the land and large impacts on our environment. For example, major changes in Europe (Russian Federation excluded) during the last 40 years have included a net forest gain of about 10%, a net loss of arable land of about 11% and a net loss of permanent pasture of about 11% (source: FAO land use statistics[1]). Changes in land cover within Europe have been triggered by, amongst others, the subsidy and set-a-side policy of the Common Agricultural Policy (CAP) of the European Union and the recent upsurge of land privatization in the Eastern European countries. Both marginalization and intensification exist in Europe, and are seen as threats to the European landscapes and their biodiversity (Jongman, 1996). In current environmental policy plans there is an increasing need for up-to-date and reliable information on land use and land cover (LULC) that covers the whole of Europe (Stanners and Bourdeau, 1995). We will refer to this area as pan-Europe, covering Europe from Iceland to the Ural Mountains in the west–east direction and from Scandinavia to the Mediterranean Sea in the north–south direction. Many environmental policies rely greatly on the outcome of environmental models, which in turn are significantly influenced by the areal and spatial accuracy of LULC data.

The ten-minute pan-European land use database (ELU-1) of the Dutch National Institute for Public Health and the Environment (RIVM) was a first step towards meeting the demands of environmental models on a European scale (Van de Velde et al., 1994; Veldkamp et al., 1995). The database was compiled from a combination of non-spatial statistical information with spatial information from available land cover maps using a calibration procedure. The procedure consists of an iterative process by which the regional land use is calculated and compared with the statistical figures, and consequently adjusted. The resolution (administrative level) of the statistical database determines the areas for which the land use is summed and adjusted. A major drawback of the database is that the statistical and spatial data are derived from many sources that differ in spatial accuracy, reliability, acquisition date and class definitions. Moreover, most statistical data have been collected on NUTS (Nomenclature d'Unite´s Territoriales Statistiques) level 0 and 1 (Van de Velde et al., 1994), causing a low spatial accuracy. Use of remotely sensed data eliminates this problem, as up-to-date land cover data may be inferred with a high spatial accuracy in a consistent manner.

[1] The statistics were derived from FAO website: http://apps.fao.org/default.htm, also available on the CDROM FAOSTAT statistical database 1961-1996.

Current activities on the derivation of pan-European land cover databases from remotely sensed data include the CORINE (Coordination of Information on the Environment) land cover project (CEC, 1993), now under supervision of the European Environment Agency (EEA), and the development of a 1 km global land cover product, DISCover (Loveland and Belward, 1997), under the coordination of the International Geosphere and Biosphere Programme’s Data and Information System (IGBP-DIS). These are described briefly below. Other activities that use remotely sensed data for European land cover mapping, such as for example forest mapping (Häusler et al., 1993; Roy et al., 1997), are not described because they are confined to a limited number of classes. The CORINE land cover database is being compiled by visual interpretation of high-resolution satellite images, e.g., Landsat Thematic Mapper (TM) and SPOT HRV data, at a scale of 100 000, with simultaneous consultation of ancillary data (CEC, 1993). The CORINE legend distinguishes between 44 classes grouped in a hierarchical nomenclature and is landscape-and ecology-oriented. For the time being, the CORINE database is the most detailed database that covers a large part of Europe. The CORINE database has several limitations. First of all, the project started in 1986 and is still under development, leading to large differences in acquisition dates and is still incomplete for Europe. Second, most CORINE classes are heterogeneous, and/or are determined by functional land use and consequently consist of various land cover types. Third, some CORINE classes, e.g., sport and leisure facilities, are difficult to recognize unambiguously in the high-resolution satellite images and their delineation and/or identification have been strongly supported by ancillary data. The subjectivity and the dependence on ancillary data for some classes will have major consequences on any updating procedures (Thunnissen and Van Middelaar, 1995; Perdigão and Annoni, 1997).

IGBP-DIS began a project in 1992 to produce a global land cover data set at a spatial resolution of 1 km, derived from the Advanced Very High Resolution Radiometer (AVHRR) onboard the US National Oceanic and Atmospheric Administration’s (NOAA) polar-orbiting satellite series (Loveland and Belward, 1997). The methodology is based on unsupervised clustering of monthly NDVI maximum value composites (MVCs) on a continental basis. The clusters are labelled by expert knowledge. A major limitation of the approach is that it is implemented on a continental basis without any stratification. Therefore, the result may be more closely related to agro-ecological zones, i.e. zones of similar phenology, than to the different land cover types existing in each agro-climatic zone. The European landscape is heterogeneous and fragmented and requires a stratified approach. Moreover, experiences indicate that the clustering technique does not identify forests satisfactorily (Champeaux et al., 1998). An additional limitation is that the 1 km database according to the DISCover legend contains complex classes, e.g., cropland/natural vegetation mosaics (about 27% of the pan-European land surface), which are difficult to apply in environmental studies. However, it must be stressed that the project is unique and enormous effort had to be invested in order to establish an up-to-date global land cover database at a 1 km resolution in a consistent manner. Application of the database in environmental and climate studies for pan-Europe may be limited. Besides the detailed CORINE land cover database and the global DISCover database, each with their own advantages and disadvantages, there is a need for additional land cover data sets derived from remotely sensed data that fulfils the needs for pan-European environmental modelling. These needs comprise a consistent land cover database that covers pan-Europe, that can be easily updated and contains main land cover classes such as arable land, grassland, urban areas, waterbodies, wetlands, barren land and various forest types in sufficient regional detail (Van de Velde et al., 1994). Therefore a study was initiated to investigate the applicability of AVHRR satellite data for Pan-European Land Cover Monitoring (PELCOM[2]). Different methodologies are assessed to map and monitor land cover of entire Europe with low-resolution satellite data. The main objective is to arrive at a consistent and reliable methodology for establishing and updating a 1km pan-European land cover database that can be used as input for environmental impact studies and climate research.

In §2 the results of land cover mapping with AVHRR data are discussed as obtained in the framework of the Dutch National Remote Sensing Programme (NRSP). Advantages of various classification methodologies have been exploited to arrive at an operational methodology for land cover mapping. In §3 the PELCOM approach for establishing a pan-European land cover database is described. Because of the large difference between mapping and monitoring, aspects of land cover monitoring and change detection applying linear unmixing are discussed in §4. Section 5 summarizes and concludes the presented methods.

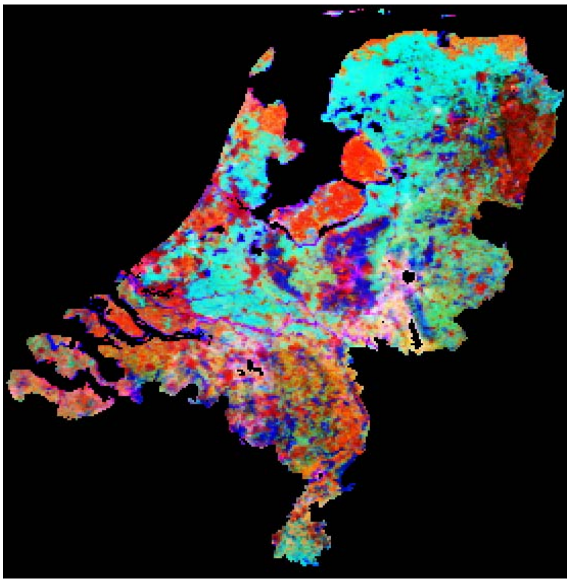
[2] The study was initiated in 1996 for a 3-year period and is funded by the European Union. The project consists of a consortium of the following institutes in Europe: Meteo-France/CNRM, Austrian Research Centre Seibersdorf (ARCS), Instituto Universitario di Architettura, Italy (IUAV), Dutch National Institute for Public Health and the Environment (RIVM), Swedish Space Corporation (SSC), Space Applications Institute of the Joint Research Centre, Italy (SAI/JRC), Geodan and DLO-Winand Staring Centre (SC-DLO). The institutes RIVM, ARCS and CNRM are also involved as end-user to apply the land cover data into their environmental and climate models.

5.2 Past results with AVHRR land cover mapping

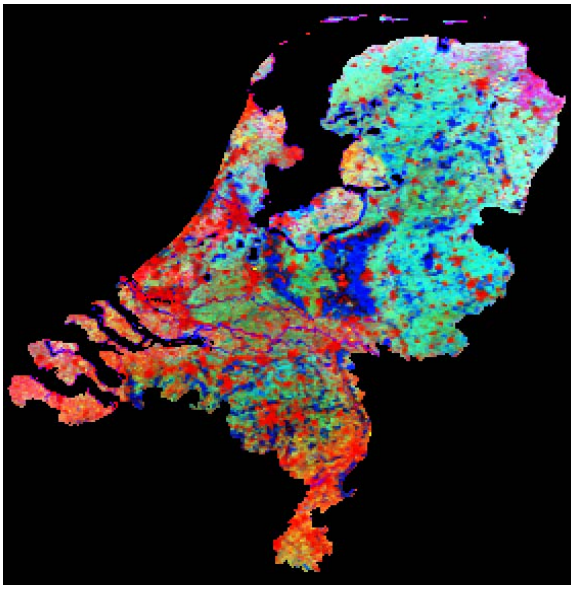
Since 1993, various pilot studies (Mücher et al., 1994; Mücher et al., 1996) have been implemented in the framework of the NRSP to assess the use of 1 km AVHRR data for land cover mapping. In particular, improvement of the spatial accuracy of the ten-minute pan-European land use database (ELU-1) as described in §1 was investigated. At first the Netherlands and Eastern Spain were selected as test sites.

Supervised classification of several cloud-free daily AVHRR images for 1989 of the Netherlands, using the AVHRR channels 1, 2, 3 and/or 4, indicated that main land cover classes such as grassland, arable land, forest and water could be easily identified (Mücher et al. 1994). In early spring, there is a significant difference in spectral reflectance between grassland and arable land because most arable land is still bare. Exceptions are areas covered with winter wheat, which will be confused with grassland. However, as winter wheat is harvested around the end of July, wheat can be separated from grassland using data acquired after July. A second source of confusion is the distinction between bare soil and urban areas in early spring. This confusion can be reduced using data from late spring or early summer, where most arable land is already covered by vegetation and so urban areas can be distinguished more easily (fig. 5.1). This means that several multi-spectral images are needed over the growing season for detection of main land cover types.

Unsupervised classification (e.g., ISODATA, Tou and Gonsalez, 1974) of monthly MVCs for the period March to September 1989 was found to be of limited value for the Netherlands (Mücher et al. 1994). Forested areas were difficult to identify and most NDVI profiles were highly disturbed by frequent cloud coverage. Besides, NDVI composites comprise only information from channel 1 and 2, ignoring valuable information in the other AVHRR channels. Moreover, most MVCs had a blurred effect due to the restricted geometric accuracy of individual images, and therefore lost spatial detail on specific features and classes such as urban areas. The main conclusion was that supervised classification of several ‘cloud-free’ multi-spectral AVHRR images at various stages of the growing season provided the best classification result using the CORINE land cover database as reference. The classification result of each single scene was integrated in a Geographic Information System (GIS) in which the decision rules were defined explicitly, leading to the final classification result (Fig. 5.3).



23 May 1989



5 July 1989

Fig. 5.1 Figure on the left shows an AVHRR multi-spectral colour composite acquired on 23 May 1989 (RGB: 1/2/3). At this time period most arable land is still bare. Orange/red colours indicate arable land or urban area. Dark blue colours indicate forest and light green colours indicate grassland. Figure on the right shows an AVHRR multi-spectral colour composite acquired on 5 July 1989 (RGB: 1/2/3). At this time period all arable crops cover the surface completely. There is no spectral difference between grassland and arable land. All urban areas can now be detected.

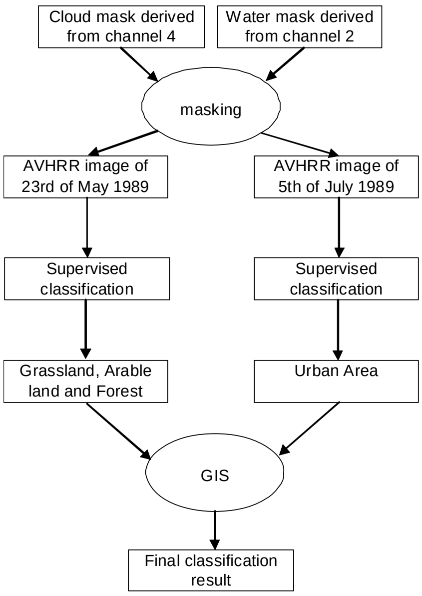


Fig. 5.2 The classification methodology as proposed by Mücher (1994) in which multi-spectral AVHRR scenes at specific stages over the growing season (spring/summer/autumn) are combined to identify major land cover types.

For the Netherlands the AVHRR-derived land cover classification has been compared with the National Land Cover Database of the Netherlands (LGN-1) (Thunnissen et al., 1993; Thunnissen et al., 1996. The LGN database is a land cover database with a spatial resolution of 25m that is updated approximately every 4 years. It is based on Landsat TM images of 1986 and was compiled using an automatic classification procedure resulting in 18 different classes. The overall accuracy of LGN-1 was around 70% and this has been improved up to 85% in successive versions of LGN. In order to allow a comparison with the AVHRR classification, the reference database LGN-1 has been recoded and aggregated to a 1 km spatial resolution (Fig. 5.3).

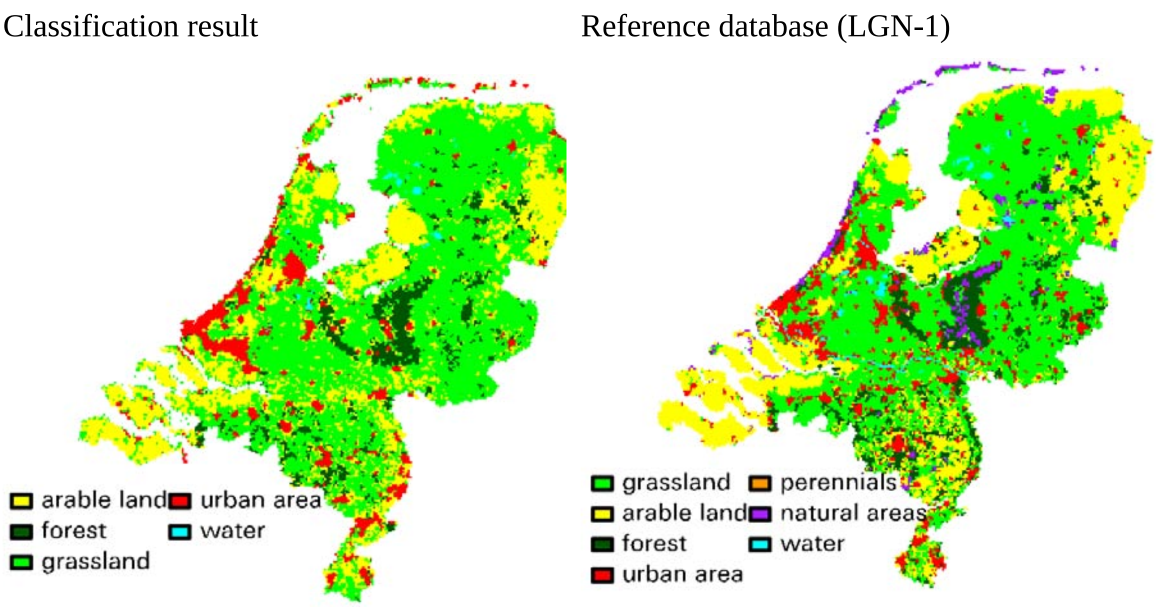


Fig. 5.3 Figure on the left side shows the classification result for the Netherlands. The results is based on combined use of a AVHRR image of 23 May 1989 and an image of 5 July 1989. Figure on the right side shows reference database. The National Land Cover Database of the Netherlands (LGN) is based on Landsat TM images of 1986 with a spatial resolution of 25m. To be able to make a comparison with the AVHRR classification result, the reference database has been recoded to seven main classes and aggregated to a spatial resolution of 1.1 km.

Both figures in Fig. 5.3 show the same land cover patterns. Quantitative validation is limited by the geometrical inaccuracy of the AVHRR derived land cover database. A cross tabulation between the two databases showed reliabilities from 44% for inland water to 80% for grassland (Mücher et al., 1994). The accuracy is the probability for a reference sample to be correctly classified; the reliability is the probability that a sample from the classified image actually represents that category (Story and Congalton, 1986). For eastern Spain the classification results were less satisfactory. One reason for this is that in Spain various regions, e.g., the Mediterranean region, have a very heterogeneous land cover which is difficult to classify with AVHRR data. In addition, the accuracy of ELU-1 and the AVHRR-derived classification were compared for the Netherlands using LGN-1 as the reference database. As expected, the spatial accuracy of the ELU-1 was significantly lower than that of the AVHRR derived land cover database. The mean difference (difference in percentage per 10-minute pseudo grid divided by number of grids) between ELU-1 and the LGN-1 database was 23.3% for arable land, 13.0% for forest and 20.3% for grassland, while the mean difference between the AVHRR-derived land cover database and LGN-1 was respectively 6.3%, 1.6% and 6.2% (Mücher et al., 1994). It was concluded that applying AVHRR-derived land cover data would improve the ELU-1 considerably.

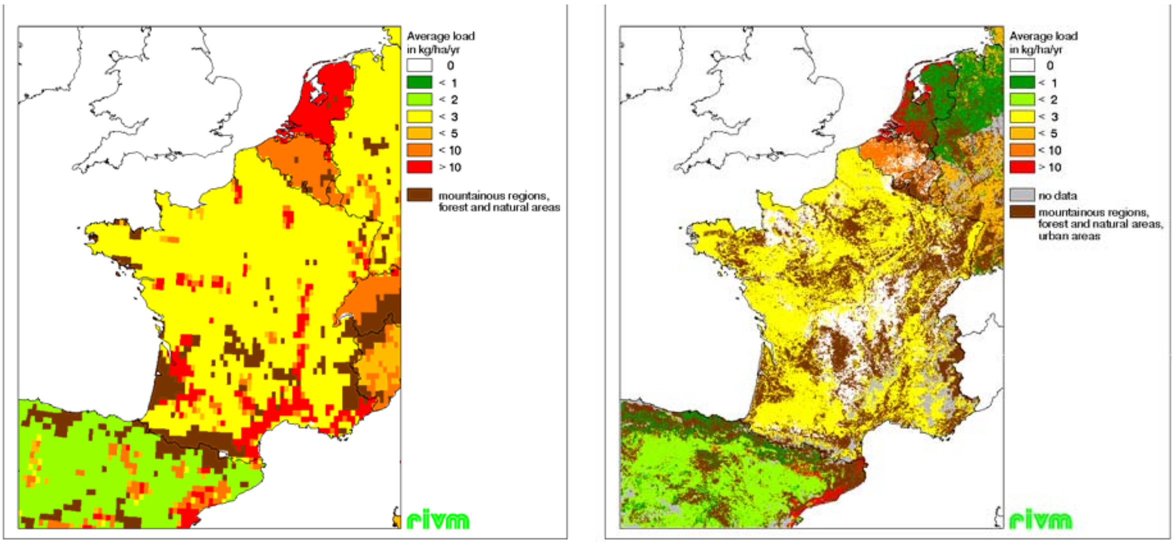


Fig. 5.4 Figure on the left shows the average pesticide load (kg /ha /year) on arable land, permanent crops and grassland using the RIVM's ten minute pan-European land use database (ELU-1). Statistics of pesticides sold per crop and per country have been obtained from Eurostat. Figure on the right shows average pesticide load (kg /ha /year) on arable land and grassland using the 1 km AVHRR-derived land cover database. Statistics of pesticides sold per crop and per country have been obtained from Eurostat.

When the AVHRR-derived land cover database was extended to France and its immediate surroundings, the database and ELU-1 were both used as an input in a pesticide load model designed by RIVM, and results were compared (Fig. 5.4). An important conclusion was that load maps using AVHRR-derived land cover data as input are to be preferred (Mücher et al., 1996). Land use databases such as ELU-1 suffer from averaging the pesticide load due to a lower spatial accuracy. The main disadvantage of the AVHRR-derived land cover database compared with ELU-1 was the absence of the class permanent crops, e.g., vineyards, which receive high pesticide doses.

5.3 Towards an operational methodology for land cover mapping

Using only the multi-spectral (supervised) classification approach as described above is not feasible for pan-Europe due to frequent occurrence of clouds. Therefore, decision keys should be developed that exploit both the uses of multi-temporal composites and multi-spectral AVHRR scenes at specific dates. Within the framework of PELCOM a fast-track classification methodology has been developed that is applicable for pan-Europe (Fig. 5.5). The PELCOM classification scheme consists of nine major land cover classes: forest, grassland, rainfed arable land, irrigated land, urban area, permanent ice and snow, barren land, wetlands and water bodies. The fast-track classification methodology is now discussed.

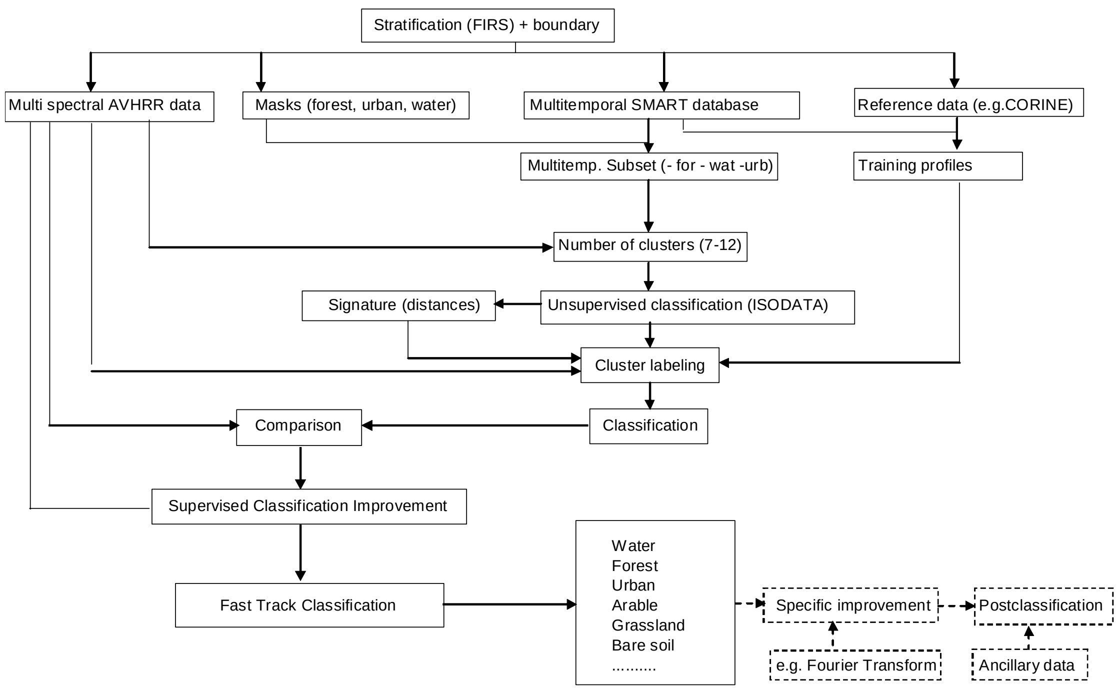


Fig. 5.5 Schematic overview of PELCOM fast-track classification approach

5.3.1 Stratification

Working on such a large area as pan-Europe makes stratification a prerequisite. The purpose of any stratification is to divide the area of interest into strata that are more homogeneous in LULC and in phenology than the area as a whole and to reduce the impact of climatic gradients (Thunnissen et al. 1993; DeFries and Townshend, 1994; Mücher et al. 1996). Successive classification of different strata enables improvement of the discrimination process on difficult classes and reduces the number of misclassifications due to spectral confusion (Thunnissen et al., 1993). A stratified approach improves the accuracy and detail of the classification. In the framework of the FIRS (Forest Inventory by Remote Sensing) project of SAI/JRC (Space Applications Institute of the Joint Research Centre), a regionalization and stratification was made for European forest ecosystems (EC, 1995; Kennedy et al. 1996). On the first level Europe has been divided into a small number of ecosystem regions based on geofactors, such as climate, soil and topography. On the second level the division has been guided by biofactors (e.g., potential forest species) to identify the various forest ecosystems. Regional expert judgement indicated that the 115 strata (level 2) constituting the output of the FIRS stratification were preferred over other stratification's for the PELCOM classification purposes. The 115 strata have a total surface of 9 736 231 km^2, a mean surface of 84 663 km^2, a minimum surface of 3329 km^2 and a maximum surface of 855 261 km^2. In regions like the Alps with a large variance in topography the strata are the smallest, while in eastern Europe the strata are much larger. In a few cases the strata are aggregated or divided into several strata depending on the experience of the interpreter.

5.3.2 Data pre-processing

A major AVHRR data source is the MARS (Monitoring Agriculture by Remote Sensing) archive at the Space Applications Institute of the Joint Research Centre in Ispra, Italy (SAI/JRC). The archive has two components: SPACE (Software for Processing AVHRR data for the Communities of Europe) generates daily AVHRR mosaics, while the SCAN system extracts parameters, such as NDVI from daily mosaics (Millot 1995; SAI/JRC 1996; Roy, 1997). Presently, SPACE processes AVHRR 10 bit raw data in the SHARP-1† format (ESA, 1989). SPACE calibrates the data, detects clouds, corrects channels 1 and 2 for atmospheric effects, navigates the data using an orbital model and automatically detects ground control points (GCPs) on the coast and outputs the five channel data in a given projection over a predefined area (Kerdiles, 1996). Unfortunately, GCPs are frequently lost due to cloud coverage, which causes low geometric accuracy. For that reason, MVCs derived by SCAN did not meet the required quality. Instead, a multi-temporal data set was processed by the SMART (Smoothing AVHRR Reflectances Technique) algorithm, which has been developed by SAI/JRC. The algorithm contains the following steps (Loudjani et al., 1998): missing data, high scan angle rejection; scan angle effect correction; cloud screening; sharp variation rejection; weighted moving average smoothing; and time interpolation. Images with a low geometric accuracy are ignored due to the sharp variation rejection. The algorithm processes the smoothed profiles for the visible and near-infrared channels and gives the end-user the opportunity to choose a specific vegetation index. From the SMART database the NDVI profiles are derived with a temporal resolution of one day for each pixel and these profiles form the basic data set in the classification.

5.3.3 Masking

As mentioned before in §2, forests are generally not satisfactorily identifie ed in a clustering procedure using NDVI profiles (Champeaux et al., 1998). In a supervised classification forests can be identified on individual multi-spectral scenes using AVHRR channels 1, 2 and 3 (ESA, 1992; Mücher et al., 1994). However, such an approach is hampered for pan-Europe due to the frequent occurrence of clouds. Therefore, identification of forests was implemented on basis of thresholding the synthesis of visible reflectance of AVHRR channel one (Champeaux et al., 1998; Champeaux et al., 2000). The result was a forest map with a reliability of 80% and an accuracy of 60% when compared with the CORINE land cover database (for this purpose aggregated to a 1.1km spatial resolution and a 75% homogeneity threshold). Additional masks were produced for water bodies and urban areas by integration of various ancillary sources, such as the Digital Chart of the World (DCW) and the CORINE land cover database. All three masks (forests, water and urban areas) were applied on the SMART database before any classification was carried out.

5.3.4 Classification methodology

For each stratum seven to twelve clusters are defined depending on its size and the diversity of land cover types expected for the stratum in question. Assessment of an adequate number of clusters is based on visual interpretation of multi-spectral AVHRR scenes, training samples derived from the CORINE land cover database and/or statistical data from the region. An unsupervised classification (ISODATA) is performed on the SMART data (daily NDVI profiles), resulting in a set of spectral signatures for each cluster. These clusters do not necessarily represent the required land cover classes, but might reflect heterogeneous areas consisting of several land cover types. In order to assess those clusters that represent homogeneous land cover types the subsequent classification is based on the first and second spectral distance. For that purpose the individual signatures from the signature file are used for successive supervised classifications and the main output of these classifications are the spectral distance files (minimum distance is used as parametric rule). These distance files contain the minimum distance to the respective signature of a cluster on a pixel basis. For each pixel the two smallest distances will be retrieved and the related signatures/cluster numbers will be assigned to two image layers, i.e. each pixel will receive a first and a second ‘probability’ cluster number. In addition, the ratio between the first and second distance is computed as D1/D2 and assigned to a third layer. The ratio between the distances can be used as a measure for the ‘purity’, i.e. homogeneity, of the single pixel and is valuable information to the end-user.

The clusters with a minimum spectral distance (from layer one) are then compared with reference data. Training sets are derived from homogeneous areas of the CORINE land cover database, i.e. areas of one or several AVHRR pixels that contain a high percentage of one, and only one, CORINE land cover class. First, all homogenous clusters that correspond to one specific land cover class of the reference data set are labelled. In an ideal case each cluster would represent exactly one land cover class and the classification would be finished. In reality some clusters do not correspond to one land cover class. The reason for this is that these cluster signatures are spectrally located between two or more training sets, i.e. they are heterogeneous clusters. These heterogeneous clusters can be defined by the ratio between the distances from real clusters. Classification of pixels that fall in such a virtual cluster can be performed by simple decision rules. A rule such as ‘find all pixels that have a first and second class assigned n or m and a ratio close to one’ would create a ‘virtual’ cluster that is located between cluster m and cluster n. In our case those pixels with a ratio close to one for the remaining heterogeneous clusters will receive the cluster number from layer two (second most likely cluster number) if this cluster number has been labelled in layer one as a homogeneous cluster.

For each stratum the results from the unsupervised classification will be compared interactively with the visual information in the multi-spectral AVHRR scenes. The information in either the multi-temporal or multi-spectral AVHRR data will be strongly influenced by the quality of the concerned data and the specific land cover features present in the specific stratum. If specific features, e.g., linear features, and specific land cover classes are only visible in the multi-spectral AVHRR scenes they will be derived from these scenes by a supervised classification. After the fast-track classification specific improvements will be made, amongst others by integration with thematic ancillary in a post-classification procedure.

5.3.5 Classification result

Fig. 5.6 shows the preliminary classification result according to the PELCOM fast-track approach as described above. The SMART data, i.e. NDVI time series, are in this case from 1991. The final land cover database will be based on AVHRR data from 1997. In this example the AVHRR-derived land cover database (Fig. 5.6) covers, with approximately 460.000 km^2, a large part of western Europe. For this area the database contains eight land cover classes: urban areas (4.3%), arable land (58.3%), permanent crops (1.7%), pastures (11.4%), forest (21.5%), natural grassland (0.9%), bare soil (1.5%) and water (0.4%).

An assessment of reliability and accuracy has been carried out for the classification using the CORINE land cover database as reference. For this purpose the CORINE land cover database has been recoded from 44 classes (level 3) to eleven main classes (more or less according to the hierarchical CORINE nomenclature). After this the database was aggregated to a spatial resolution of 1.1km using a majority filter. Only those pixels with a majority count of more than 75% have been used in the evaluation. Because the land cover classes urban areas and water are derived from ancillary data, these classes are not taken into consideration in the error matrix (Table 5.1). Forest and arable land cover 80% of the area and have an acceptable reliability of 77.8 and 69.6% respectively. If one adds the CORINE land cover class ‘heterogeneous agricultural land’ to the CORINE class ‘arable land’, the reliability of the classified class arable land becomes 80.2%. Permanent crops and natural grassland cover only 2.6% of the area and have a very low reliability of 38.2 and 30.2% respectively. The same trend is present for the accuracies.

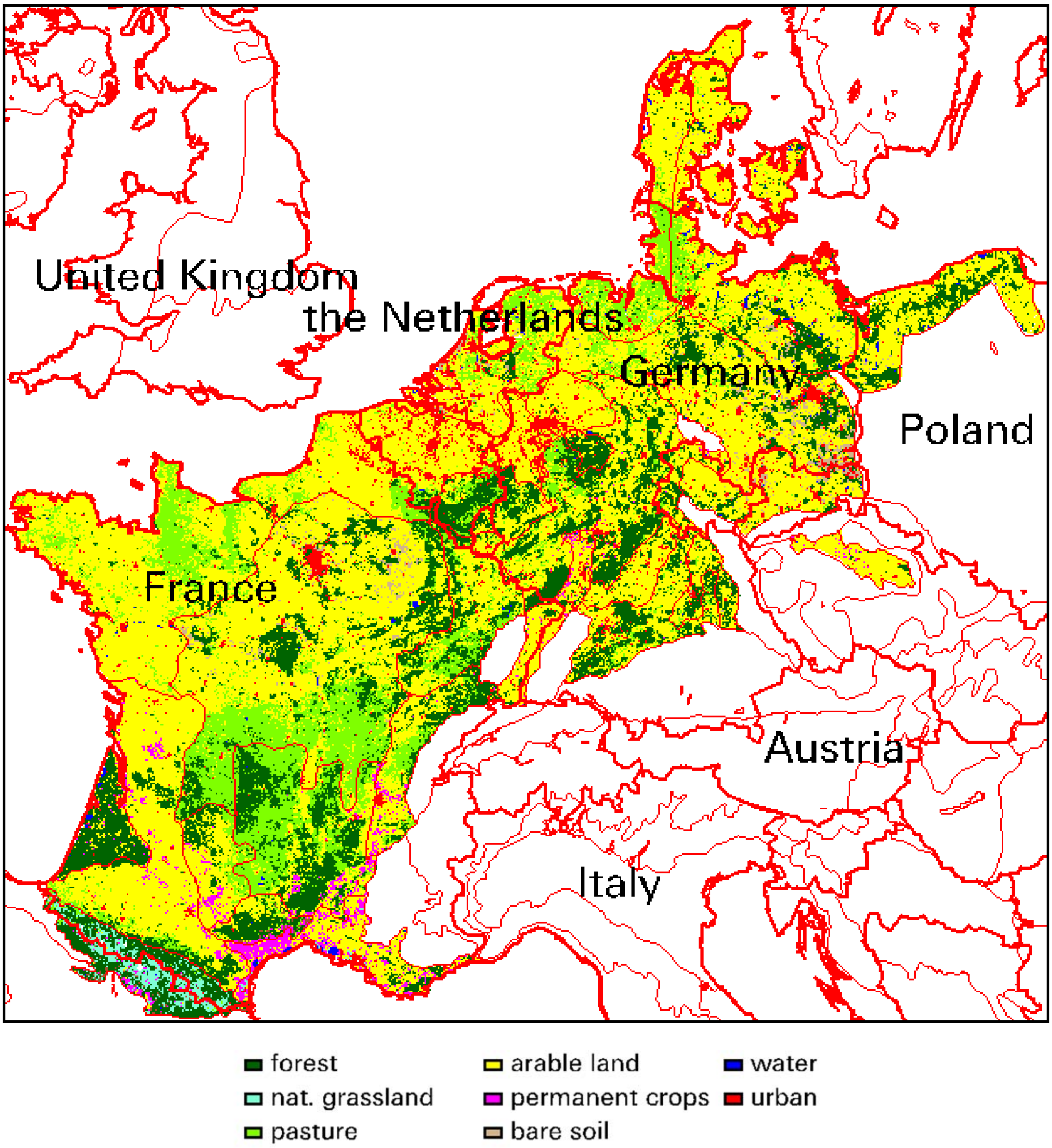


Fig. 5.6 AVHRR-derived land cover database for a part of Western Europe according to the PELCOM fast-track classification methodology.

The CORINE land cover class 'heterogeneous agricultural land' has been classified for 71 % as arable land, which is reasonable.

Table 5.1 Error matrix showing the results for the AVHRR-derived land cover classes. The CORINE land cover database is used as reference and has been recoded to 11 major classes (urban areas and water are not shown below) and aggregated to a spatial resolution of 1.1 km. Numbers in the matrix express number of pixels.

	Classified data							
Reference data (CORINE)	arable land	permanent crops	pasture	forest	natural grassland	bare soil	total	Accuracy (%)
Arable land	161094	1658	6010	9738	58	3605	182163	88,4
Permanent crops	3329	2566	121	290	69	62	6437	39,9
Pastures	13617	41	24506	3207	115	145	41631	58,9
Heterogeneous. agr. land	24651	658	6167	2926	89	191	34682	
Forest	25881	815	7964	66628	1140	1470	103898	64,1
Natural grassland	566	235	372	1184	1112	161	3630	30,6
Shrub and/or herbaceous vegetation	1672	607	166	1390	375	188	4398	
Open spaces with little or no vegetation	78	100	11	211	666	17	1083	
Wetlands	615	41	82	110	60	37	945	
Total	231503	6721	45399	85684	3684	5876	378867	
Reliability (%)	69,6	38,2	54,0	77,8	30,2			

So far it can be concluded that only the land cover types arable land and forest, which are responsible for 80% of the study area, can be classified with an acceptable reliability and accuracy.

5.4 Approach towards monitoring

It is a prerequisite for applications of environmental monitoring models that the land cover database can be easily updated. In other words, one should be able to establish where certain land cover changes have taken place over a certain period of time. The problem of the above-mentioned approach towards land cover mapping is that it cannot be used directly for change detection. First, the authors are convinced that the overall accuracy of AVHRR-derived land cover maps at a continental or global scale will not exceed 70%. This means that if two land cover maps are compared one will not find areas of change, but instead noise as a limitation of the mapping accuracy. Second, most land cover changes in Europe are highly fragmented and do not exceed areas of more than a few square kilometres at one place. This means that additional techniques have to be developed to detect land cover changes for Europe as a whole.

5.4.1 Digital techniques for change detection

Digital change detection algorithms can be summarized in two broad categories to which different definitions have been attached that vary in complexity and, to a certain extent, in coverage (Coppin and Bauer, 1996). Singh (1989) differentiates between these approaches as follows:

1. comparative analysis of independently produced classifications for each of the image dates (often known as ‘post-classification change detection’);
2. simultaneous analysis of multi-temporal data.

In terms of change detection analysis, post-classification techniques are perhaps the easiest to implement because two independently produced information layers are compared on a pixel-by-pixel basis at a thematic level. Change maps can be derived quickly, as ‘confusion’ (or ‘contingency’) matrices can show a summary of all changes. The accuracy of such a change map is, however, dependent on the accuracy of each of the single-date classifications—it is the product of these two values. Since an error on either date will give a false indication of change, a large number of erroneous change indications will typically be produced.

The alternative to post-classification change detection is the use of original image data. Changes are detected by comparing either multi-date channels or transformed image data. The simplest method is image differencing, where the image taken at time t1 is subtracted pixel-by-pixel from that taken at time t2. The resulting ‘difference’ image is assumed to show high absolute pixel values in areas of change, whereas pixels representing unchanged areas should have values around zero. This method is easy to apply but has a number of drawbacks. First, the resulting differences might not only be due to land cover/land use change, but also to external influences caused by differences in atmospheric conditions, differences in Sun angle or differences in soil moisture. Second, the nature of change is difficult to detect as the method provides only differences of the radiance in different wavelengths. Third, the decision which threshold to use to separate ‘change’ from ‘no change’ is highly subjective and scene-dependent. Application of similar approaches such as regression analysis of the two images, image rationing and comparison of image indices can reduce the impact of the external influences. However, a clear interpretation of the detected changes is still difficult to achieve (Green et al., 1994; Lambin and Strahler, 1994).

We therefore propose a different technique that offers many of the advantages of the traditional approaches without their attendant disadvantages. This technique is a linear unmixing algorithm, which applies a linear transformation to the multispectral channels of an image to derive continuous thematic layers, each pertaining to one, and only one, land cover type (Adams and Smith, 1986; Settle and Drake, 1993). Differencing of multi-temporal fraction images representing the same land cover type will result in thematic change images. A detailed discussion follows below.

5.4.2 Linear unmixing

The aim of linear unmixing is to estimate the proportion of each land cover type to each pixel in the image. This results in a series of images, each having the size of the original image, giving each a map of the concentration of a different cover type across the scene (Settle and Drake 1993). Unmixing has already been applied to coarse resolution data in a number of studies, especially for vegetation monitoring. While some were based on the first two channels (Quarmby et al., 1992; Hlavka and Spanner, 1995) others used the reflective part of the third channel as well (Holben and Shimabukuro, 1993; Shimabukuro et al., 1994). The first four AVHRR channels were used by Cross et al. (1991) for unmixing to differentiate tropical forest from non-forest, with satisfactory results compared with TM images. More recent studies (Bastin, 1997; DeFries et al., 1997) reflect the ongoing interest in subpixel analysis using coarse resolution satellite imagery.

In the following case study, the unmixing procedure described above is applied to an AVHRR image. Although some bands do not lie in a spectral region that follows the underlying assumption of linearity, it will be shown that the method is still suitable for acquisition of basic land cover information.

5.4.3 Case study for the Netherlands

One AVHRR image, sensed on 25 July 1995, was available for this study. Only the first four bands were used for the analysis as the fourth and fifth band, both in the thermal region, have a correlation greater than 99%. Pre-processing was carried out by SAI-JRC (SAI-JRC 1996).

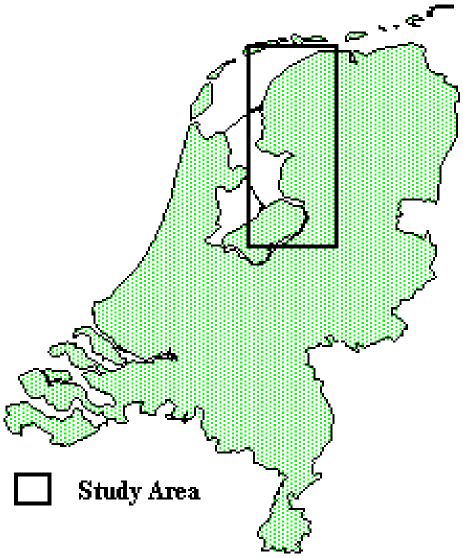


Fig. 5.7 Location of the study area in the Netherlands concerning the linear unmixing technique.

The study area lies in the north of the Netherlands, covering the western part of the Friesland province (Fig. 5.7). It is an agricultural area with mainly grassland and arable land (see also Fig. 5.3). The area measures approximately 70 km x 110 km, of which 35% is covered by water. Water was masked out on the basis of a mask supplied by SAI-JRC, and will only be considered if it appears in pixels, not defined as water by the pre-processing routine.

Endmembers were defined by selecting appropriate pixel vectors from the image, one for each land cover type. They represent grassland, urban areas, arable land and forest. These endmembers were used to transform the satellite image, resulting in four fraction images, one for each land cover type defined. As only four channels were available for each image and as many endmembers were defined, no root mean square (rms) error was calculated. In order to examine the validity of the results, the fraction images were compared with the National Land Cover Database of the Netherlands, the LGN-2 database (Thunnissen and Noordman, 1996)—the updated version of LGN-1 (see §2). The data set covers 24 different classes (excluding water) with a spatial resolution of 25 x 25 m2. The classes were aggregated to four main classes representing grassland, urban areas, forest and arable land. To visually compare the fraction images with the LGN-2 database, pseudo fraction images were created by resampling the database to 1.1km and calculating the proportion of each class within each pixel.

Fig. 5.8 – Fig. 5.11 show the fraction images derived from the AVHRR image as well as the pseudo fraction images, derived from the LGN-2 database. Light shades signify a high proportion within a pixel and dark shades indicate a low proportion.

It can be seen in Fig. 5.8 that grassland is the most prominent land cover in the study area. Both fraction images show very similar distributions. Also, the results for urban areas (Fig. 5.9) correspond very well. The most notable difference is in the extreme south of the fraction image. This is an area with mainly natural vegetation, i.e. not defined by any of the endmembers. However, a combined analysis of more than one fraction image would make it possible to separate it from urban areas. The fraction image for forest shows the most notable differences (Fig. 5.10). It is especially near shorelines and around inland water areas that high concentrations of forest appear. This is due to the fact that water could not be masked out altogether, leaving pixels with a mixture of water and other land cover. As water was not defined as an endmember, it was apparently picked up by the forest endmembers, signalling spectral similarities. This makes it possible to identify those pixels which cannot be analysed any further because of water. According to the LGN-2 database, arable land is concentrated in the north and south-west of the study areas. This is confirmed by the results of the unmixing procedure, showing the same concentrations (Fig. 5.11). In order to carry out a quantitative evaluation, both sets of fraction images were classified according to the same decision rule. Each pixel was assigned to the land cover type having the highest proportion in this pixel, thus allowing the calculation of an error matrix (Table 5.2). The overall accuracy of the classification is 82.0%; the highest accuracy was found for grassland (84.5%) and the lowest for urban areas (44.7%). Grassland has also the highest reliability at 93.0% and forest the lowest at 37.8%. The largest confusions occur between grassland and agricultural areas and between forest and grassland. As only one satellite image was analysed, these confusions do not come as a surprise and should reduce when more images are included in the analysis.

Overall, it can be seen that the results of the unmixing procedure are very consistent when compared with the reference data. The linear unmixing procedure allows a quick recovery of basic information about the distribution of different cover types in the form of thematic layers. These layers may be the starting point for a number of different applications, ranging from determining overall proportion to classification and change detection.

LGN-2 (Reference) Classification result

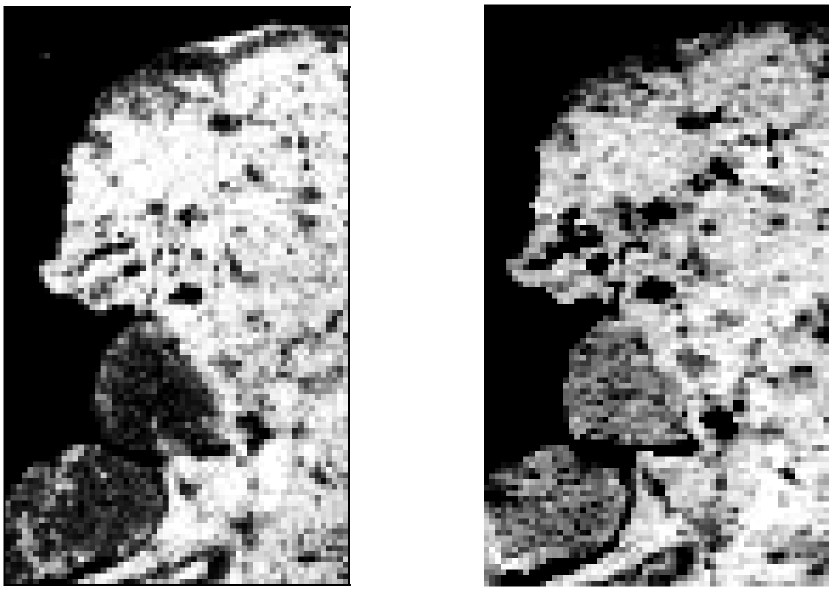


Fig. 5.8 Fraction images for <u>grassland</u> obtained by linear unmixing. The left fraction image is derived from the reference database LGN-2. The right fraction image is derived from the classified AVHRR image acquired on 25 July 1995.

LGN-2 (Reference) Classification result

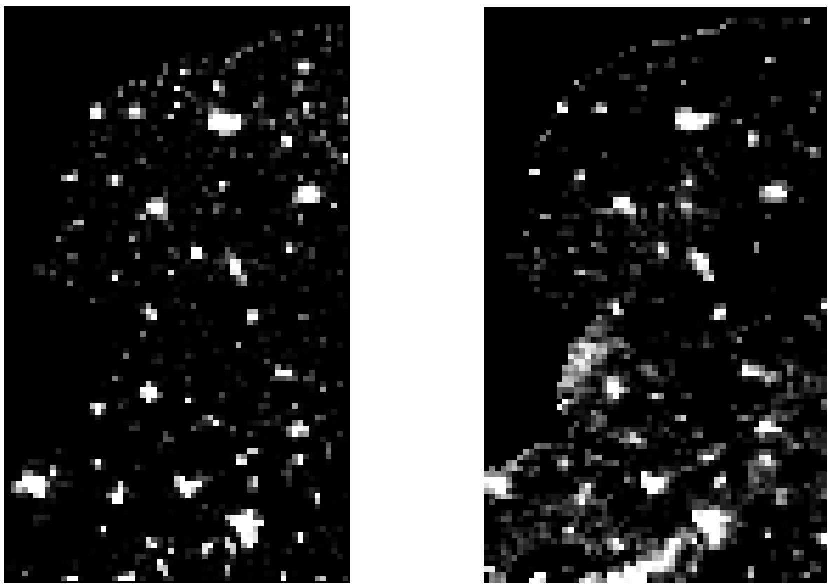


Fig. 5.9 Fraction images for <u>urban areas</u> obtained by linear unmixing. The left fraction image is derived from the reference database LGN-2. The right fraction image is derived from the classified AVHRR image acquired on 25 July 1995.

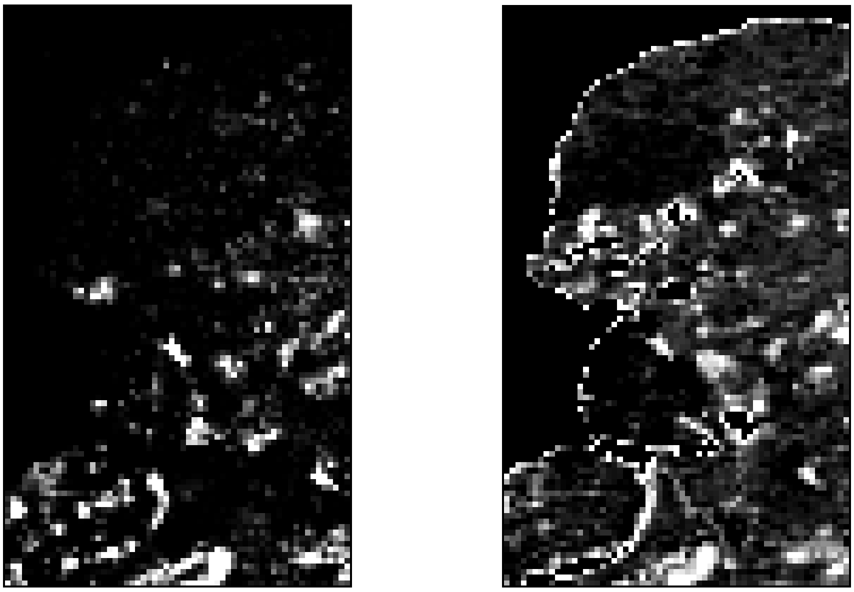


Fig. 5.10 Fraction images for forest obtained by linear unmixing. The left fraction image is derived from the reference database LGN-2. The right fraction image is derived from the classified AVHRR image acquired on 25 July 1995.

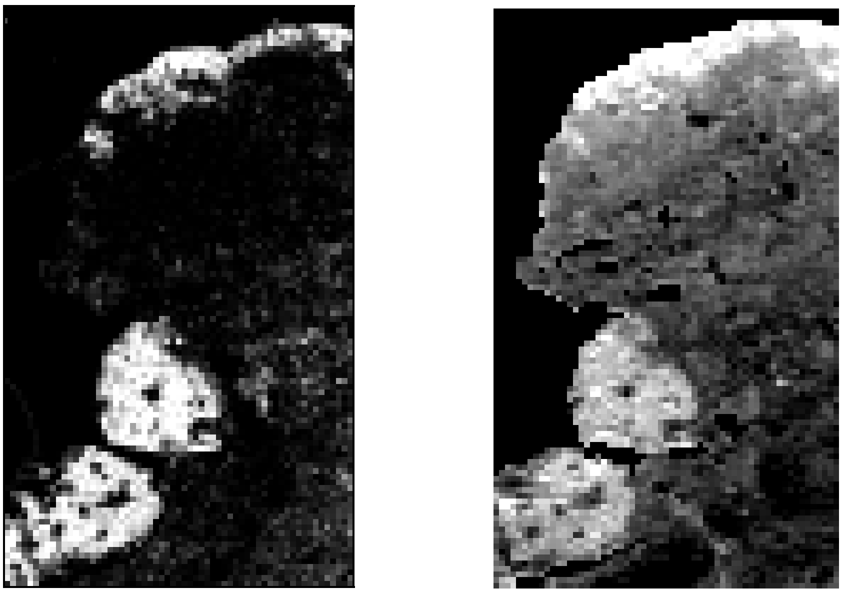


Fig. 5.11 Fraction images for arable land obtained by linear unmixing. The left fraction image is derived from the reference database LGN-2. The right fraction image is derived from the classified AVHRR image acquired on 25 July 1995.

Table 5.2 Error matrix showing the results for the AVHRR-derived land cover classes. The CORINE land cover database is used as reference and has been recoded to 11 major classes (urban areas and water are not shown below) and aggregated to a spatial resolution of 1.1 km. Numbers in the matrix express number of pixels.

	Reference data					
Classified data	Grassland	Urban	Forest	Agriculture	Total	Reliability (%)
Grassland	*2865*	40	109	66	3080	93,02
Urban	40	*59*	2	2	103	57,28
Forest	175	4	*116*	12	307	37,79
Agriculture	312	29	31	*701*	1073	65,33
Total	3392	132	258	781	4563	
Accuracy (%)	84,46	44,70	44,96	89,76		
Overall Accuracy (%)		81,99				

5.4.4 Potential of fraction images for change detection

Fraction images are the result of a transformation showing the proportions of spectrally pre-defined land cover types for each pixel. A direct comparison of fraction images calculated from satellite images recorded at different dates makes it possible to highlight those areas where the proportion of the different land cover types has changed. Using precisely georeferenced images, areas of change may be highlighted by a pixel-per-pixel comparison (Kressler and Steinnocher, 1999). However, even without this kind of agreement, basic information about broad developments may already be gained by a visual comparison of fraction images calculated from images recorded at different dates. A more detailed analysis may then be limited to those areas highlighted as change. This focus on areas where changes are most likely to have occurred allows a more efficient use of available resources.

As some of the AVHRR channels do not follow the underlying assumption of linearity, quantitative information going beyond the statement that a certain class occurs or does not occur within a pixel, cannot be made reliably. The full potential of fraction images for monitoring changes may be realized with the development of new coarse resolution sensors, which not only utilize channels in the visible and near and middle infrared part of the spectrum (e.g., SPOT Vegetation) but also have improved geo-referencing capabilities.

5.5 Conclusions and outlook

This paper has described an improved stratified and integrated classification methodology to map major land cover types for pan-Europe using NOAA-AVHRR satellite and additional geographic data, in the framework of the European Union funded PELCOM project. Both multi-temporal NDVI profiles and multi-spectral AVHRR scenes are used as input in the classification procedure, thus exploiting the advantages of both data types. Due to the limited accuracy of identifying forests on basis of unsupervised clustering of NDVI time series, the identification of forests was implemented on basis of thresholding the synthesis of the visible reflectance of channel one (Champeaux et al., 1998, 2000). In addition, urban areas and inland water were masked on basis of ancillary data. The classification scheme will be used to establish a land cover database of pan-Europe with a 1km spatial resolution that fulfils the needs for environmental modelling. Such a database requires identification of major land cover types such as forests, grassland, arable land and water. Unfortunately, the first classification results indicate that only forest and arable land, which are responsible for 80% coverage of the test area, can be classified with an acceptable reliability and accuracy.

A restriction of AVHRR-derived land cover maps is the low overall accuracy, which in general does not exceed 70%. Comparing two AVHRR-derived land cover maps of different dates for change detection will result in change maps of even lower accuracy. Therefore, additional techniques are suggested for change detection. A direct comparison of fraction images, calculated from satellite images recorded at different dates, makes it possible to highlight those areas where the proportion of the various land cover types has changed. The fraction images are the result of linear unmixing techniques and can be regarded as continuous thematic layers. Because the maximum number of endmembers and thus the number of thematic fraction images is limited by the number of spectral channels of the satellite image, a stratified approach based on existing land cover data sets and/or additional geographic information is a prerequisite.

Besides the demonstrated application of the AVHRR-derived land cover database in estimates of pesticide loads, such a database could play an important role in, for example, biodiversity research related to fragmentation and potential habitat studies or biogenic emission inventories on a European scale. Unfortunately, the use of AVHRR data is limited in the identification of classes such as wetlands and forest subclasses within the European context.

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References

Adams, J.B., Smith, M.O., 1986. Spectral mixture modelling: a new analysis of rock and soil types on the Viking Lander 1 Site. J. Geophys. Res., 91, 8098–8112.

Bastin, L., 1997. Comparison of fuzzy c-means classification, linear mixture modelling and MLC probabilities as tools for unmixing coarse pixels. Int. J. Remote Sens., 18 (17), 3629-3648.

CEC, 1994, CORINE Land Cover Technical Guide. European Union, Directorate-General Environment, Nuclear Safety and Civil Protection, Office for Official Publications of the European Communities, Luxembourg. EUR, ISSN 1018-5593, ISBN 92-826-2578-8.

Champeaux, J.L., Arcos, D., Bazile, E., Giard, D., Noilhan, J. 1998. Vegetation parameters maps over Europe using NOAA/AVHRR in meteorological models. Int. Geosci. Remote Sens. (IGARSS), 3, 1726-1728.

Champeaux, J.L., Arcos, D., Bazile, E., Giard, D., Goutorbe, J. P., Habets, F., et al., 2000. AVHRR-derived vegetation mapping over Western Europe for use in Numerical Weather Prediction models. Int. J. Remote Sens. 21 (6-7), 1183-1199.

Coppin, P.R., Bauer, M.E., 1996. Digital Change Detection in Forest Ecosystems with Remote Sensing Imagery. Remote Sensing Reviews 13 (3-4), 207-234.

Cross, A. M., Settle, J.J., Drake, N.A., Paivinen, R.T.M., 1991. Subpixel measurement of tropical forest cover using AVHRR data. Int. J. Remote Sens. 12 (5), 1119-1129.

DeFries, R., Hansen, M., Steininger, M., Dubayah, R., Sohlberg, R., Townshend, J., 1997. Subpixel forest cover in central Africa from multisensor, multitemporal data. Remote Sens. Environ. 60 (3), 228-246.

Defries, R.S., Townshend, J.R.G., 1994. NDVI-derived land cover classifications at a global scale. Int. J. Remote Sens. 15 (17), 3567-3586.

EC, 1995. Regionalization and Stratification of European Forest Ecosystems, Internal Special Publication of the Joint Research Centre of the European Commission. S.I.P.95.44, European Commission Joint Research Centre, Institute for Remote Sensing Applications, , Italy, p. 69.

ESA, 1989. SHARP-1, Technical Specifications of CCT format. European Space Agency- Earthnet Programme Office, Frascati, Italy.

ESA, 1992. Remote Sensing Forest Map of Europe. ESA/ESTEC, ISY Office, Noordwijk, the Netherlands.

Green, K., Kempka, D., Lackey, L., 1994. Using remote sensing to detect and monitor land-cover and land-use change. Photogramm. Eng. Rem. S. 60 (3), 331-337.

Häusler, T., Saradeth, S., and Amitai, Y., 1993. NOAA-AVHRR forest map of Europe. Proceedings of the International Symposium Operationalization of Remote Sensing, ITC, Enschede, the Netherlands, 19-23 April 1993, pp. 37–48.

Hlavka, C.A., Spanner, M.A., 1995. Unmixing AVHRR imagery to assess clearcuts and forest regrowth in Oregon. IEEE Transactions on Geoscience and Remote Sensing 33 (3), 788-795.

Holben, B.N., Shimabukuro, Y.E., 1993. Linear mixing model applied to coarse spatial resolution data from multispectral satellite sensors. Int. J. Remote Sens. 14 (11), 2231-2240.

Jongman, R. H. G., 1996, Ecological and Landscape consequences of land use Change in Europe. Proceedings of the First ECNC Seminar on L and Use Change and its Ecological Consequences, T ilburg, the Netherlands, 16–18 February 1995. ECNC Publication Series on Man and Nature, ISBN 90-802482-1-5, Volume 2, November 1996..

Kennedy, P., Roy, D.P., Folving, S., and Megier, J., 1996, The application of the FIRS Project's Foundation Action 1, the regionalization and stratification of European forest ecosystems, for providing a European NOAA-AVHRR-based forest map. Proceedings of the 15th EARSeL Symposium on Progress in Environmental Research and Applications, Basel, Switzerland, 4–6 September 1995, edited by E. Parlow (Rotterdam: Balkema), pp. 43–53.

Kerdiles, H., 1996. Software for Processing AVHRR data for the Communities of Europe (SPACE): algorithms used in SPACE version 2. Part 1: calibration, atmospheric correction and cloud detection. JRC Technical Note, Ispra, Italy.

Kressler, F. P., Steinnocher, K. T., 1999. Detecting land cover changes from NOAA-AVHRR data by using spectral mixture analysis. Int. J. Appl. Earth Obs. (1), 21-26.

Lambin, E.F., Strahler, A.H., 1994. Indicators of land-cover change for change-vector analysis in multitemporal space at coarse spatial scales. Int. J. Remote Sens. 15 (10), 2099-2119.

Loudjani, P., Pinty, B., and Verstraete, M., 1998. The SMoothing AVHRR Reflectances Technique (SMART): a method for smoothing AVHRR reflectance time-series. In prep.

Loveland, T.R., Belward, A.S., 1997. IGBP-DIS global 1 km land cover data set, DISCover: First results. Int. J. Remote Sens. 18 (15), 3289-3295.

Millot, M., 1995. NOAA AVHRR pre-processing. Agrometeorological models: theory and applications in the MARS project, proceedings, edited by J. F. Dallemand and P. Vossen. Publication EUR 16008 EN of the Office for Official Publications of the European Communities, Luxembourg, pp. 173–179.

Mücher, C. A., van de Velde, R. J., and Nieuwenhuis,G. J. A., 1994,Mapping Land Cover for EnvironmentalMonitoring on a European Scale. Pilot project for the applicability of NOAA/AVHRR HRPT data. Report 93, SC-DLO, Wageningen, the Netherlands. RIVM report no. 402001004.

Mücher, C. A., Veldkamp, J. G., van Katwijk, V. F., Nieuwenhuis, G. J. A., and van de Velde, R. J., 1996, Applicability of NOAA-AVHRR 1-km data for land cover based environmental monitoring in Europe: final report part 1. Report 128, SC-DLO, Wageningen, the Netherlands. RIVM report no. 724001002.

Perdigão, V., Annoni, A., 1997. The technical and methodological guide for updating CORINE land cover database. Report EUR 17288 EN, ECSC-EC-EAEC, Brussels, Luxembourg.

Quarmby, N. A., 1992. Linear mixture modelling applied to AVHRR data for crop area estimation. Int. J. Remote Sens. 13 (3), 415-425.

Roy, D.P., 1997. Investigation of the maximum Normalized Difference Vegetation Index (NDVI) and the maximum surface temperature (Ts) AVHRR compositing procedures for the extraction of NDVI and Ts over forest. Int. J. Remote Sens. 18 (11), 2383-2401.

Roy, D. P., Kennedy, P., Folving, S., 1997, Combination of the normalised difference vegetation index and surface temperature for regional scale European forest cover mapping using AVHRR data. Int. J. Remote Sens., 18, 1189–1195.

SAI-JRC, 1996, An Outline of the NOAA-AVHRR MARS Archive, SAI-JRC, Ispra, Italy.

Settle, J.J., Drake, N.A., 1993. Linear mixing and the estimation of ground cover proportions. Int. J. Remote Sens. 14 (6), 1159-1177.

Shimabukuro, Y.E., Holben, B.N., Tucker, C.J., 1994. Fraction images derived from NOAA AVHRR data for studying the deforestation of the Brazilian Amazon. Int. J. Remote Sens., 15, 517–520.

Singh, A., 1989. Digital change detection techniques using remotely-sensed data. Int. J. Remote Sens. 10 (6), 989-1003.

Stanners, D., Bourdeau, P. (Eds.), 1995. Europe's environment: the Dobris assessment. Office for Official Publications of the European Communities, ISBN 92-826-5409-5, Luxembourg.

Story, M., Congalton, R.G., 1986. Accuracy assessment: a user's perspective. Photogramm. Eng. Rem. S. 52 (3), 397-399.

Thunnissen, H.A.M., Noordman, E., 1996. Classification methodology and operational implementation of the land cover database of the Netherlands. Report 124, SC-DLO, Wageningen, the Netherlands.

Thunnissen, H.A.M., van den Boogaard, P.J., Ullenbroeck, H.P.T., 1993. Operational land cover classification in the Netherlands using satellite images and other geographical information. Proceedings Operationalisation of Remote Sensing, ITC, Enschede, the Netherlands, 19–23 April 1993, Vol. 3, pp. 9–20.

Thunnissen, H.A.M., and VanMiddelaar, H.J., 1995. The CORINE Land Cover database of the Netherlands: Final report of the CORINE Land Cover project in the Netherlands. Report 78, SC-DLO, Wageningen, the Netherlands.

Tou, J.T., Gonsalez, R.C., 1974. Pattern Recognition Principles MA: Addison-Wesley.

Van de Velde, R.J., Faber, W.S., van Katwijk, V.F., Kuylenstierna, J.C. I., Scholten, H.J., Thewessen, T.J.M., Verspuij, M., Zevenbergen, M., 1994. The preparation of a European land use data base. Report no. 712401001, RIVM, Bilthoven, the Netherlands.

Veldkamp, J.G., Faber, W.S., Van Katwijk, V.F., Van de Velde, R.J., 1995. Enhancements on the European land use database. Report no. 724001001, RIVM, Bilthoven, the Netherlands.

Photo: Unpaved road with low stone walls on Saaremaa, island in Baltic Sea, Estonia.

CHAPTER 6

A standardized procedure for surveillance and monitoring European habitats and provision of spatial data

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A standardized procedure for surveillance and monitoring European habitats and provision of spatial data

Abstract

Both science and policy require a practical, transmissible, and reproducible procedure for surveillance and monitoring of European habitats, which can produce statistics integrated at the landscape level. Over the last 30 years, landscape ecology has developed rapidly, and many studies now require spatial data on habitats. Without rigorous rules, changes from baseline records cannot be separated reliably from background noise. A procedure is described that satisfies these requirements and can provide consistent data for Europe, to support a range of policy initiatives and scientific projects. The methodology is based on classical plant life forms, used in biogeography since the nineteenth century, and on their statistical correlation with the primary environmental gradient. Further categories can therefore be identified for other continents to assist large scale comparisons and modelling. The model has been validated statistically and the recording procedure tested in the field throughout Europe. A total of 130 General Habitat Categories (GHCs) is defined. These are enhanced by recording environmental, site and management qualifiers to enable flexible database interrogation. The same categories are applied to areal, linear and point features to assist recording and subsequent interpretation at the landscape level. The distribution and change of landscape ecological parameters, such as connectivity and fragmentation, can then be derived and their significance interpreted.

Keywords: field recording, stratified sampling, biodiversity, monitoring, surveillance, Raunkiaer plant life forms, general habitat categories

6.1 Introduction

When recording habitats and biodiversity at the landscape level, the difficulty has always been in reconciling the observed complexity of points, lines and patches with recognisable categories that can be consistently and repeatedly recorded in the field and then converted into national and regional estimates. It is therefore necessary to link the detailed records to a strategic framework, as described by Sheail and Bunce (2003). Monitoring and surveillance also have to be integrated spatially and temporally with other data sources. The primary goal of this paper is to describe a system that can lead to the production of a statistical profile of interdependent systems that make up European landscapes, and subsequently to enable the assessment of changes resulting from landscape ecological processes, such as fragmentation. The approach will enable the landscape ecological resources of the continent to be determined and, because it is based on plant life forms which are applicable throughout the world, further categories could therefore be developed for other continents.

In the final plenary session at the 2007 IALE World Congress (International Association for Landscape Ecology), the assessment of change in landscape ecological elements at the strategic level was identified as an important topic for future research. Many regional studies and some national inventories are provided in Bunce et al. (2007), but none at a continental scale. Surprisingly, within the Congress, the Symposium on Monitoring did not identify any new methodologies, probably because of regular communication within the IALE community.

Policy makers and land managers increasingly demand hard figures that detail the state of biodiversity and habitats, as well as the definition of historical trends. Arguments over the responsibility of man in driving global environmental change make the demand for incontrovertible evidence ever greater (Reid, 2005). Such statistics are not only important for local and national policies, but may also be used to evaluate international conventions and commitments (e.g., the Goteborg Commitment by the European Union (EU) to halt biodiversity loss by 2010). However, there is a lack of consistent data to meet these requirements, especially at the supra-national level. Currently, reporting is based on national programs, without accepted protocols. As a result there are no consistent figures on habitats for Europe, because the available maps are derived from satellite imagery and are not at a sufficiently detailed level.

Throughout the world there are also many products at a strategic scale derived from satellite imagery, but usually with no link to in-situ data. Regional landscape ecological studies are more common; e.g., Jones et al. (2001) provide a broad view of the relevance of assessing landscape ecological changes and give an example at the regional scale in the United Sates. They point out that, whilst there had been successful development of methods for broad scale assessment, a critical limitation was that field based methods had proved to be inconsistent. However, new data on land cover change are now available; e.g., the North American Landscape Characterisation program (NALC) contains an archive of Landsat Multispectral Scanner (MSS) images. Vogelman et al. (2001) also describe a comparable program. Taken together these two programs permit relatively fine scale assessments of landscape change across large areas, but they are not integrated with habitat records. Also, in the United States the Environmental Protection Agency (EPA, http://www.epa.gov/emap) is developing tools for monitoring, but there is no national coverage of habitats. In Australia, in various papers, Austin has explored a range of different sampling techniques and scales; e.g., Austin and Myers (1995); but has never applied them in a strategic, integrated project; although some of the conclusions were incorporated in the development of the present procedure. Some Australian habitats have national coverage; e.g., coastlines in the Coastal Water Mapping project (CWHM); but otherwise only regional specialist studies have been carried out, e.g., New (2000). A commentary on the situation in Australia, as reported in (http://www.environment.gov.au/ soe/2006/publications/commentararie), stated that currently there was imperfect knowledge of the state and trends in biodiversity at any scale. Relevant figures were therefore derived from fragmented sources and expert opinion, as has been carried out in similar assessments in Europe.

Fundamental landscape ecological concepts, such as connectivity, isolation and dispersal, also require basic data on the spatial arrangement of habitats in landscapes. Changes in patterns can then be determined and the processes of change defined and interpreted. For example, Petit et al. (2004) used spatial data from habitats recorded in the UK Countryside Survey (Haines-Young et al., 2003) to assess changes in landscape ecological parameters, such as the adjacency of woodland elements. The definition of the landscape ecological characteristics of a particular area, or sample unit, also needs information about the habitats present, e.g., in landscape fragments, as well as associated species. Such information can enable the landscape ecology of an entire region to be understood, e.g., the long term studies of Bocage landscapes of Brittany (France) by Baudry (e.g., Baudry et al., 2000). Specific landscape ecological elements such as linear and point features may also be described (Hermy and De Blust, 1997). Alternatively, data may be recorded from a series of samples and then used to build up landscape ecological descriptions based on statistically derived landscape units (Bunce et al., 1993).Whatever the objectives of a specific study might be, standardized categories would enable the results to be transferable. International modelling exercises would similarly benefit from common categories and protocols.

Although field recording has been central to ecology and landscape ecology since their inception, relatively little attention has been paid to the development of consistent recording procedures for monitoring habitats within landscape elements. Furthermore, the majority of the extensive literature on vegetation (e.g., Braun-Blanquet 1932) is not designed for long-term monitoring, although the individual records can be repeated, if the sites are re-locatable (e.g., Grabherr et al., 1994). Kirby et al. (2003) showed that consistent recording is essential for long-term monitoring of woodland vegetation. The data on point features collected thirty years before (using the standardized procedure of Bunce and Shaw 1973) was sufficiently accurate to detect changes in habitats, such as forest glades. However, studies of vegetation change are rarely integrated at the landscape level, although Sheail and Bunce (2003) describe how the principles of standardized recording and statistical sampling of vegetation were extended to the landscape level.

Landscape ecologists have been successful in the application of their results to spatial planning but have had limited impact in the development of strategic conservation policies, as described by Bunce and Jongman (2007). Many conservation agencies neither appreciate the need to sample landscape complexity nor consider it necessary to analyze the interrelationships between component elements. Conservation managers are also not familiar with standardized methods of recording and sampling, or the statistical procedures, and are inevitably usually concerned only with local issues. The present methodology was designed to provide categories that are at a level of detail for consistent recording of habitats, which can be linked to other measures of biodiversity. However, it is recognized that a major program of work would be needed to carry out integration with existing data. Common standards could also provide the basis for stimulating scientific enquiry into the characteristics and relationships between landscape ecological units in entire landscapes.

Whilst the development of the ecosystem concept was originally mainly based on vegetation, it is now widely recognized that habitats should be defined independently. This is partly because, in terms of significance for animal populations, vegetation structure is often more important than vegetation classes (cf Fox et al., 2003), but also because some widely recognized habitats are not directly linked to traditional vegetation associations (Rodwell et al., 2002). In the 1980s, habitat mapping progressively became a separate exercise from vegetation recording, because strategic conservation surveys could be carried out more rapidly and cost-efficiently without the involvement of vegetation experts. For example, Agger and Brandt (1988) monitored changes in small landscape patches (biotopes) on intensively farmed land, without using plant communities. In an examination of the development of the Countryside Survey (CS) in Great Britain (GB) Firbank et al. (2003) indicate that, although the project in 1978 initially concentrated on vegetation, by 2000 the reporting of status and change was integrated with habitats in landscape units, because these are more convenient for reporting and more readily understandable by policy makers. Nevertheless, whilst detailed vegetation records are not required for monitoring habitat extent, such data are essential in determining habitat quality and condition; i.e., conservation status (Haines-Young et al., 2003). Over the same period landscape ecologists were developing techniques for analysing changes in patterns, often utilizing detailed habitat maps but using different systems of classification and scales, according to individual objectives and landscape characteristics. For example, Bunce et al. (1993) analyzed the relationships between the composition of linear features and the surrounding land in GB and showed that in lowland landscapes the majority of biodiversity was restricted to such elements, whereas in the uplands it was dispersed more widely.

The initial objective of the BioHab project was to develop a framework for surveillance and monitoring of European habitats, using existing classifications. However, it did not prove possible to develop adequate field rules for these classifications that were sufficiently consistent for recording change. Accordingly, the project team combined basic scientific knowledge from the literature, practical knowledge from previous field experience, and trial surveys across Europe to develop General Habitat Categories (GHCs) based on plant life forms.

The present paper firstly summarizes the conceptual principles behind European habitat monitoring and the creation of consistent habitat categories. Secondly, the recording procedure is described, explaining the rules needed for field survey. Finally, field testing, and policy relevance are discussed.

6.2 Conceptual principles

6.2.1 Surveillance and monitoring

It is first useful to summarize several conceptual principles relevant for the present study, starting with the definitions adopted of two frequently used terms, surveillance and monitoring, because they are often used elsewhere in different ways. Surveillance is the act of surveying, i.e. the recording of features at a specific location in one time frame, i.e., taking stock. In contrast, monitoring involves repeated observation on a time-line such that change can be detected, i.e., assessing both stock and change.

For small areas (e.g., some nature reserves) it may be possible to survey the entire site, but in most cases the assessment of biodiversity or habitats must be based on samples. One of the main factors in deciding the characteristic of samples is that habitats often occur in patches of different sizes in contrasting landscapes. Sampling procedures must not be compromised by spatial heterogeneity or complexity. As sampling effort (i.e., the time taken to record information) is usually fixed, a choice has to be made between recording many small sample units or a smaller number of larger units. As discussed by Bunce et al. (1996) it costs more per unit area to sample many small units, although they may give statistically more precise estimates (Gallego, 2002). On the other hand, Brandt et al. (2002) argue that larger sample units provide a more systematic inclusion of variations due to management. As there is no optimal sample unit size for all the habitats and landscapes at a continental scale; due to variation at landscape, patch and management scales; a 1 km square is a workable compromise, matching ease of survey, data content, and obtaining an adequate number of sample units for estimates of statistical probability. For some complex landscapes; e.g., Northern Ireland; sampling units of 0.25 km square may be more appropriate (Cooper and McCann 2002) and for aerial photographs larger units may be needed (Olschofsky et al., 2006). Using a standard size enables the direct comparisons to be made of relative heterogeneity. The 1 km square unit also enables internal spatial modelling of habitat patches and is suitable for scenario testing (Bunce et al., 1993).

The methodology is based on the principle that statistical inference requires samples (e.g., 1 km squares) to be drawn randomly from a defined population (e.g., Europe). Samples can be drawn from strata derived from the partitioning of the land surface by statistical analysis of climatic and topographic data from 1 km squares. The samples can then be analyzed to generate statistical estimates of the extent of required parameters for the region concerned.

Bunce et al. (1996) described 32 classes for GB and Metzger et al. (2005) 84 strata for Europe. The former have been used for estimating habitat areas in the Countryside Survey of GB and the latter are appropriate for Europe (Jongman et al., 2006).

The majority of field habitat mapping projects involve surveillance and are not intended to monitor change. Monitoring requires more stringent procedures to ensure that differences recorded represent real change and not distortions due to differences between observers or recording technique, as described by Brandt et al. (2002). Further discussion of the details of the design of the monitoring procedure is given by Bunce et al. (2005)

Across Europe, there is much experience in applying such methodology in the detection of change; e.g., GB (Haines-Young et al., 2003), Northern Ireland (Cooper and McCann 2002), Denmark (Agger and Brandt, 1988), and in interpreting changes from aerial photographs, e.g., Sweden (Skånes, 1996). Strict rules have been developed for updating the initial information, including procedures for correcting errors in the baseline data. Investigators are therefore able to use the results to detect and evaluate alterations in a landscape context, e.g., changes in patterns of linear features or whether new forestry is planted on semi-natural vegetation or on arable land (Petit et al., 2001).

6.2.2 Consistent habitat definition

Monitoring European habitats requires definitions that can be applied consistently in the field across Europe (Brandt et al., 2002). Habitats are defined as: ‘‘An element of the land surface that can be consistently defined spatially in the field in order to define the principal environments in which organisms live’’ (Bunce et al., 2005). This definition includes water bodies and extends to the Mean High Water (MHW) at the coast. It therefore excludes marine systems. Existing European habitat classifications have been based on species, geographical location, vegetation classes and environmental factors (e.g., the EUNIS system, Davies and Moss, 2002). Whilst these classifications have been successfully applied to produce general descriptions of the occurrence of classes in protected areas, they are not appropriate for monitoring, because definitions of many of the terms used; e.g., montane and sub-Mediterranean; are not provided.

The present recording procedure therefore adopted plant life forms, as described by Raunkiaer (1934) as the basis of the habitat categories. It is widely recognized (e.g., Woodward and Rochefort, 1991) that, at a continental level, biomes need to be defined in terms of the physiognomy and life forms of the dominant species, because individual species are too limited to encompass widely dispersed geographical locations. Ecological behaviour of species can also vary within their distribution and vicarious species further preclude the use of individual species. A given species may also show plasticity, because of environmental and local factors such as grazing, so the overall height of the whole unit is used a measure of its status at a given time. Further advantages of using life forms are that they provide direct links between in-situ data and dynamic global vegetation models (e.g., Sitch et al., 2003), but also with the patterns present on satellite images because of their relationship with vegetation structure. Plant life forms (Raunkiaer, 1934) are defined on the basis of the location of buds in the adverse season and separate grassland, shrub and forest species which can be used to develop rules for habitats that can be applied consistently in the field. Within the shrub and forest categories a further breakdown is made according to the way the leaves of the plants are retained in the adverse growth season. Raunkiaer demonstrated that the life form spectra in different regions were correlated with the main environmental gradient from the equator to the arctic: they are therefore widely used in global change modeling as indicators for projecting vegetation change (e.g., Sitch et al., 2003).

Various floras were consulted, e.g., Clapham et al. (1952), to determine at what level to treat life forms, as some floras (e.g., Oberdorfer et al. 1990) give many categories. However, as Raunkiaer (1934) originally emphasized, a more detailed breakdown of life forms loses the strong relationship with the environment. It was therefore decided to use 16 life forms (e.g., Herbaceous and Annual), and five leaf retention divisions of shrubs and trees (e.g., Summer Deciduous) derived from the original enumeration of Raunkiaer of seven leaf size categories, as shown in Table 6.1. The plant height ranges were taken from appropriate literature (e.g., Quetzal and Barbero, 1982). The main problem however was with Gramineae, Cyperaceae and Juncaceae, where many species have rhizomes, which are primarily for vegetative reproduction rather than for over-wintering. There are also differences between floras in the attribution of life forms to species, as well as difficulties in the determination of the actual position of the rhizomes in the field. It was therefore decided to group these three taxa together as ‘Caespitose Hemi-cryptophytes’. Further details and examples of the species in the 16 life forms are given in Bunce et al. (2005).

Table 6.1 Life forms for recording General Habitat Categories (GHCs), based on life forms as defined by Raunkiaer (1934).

Herbaceous	**HER**	
1. Submerged hydrophytes	SHY	Plants that grow beneath the water. This category includes marine species and floating species which over-winter below the surface.
2. Emergent hydrophytes	EHY	Plants that grow in aquatic conditions with the main plant above water.
3. Helophytes	HEL	Plants that plants that grow in waterlogged conditions.
4. Leafy hemi-cryptophytes	LHE	Broad leaved herbaceous species, sometimes termed forbs.
5. Caespitose hemi-cryptophytes	CHE	Perennial monocotyledonous grasses and sedges.
6. Therophytes	THE	Annual plants that survive the unfavorable season as seeds.
7. Succulent chamaephytes	SUC	Plants with succulent leaves.
8. Geophytes	GEO	Plants with buds below the soil surface.
9. Cryptogams	CRY	Non-saxicolous bryophytes and lichens, including aquatic bryophytes,
10. Herbaceous chamaephytes	HCH	Plants with non-succulent leaves and non-shrubby form.
Shrubs and trees	**TRS**	
11. Dwarf chamaephytes	DCH	Dwarf shrubs: below 0.05 m
12. Shrubby chamaephytes	SCH	Under shrubs: 0.05-0.3 m
13. Low phanerophytes	LPH	Low shrubs buds: 0.30-0.6 m.
14. Mid phanerophytes	MPH	Mid shrubs buds: 0.6-2.0 m
15. Tall phanerophytes	TPH	Tall shrubs buds: 2.0-5.0 m
16. Forest phanerophytes	FPH	Trees: over 5.0 m
Leaf retention divisions (to be used in conjunction with TRS)		
Winter deciduous	DEC	
Evergreen	EVR	
Coniferous	CON	
Non-leafy evergreen	NLE	
Summer deciduous and/or spiny cushion	SPI	

Land associated with built structures and infrastructure (termed ‘Urban’ in a broad sense) and agricultural cropland (termed ‘Crops’) cannot be defined solely in terms of life forms. However, for policy and practical reasons it is essential that such land is identified. Hence, ‘Urban’ and Crops’ have been separated as ‘super categories’ at the first level of the hierarchy, as shown in Fig. 6.1, with the rules to identify them being provided by Bunce et al. (2005).

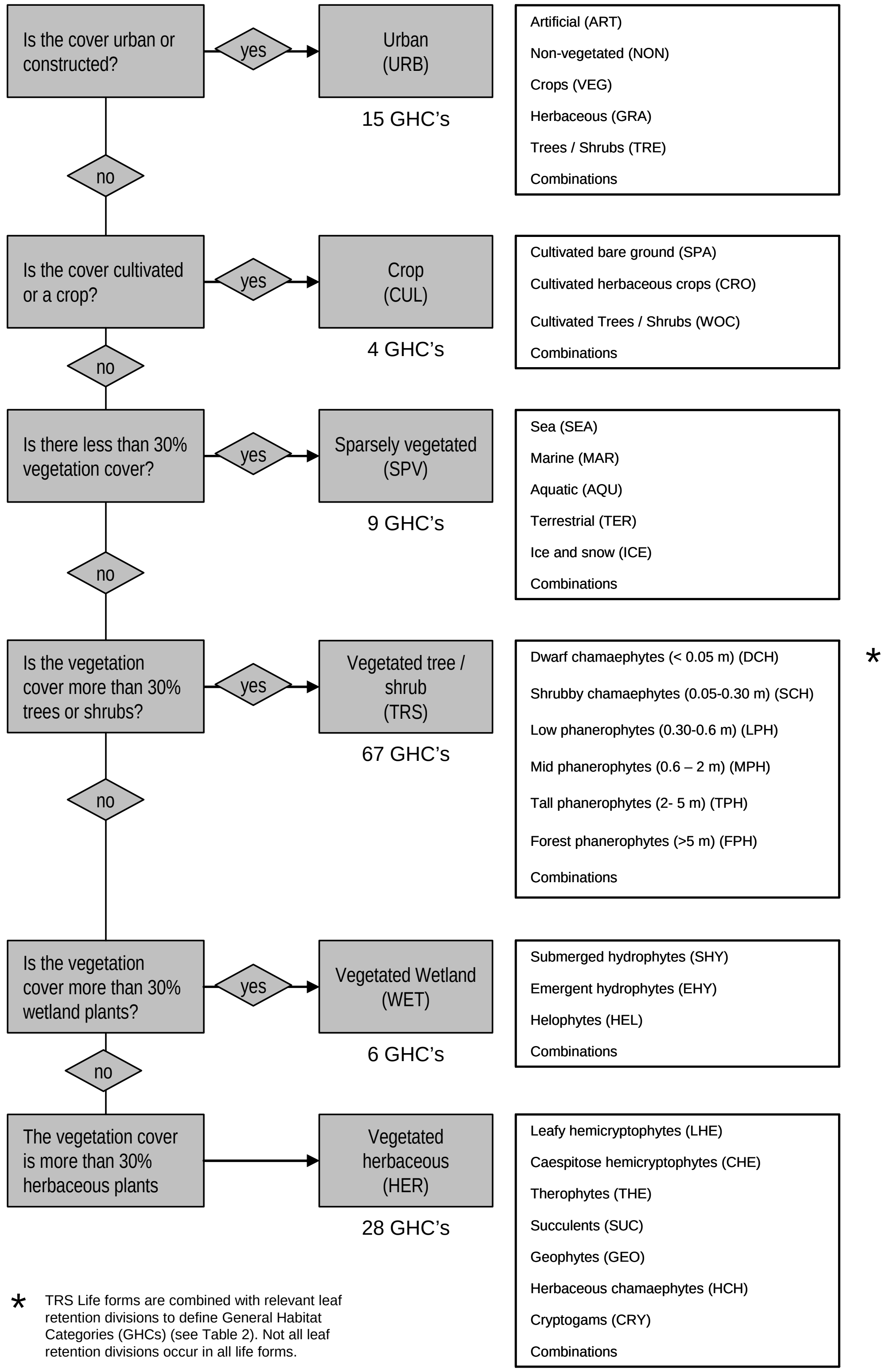

Fig. 6.1 Decision tree for the high level divisions, termed super categories, which form the basis for the General Habitat Categories (GHCs).

However, within the ‘Crop’ and ‘Urban’ categories, subsequent divisions are then based on life forms at the second level of Fig. 6.1. In addition, the ‘Sparsely Vegetated’ super category is separated to cover land with vegetation cover below 30%; e.g., glacial moraines.

A major problem of using theoretical habitat classifications for monitoring is the proliferation of classes; e.g., Morillo Fernandez (2003) distinguished almost 1,000 classes and in EUNIS there are 350 classes at level three. Within the BioHab, as shown in Fig. 6.1, all possible feasible combinations of grouped pairs of life forms are included, to ensure complete coverage of Europe. The number is restricted by rules using percentages and prioritisation to exclude combinations which would include more than two life forms. For ‘Trees and Shrubs’ leaf retention divisions are also included, but not all of these are present in all height categories; e.g., there are no native Summer Deciduous trees over five metres in height in Europe. This procedure is arbitrary, but reproducible, and has restricted the number of GHCs to 130 in the Pan-European region, excluding Turkey. Other life forms, e.g., tall succulents, would have to be included for other continents. This restricted list acts as a lowest common denominator and enables decisions at the highest level to be made in the field, or to be derived from extant data (e.g., vegetation releve´es). More detailed information (see below) is recorded in subsequent columns for the interpretation of change at the landscape level.

The determination of the GHC is based upon a series of five dichotomous divisions as shown in Fig. 6.1. These determine the set of life forms that can be used to identify the appropriate GHC. The first decision concerns whether the element is ‘Urban’, the second whether it is a ‘Crop’, the third whether it is ‘Sparsely Vegetated’, the fourth whether it is ‘Trees or Shrubs’, and the fifth whether it is ‘Wetland’ (Fig. 6.1). As discussed below, rules have then been added for further divisions in all super categories and habitat categories, including percentage criteria.

6.2.3 Additional qualifiers

Additional qualifiers are essential for further description of the GHCs and the determination of landscape ecological characteristics. Lists of global (e.g., percentage cover), environmental (e.g., soil moisture), site (e.g., moraine) and management (e.g., cattle grazing) qualifiers have been constructed. These qualifiers are recorded in combination with the GHC to provide information on variation between elements that may have the same GHC, as shown in Fig. 6.2, but different associated characteristics.

A matrix of environmental conditions was constructed for ease of recording, as described by Bunce et al. (2005), with moisture classes on the horizontal axis and soil factors on the vertical axis. Moisture classes suitable for application across the range of European habitats were adapted from Pyatt (1999). The soil factors are based on indicator values originally developed by Ellenberg et al. (1992) for Central Europe, but these are not available for all regions, so local experience on the ecological amplitude of indicator species may be needed. The overall balance of species should be used, not individual indicator plants. For example, in the Pannonian region the presence of some individuals of *Melica ciliata* is insufficient to assign the term ‘xeric’ to the element.

A provisional list of site qualifiers has been constructed (Bunce et al. 2005) and includes factors such as coastal attributes and rock types. Management qualifiers are grouped in convenient sections, e.g., ‘Forestry’ and ‘Recreation’, and are designed to give information on potential causes of change. This list will need further refinement and validation in a Pan-European field survey. Whilst the management qualifiers are more difficult to record consistently, Kirby et al. (2005) showed that if sufficiently well defined habitat categories are provided, then change can be reliably determined.

6.3 The recording procedure

The following section discusses the principal aspects of the recording process including practical mapping procedures. Standard data sheets and provisional lists of qualifiers are given in Bunce et al. (2005).

6.3.1 Preparation

No continent-wide survey can be carried out without adequate field training for all surveyors to ensure that terms are fully understood and interpreted in the same way. For example, environmental terms are often used within a local context, e.g., ‘dry’ in Scotland may be ‘mesic’ compared with southern Italy. Surveyors across Europe therefore need to be familiar with predefined environmental categories. In the field, combined teams of two people, preferably consisting of a botanist and a cartographer, are needed to ensure that the necessary expertise is available.

Code	Field 1	Field 2	Field 3	Field 4	Field 5				Field 6	Field 7	Field 8
α	General Habitat Category	Global Env. Qualifier	Site Qualifier	Man. Qualifier	Life form / Species: Life form	%	Species	%	Pan Europ class	Regional Class (SBMP)	Phytosociology
A	HER/LHE/CHE	5.3	106	402	LHE CHE	60 40	- -	- -	EUNIS - E2.7	ARE/BRA	-
B	HER/CHE	5.3			CHE LHE	90 10	- -	- -	EUNIS - E2.7	ARE/BRA	-
C	CUL/SPA	5.3	106	304/393/401	512		-	-	EUNIS - I1.3	VIA	-
D	HER/CHE	5.3			CHE LHE	80 20	- -	- -	EUNIS - E2.7	ARE	-
E	CUL/CRO	5.1	106	304/397	NA		-	-	EUNIS - I1.1	UIM	-
EA	CUL/CRO	5.1	106	304	CROP	100	-	-	EUNIS - I1.1	UIM	-
F	TRS/TPH/EVR60/HER/LHE 40	5.3	106				-	-	EUNIS - G5.6	PSA	-
G	HER/LHE/CHE	5.1	106	402	LHE CHE	50 50	- -	- -	EUNIS - E2.7	ARE/BRA	-

Fig. 6.2 Example of a mapped km square and the recording sheet, reproduced from Bloch-Peterson et al. (2006). The codes for the General Habitat Categories (GHCs) are described in Table 6.1. The codes for the environmental, global, site and management categories are listed in Bunce et al. (2005). '-' means not included in survey.

The date for the recording of GHCs should be based on local phenology. The extent of the window needs to be set by region, using local information, and differs between environmental zones. The state of development of the vegetation at the recording date should therefore be relatively consistent between zones; thus in the Mediterranean region the recording period will be earlier than in central and northern Europe. Barr et al. (1993) showed that differences between dates of survey are a major source of noise in change statistics. Repeat visits for monitoring should therefore be carried out as close as possible to the date of the original visit, assuming that there is no shift in timings of the seasons.

Data quality control (i.e., supervision of surveyors) and assurance (i.e., independent checks of recording) are all essential to produce robust data. Barr et al. (1993) analyzed random checks of comparable categories to GHCs and showed a correspondence of 84%. Any future program would need to incorporate such checks, so that policy makers and scientists would have confidence in the results.

All major decisions are made in the field. At a later stage, it is possible to extract relevant data in the laboratory from available datasets (e.g., slope angles, and geology). Other more detailed data are added in the field, as described below. Brandt et al. (2002) emphasize that the quality of mapping is dependent on sufficiently accurate base maps. It is therefore preferable to carry out preparatory work on ecological interpretation and subsequent delineation of the major elements within the survey area from aerial photographs and related material, e.g., cadastral maps, preferably at a 1:10,000 scale. Surveyors therefore annotate the base map with labels attached to individual elements according to the rules. The boundaries of some elements may need to be adjusted or new parcels described which were not defined in the preparatory work, e.g., different categories of grassland can often not be seen on aerial photographs.

6.3.2 Areal elements

The procedure was initially developed for mapping 1 km square samples, but is also suitable for other scales, e.g.; Cooper and McCann (2002) used 0.25 km squares and Bloch-Petersen et al. (2006) applied the GHCs to small biotopes below about 200 m^2. Within the 1 km square sample unit, the surveyor delineates all habitats with an area greater than 400 m^2 (Minimal Mappable Element - MME). Fig. 6.2 gives an example of a mapped 1 km square and a recording sheet (Bloch-Petersen et al., 2006). For each delineated unit the surveyor determines the GHC (Field 1) and the environmental, site, and management qualifiers, which are in sequential fields on the recording sheet (Fields 2–4). Next, all life forms with a cover of over 10% are recorded and individual plant species or crops with a cover of over 30% in the mapping unit (Field 5). Three further fields are provided for existing Pan-European habitat classifications (e.g., EUNIS (Davies and Moss, 2002), national habitat classifications (e.g. (Morillo-Fernandez, 2003) and phytosociological associations (e.g., Rodwell et al., 2002) depending upon the objectives of the project and the experience of the surveyors.

Although the MME has to occupy at least 400 m^2 it can be a complex shape, so long as the shortest measurement is over 5 m, as in the GB Countryside Survey, and checked for Europe during BioHab. This contrasts with the 10,000 m^2 of the CORINE land cover map and 2,500 m^2 of the Biopress Project (Olschofsky et al., 2006). However, the finer detail of the MME is essential to express the landscape ecological characteristics of small scale landscapes; e.g., in Crete (Greece), Asturias (Spain), and Brittany (France). Bunce et al. (2005) provide detailed rules for mapping some elements, e.g., motorways will be mapped as areal elements, but may subsequently be allocated to linear features by database management for specific objectives (e.g., Haines-Young et al., 2003). The fundamental principle is that disaggregated data are collected, so that subsequent analyses can be sufficiently flexible to answer a variety of policy and landscape ecological objectives, e.g., loss of hedgerows and fragmentation of habitats.

6.3.3 Linear and point elements

Linear and point elements are often excluded from habitat surveys. However, many landscape ecological studies have shown that, especially in intensively managed agricultural landscapes, biodiversity has progressively become restricted to such features (e.g., Hermy and De Blust 1997). Whilst this process may have stabilized in Western Europe, it is likely to continue in Central Europe. Many cultural landscapes are rich in such features, largely as a result of management; e.g., terraces in Tuscany (Italy), walls in the Auvergne (France) and ponds in Cheshire (GB). It is therefore essential not only to assess the resources of linear and point elements in representative landscapes but also to monitor their patterns and change.

The same recording format as described in the previous section is used for linear and point elements, but on a separate sheet, in order to assist the recording process. The variation across different types of landscape can subsequently be integrated through the use of Geographical Information Systems (GIS), and the contribution to biodiversity of areal, linear and point features compared. In some projects, e.g., Cooper and McCann (2002) habitats only may be recorded, but data on other biota may also be collected in the same sites, e.g., vegetation and freshwater invertebrates (Haines-Young et al., 2003) in order to present an integrated picture of biodiversity at the landscape scale.

Linear elements have a Minimal Mappable Length (MML) of 30 m. Those features that comprise only vegetation must be wider than 0.5 m, but less than 5 m wide in order to exclude narrow strips (e.g., lines of vegetation beside walls). Elements that are smaller than 400 m^2 and shorter than 30 m can be recorded as points. Linear habitats often occur as complexes; e.g., a fence, a ditch and a hedge; in which case instructions are provided for mapping, so that a given combination is always recorded by single alphanumeric code incorporating its detailed composition.

In some cultural landscapes the number of point features can be large, e.g., individual trees in parkland or hedgerows. Two guidelines are provided for recording such points. Firstly, the recorded point features should add to landscape diversity, usually because they represent a particular habitat which is generally absent from the surrounding area, e.g., rock outcrops or boulders in a grass field. Secondly, the recorded point features should also have an effect on the ecological functioning of landscapes, e.g., small water bodies which act as drinking places in grasslands, or weirs in watercourses, which hinder migration of fish. However, a given survey may decide to omit point features, in which case this should be documented on the separate general information sheet, which also includes information such as the date of survey and ownership details (Bunce et al., 2005).

6.4 Discussion

6.4.1 Field testing and validation

It was essential to ensure that the categories and rules could be applied throughout Europe. The field procedure was therefore tested rigorously through excursions and field workshops to bio-geographical locations ranging from the desert of Tabernas, near Almeria (Spain), to northern Norway inside the Arctic Circle (Fig. 6.3). These sites were selected to ensure that GHCs covered all major life forms and environmental conditions, and that the mapping rules were sufficiently robust. The categories and rules were progressively refined during these visits. In addition, the exposure of the mapping procedures to external comments was also valuable and led to modifications to the original proposal. Whilst some categories are rare and may never reach an MME or MML, the inclusion of point features enables the comprehensive expression of variation within the landscape.

The theoretical basis of the model is the correlation between the complexes of life forms and the environment. It is the substance of classical biogeography and can therefore be tested. The first such test was carried out in a valley in the Picos de Europa (Spain) which extends from evergreen forest at 200 m to rock and sub-alpine habitats at 2,500 m. Orthogonal regression, as described by Bunce et al. (1996), was used to calculate the correlation between Detrended Correspondence Analysis (DCA) scores of the mixtures of plant life forms recorded in 80 stratified random samples of 0.25 km square, drawn from eight environmental strata, using the mean altitude of each stratum as the independent variable. The correlation coefficient was 0.94 (6 df) and highly significant (P\0.001) showing that the model is valid.

In the second test, the data used was for proportion of life forms in areal elements collected during the field excursions and workshops shown in Fig. 6.3. The results are only indicative because, although they include all environmental zones of Europe, they were not randomly stratified. The data were analyzed by Canonical Correspondence Analysis using the environmental zones as the independent variable (Metzger et al. 2005). The results confirm the hypothesis of Raunkiaer (1934) that life form spectra are correlated with the environment. However, these initial results indicate that there are several significant dimensions, e.g., from bare rock to habitats dominated by annual plants, and from grasslands to habitats with summer deciduous species. The axes from the analysis of the life forms were associated with the environmental zones of Europe, with Alpine North (i.e., Scandinavian mountains) and Mediterranean South (i.e., extreme southern Europe) being at the opposite ends of the primary gradient.

Life form combinations are more important than the individual categories in expressing the overall environment, but also show modified patterns because of management by man. As with recording GHCs, individual species may diverge from the overall pattern, e.g., *Koenigia islandica* is an annual which grows in arctic environments dominated by chamaephytes.

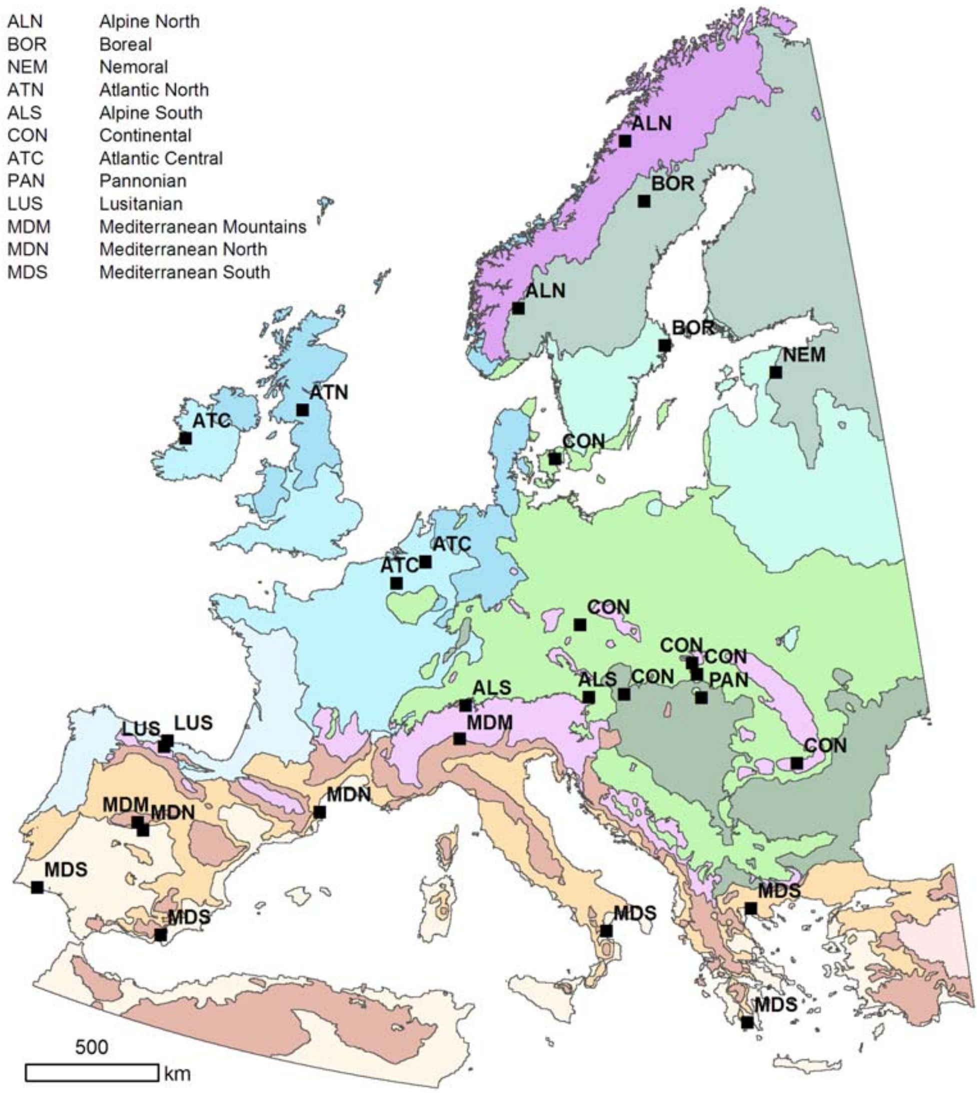

Fig. 6.3 *Distribution of the main field visits and workshops where the procedure for recording General Habitat Categories (GHCs) was tested. The data collected were used in analysing the relationship of the GHCs with the environmental zones of Metzger et al (2005) as described in the text.*

6.4.2 Policy relevance

Data collected from monitoring and surveillance of European habitats would provide direct support for European nature conservation policy. Such data would also have policy relevance to issues concerning the rural environment (e.g., agri-environment schemes). Policies on environmental issues can only be developed with knowledge of the stock and change of the environmental resources. Projects such as MIRABEL (Petit et al., 2001) have only been able to use expert judgment for assessing the distribution and extent in European habitats and the potential change caused by driving forces. The value of such studies would be greatly enhanced by actual habitat data. Mücher et al. (2005) have used the descriptions in Annex 1 of the Directive to derive rules which use existing databases to predict distribution of habitats. However, many of the descriptions do not contain enough detail for mapping, and reliable in-situ data is lacking in many cases. In addition, many large scale European projects have no field validation of the results.

Inevitably, protected sites (e.g., in Europe the Natura 2000 sites) can only cover a limited proportion of the European land surface, and outside their boundaries there is little or no protection of habitats. Nevertheless, the non-designated ‘wider countryside’ contains a high proportion of the total wildlife resource, interacts with protected sites, and is also the domain that most people experience in everyday life, with recent pressures leading to major losses of biodiversity and changing landscape patterns. On the one hand there has been agricultural intensification and urbanization and, conversely, more isolated or less productive regions have become marginalized and abandoned (EEA, 2005). Such changes will have major consequences on rural communities as well as habitats and biodiversity (Metzger et al., 2006). The BioHab procedure is designed to detect and report such change, with the ability to cover adequately the complexity of landscapes and spatial heterogeneity across Europe. It can thus provide European policy makers with statistical estimates of the stock and change in distribution of habitats in relation to environment and landscape ecology. The results need to be communicated using categories that will inform the public (e.g., figures on abandonment, marginalisation, and encroachment) and encourage further research. The data will also form a control against which to test the effectiveness of protection measures and could also be used to stimulate analysis of landscape ecological parameters at the European level. Many comparable processes are occurring throughout the world, as relevant abstracts in Bunce et al. (2007) show. The transferability of the categories described above, together with additional units for biomes not present in Europe, could help to assist international cooperation on landscape change and identify common driving forces.

A provisional list of life form categories outside Europe has already been prepared, and field work in Israel has already demonstrated how further categories can be added for deserts. However, habitats such as the tropical rain forest have complex structures with many levels of vegetation, which cannot be adequately represented by the vertical perspective. Further work is therefore needed to define appropriate additional categories and the necessary supporting rules.

A benefit of the sample approach is that detailed spatial and temporal data can be collected and can then be used in scenario studies or modelling exercises, as demonstrated in GB (Bunce et al., 1993; Parry et al., 1994). At a more detailed level, the GHCs provide a framework for placing extant figures onto a common basis, by screening available datasets, and then supplementing them by further survey, to produce data which could eventually lead to European estimates. Bloch-Petersen et al. (2006) have shown how the GHCs can be derived from existing studies. Recent work, in the GB Countryside Survey 2007 field program also indicates that there is direct correspondence of GHCs with existing disaggregated data on habitats.

In conclusion, this paper presents a procedure that has been based on experience, over the last thirty years, of recording and reporting habitats and spatial information at the landscape scale. It would enable integration between many European projects and would also enhance the understanding of landscape ecological change, as well as stimulating international collaboration.

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References

Agger, P., Brandt, J., 1988. Dynamics of small biotopes in Danish agricultural landscapes. Landscape Ecol. 1 (4), 227-240.

Austin M.P., Myers J.A., 1995. Modelling landscapes patterns and processes using biologicaldata. Sub project 4: Real data case study. Consultancy Report to ERIN. CSIRO Division of Wildlife Ecology, Canberra.

Barr C.J., Bunce R.G.H., Clarke, R.T., Fuller, R.M., Furse, M.T., Gillespie, M.K., Groom, G.B., Hornung, M., Howard, D.C., Ness, M.J., 1993. Countryside Survey 1990: main report ,vol 2. London, DOE.

Baudry, J., Burel, F., Thenail, C., Le Coeur, D., 2000. A holistic landscape ecological study of the interactions between farming activities and ecological patterns in Brittany, France. Landscape Urban Plan. 50 (1-3), 119-128.

Bloch-Petersen, M., Brandt, J., Olsen, M., 2006. Integration of European habitat monitoring based on plant life form composition as an indicator of invironmental change and change in biodiversity. Geografisk Tidsskrift 106 (2), 61-74.

Brandt, J., Holmes E., Ravn, H.P., 2002a. Biodiversity and trees outside forests: The case of Denmark. In: Puumalainen J, Kennedy P, Folving S (Eds.) Forest Biodiversity— Assessment approaches for Europe. EUR Report 20423 EN. Joint Research Centre (DG JRC). Ispra. European Communities, pp 80–85.

Brandt, J. J. E., Bunce, R. G. H., Howard, D. C., Petit, S., 2002. General principles of monitoring land cover change based on two case studies in Britain and Denmark. Landscape Urban Plan. 62 (1), 37-51.

Brandt, J., De Blust, G., Wascher, D., 2003. Monitoring multifunctional terrestrial landscapes. In: Brandt J, Vejre H (Eds.) Multifunctional Landscapes, vol II, Monitoring, diversity and management. WITPress, Southampton, pp 75–84.

Braun-Blanquet, J., 1928. Pflanzensoziologie: Grundzuge der Vegetationskunde. Springer Verlag, Berlin Bunce RGH, Shaw MW (1973) A standardized procedure for ecological survey. J Environ Manage 1:239–258.

Bunce, R.G.H., Howard, D.C., Hallam, C.J., 1993. Ecological consequences of land use change. Countryside Survey 1990, vol 1. Department of the Environment, London.

Bunce, R.G.H., Barr, C.J., Clarke, R.T., Howard, D.C., Lane, A.M.J., 1996. Land classification for strategic ecological survey. J. Environ. Manag. 47:37–60.

Bunce, R.G.H., Groom, G.B., Jongman, R.H.G., Padoa-Schioppa, E. (Eds.), 2005. Handbook for surveillance and monitoring of European Habitats, 1st edn. Alterra report 1219, Wageningen.

Bunce, R.G.H., Jongman, R.H.G., Hojas, L., Weel, S. (Eds.), 2007. 25 years Landscape ecology: scientific principles in practice. Proceedings of the 7th IALE World Congress 8–12 July Wageningen, The Netherlands, IALE Publication series 4, 1186 pp.

Bunce, R.G.H., Jongman, R.H.G., 2007. Why is strategic conservation monitoring so rare in Europe? In: Bunce RGH, Jongman RHG, Hojas L, Weel S (Eds.) 25 years Landscape ecology: Scientific principles in practice. Proceedings of the 7th IALE World Congress 8–12 July Wageningen, The Netherlands, IALE Publication series 4, pp 545–546.

Clapham, A.R., Tutin, T.G., Warburg, E.F., 1952. Flora of the British Isles. Cambridge University Press.

Cooper, A., McCann, T., 2002. Habitat change in the Northern Ireland countryside: summary report of the Northern Ireland countryside survey, 2000. Environment and heritage service, Department of the environment for Northern Ireland, Belfast.

Davies, C.E., Moss, D., 2002. EUNIS habitat classification. Final report to the European topic centre of nature protection and biodiversity, European environment agency.

EEA, 2005. The European Environment—State and Outlook (2005) European Environment Agency, Copenhagen.

Ellenberg, H., Weber, H.E., Duel, R., 1992. Zeigerwerte von Pflanzen in Mitteleuropa. Scripta Geobotanica 18, 2nd edn.

Firbank, L.G., Barr, C.J., Bunce, R.G.H., Furse, M.T., Haines-Young, R., Hornung, et al. 2003. Assessing stock and change in land cover and biodiversity in GB: An introduction to Countryside Survey 2000. J. Environ. Manag. 67 (3), 207-218.

Fox, B.J., Taylor, J.E., Thompson, P.T., 2003. Experimental manipulation of habitat structure: A retrogression of the small mammal succession. J. Anim. Ecol. 72 (6), 927-940.

Gallego, J., 2002. Building agro environment indicators. Focussing on the European area frame survey LUCAS. EUR Report 20521N. European Commission, Ispra.

Grabherr, G., Gottfried, M., Paull, H., 1994. Climate effects on mountain plants [7]. Nature 369 (6480), 448.

Haines-Young, R., Barr, C. J., Firbank, L. G., Furse, M., Howard, D. C., McGowan et al., 2003. Changing landscapes, habitats and vegetation diversity across Great Britain. J. Environ. Manag. 67 (3), 267-281.

Hermy, M., De Blust, G., 1997. Punten en Lijnen in het Landschap. Schuyt en Co, Haarlem.

Jones, K.B., Neale, A.C., Wade, T.G., Wickham, J.D., Cross, C.L., Edmonds, C.M., Loveland, T.R., Nash, M.S., Riitters, K.H., Smith, E.R., 2001. The consequences of landscape change on ecological resources: An assessment of the United States mid-Atlantic region, 1973-1993. Ecosyst. Health 7 (4), 229-242.

Jongman, R.H.G., Bunce, R.G.H., Metzger, M.J., Mücher, C.A., Howard, D.C., Mateus, V.L., 2006. Objectives and applications of a statistical environmental stratification of Europe. Landscape Ecol. 21, 409-419.

Kirby, K.J., Smart, S.M., Black, H.I.J., Bunce, R.G.H., Corney, P.M., Smithers, R.J., 2005. Long term ecological change in British woodland (1971–2001). A resurvey and analysis of change based on the 103 sites in the Nature Conservancy 'Bunce 1971' woodland survey. Peterborough: English Nature. (English Nature Research Reports No. 653), 139 pp.

Metzger, M.J., Bunce, R.G.H., Jongman, R.H.G., Mücher, C.A., Watkins, J. W., 2005. A climatic stratification of the environment of Europe. Glob. Ecol. Biogeogr. 14 (6), 549-563.

Metzger, M. J., Rounsevell, M. D. A., Acosta-Michlik, L., Leemans, R., Schröter, D., 2006. The vulnerability of ecosystem services to land use change. Agr. Ecosyst. Environ. 114 (1), 69-85

Morillo Fernandez, C., 2003. Manual de Interpretacio´n de los Ha´bitats de Espan˜a, vols 1 & 2. TRAGSA, Ministerio de Medio Ambiente, Madrid.

Mücher, C.A., S.M. Hennekens, R.G.H. Bunce and J.H.J. Schaminée, 2005. Spatial indentification of European habitats to support the design and implementation of a Pan-European Ecological Network, in: McCollin D, Jackson JI (Eds.) Planning, People and Practice. The landscape ecology of sustainable landscapes. Proceeding of the 13th Annual IALE(UK) Conference, held at the University of Northampton, 2005, pp. 217-225.

New, T.R., 2000. How useful are ant assemblages for monitoring habitat disturbance on grasslands in south eastern Australia? J. Insect Conserv. 4 (3), 153-159.

Oberdorfer, E., Müller, T., Korneck, D., Lippert, W., Markgraf-Dannenberg, I., 1990. Pflanzensoziologische Exkursionsflora. 6th edn. Stuttgart Ulmer.

Olschofsky, K., Köhler, R., Gerard, F., 2006. Land cover change in Europe from the 1950'ies to 2000, aerial photo interpretation and derived statistics from 59 samples distributed across Europe. World Forestry, Hamburg.

Parry, M.L., Hossell, J.E., Jones, P.J., Rehman, T., Tranter, R.B., Marsh, J.S. et al., 1996. Integrating global and regional analyses of the effects of climate change: A case study of land use in england and wales. Clim. Change 32 (2), 185-194.

Petit, S., Firbank, L., Wyatt, B., Howard, D., 2001. MIRABEL: Models for integrated review and assessment of biodiversity in European landscapes. Ambio 30 (2), 81-88.

Petit, S., Griffiths, L., S. Smart, S., M. Smith, G., C. Stuart, R., M. Wright, S., 2004. Effects of area and isolation of woodland patches on herbaceous plant species richness across Great Britain. Landscape Ecol. 19 (5), 463-472.

Pyatt, D.G., 1999. Correlation of European forest site classifications. EU Concerted action final report, Forest research northern station, Roslin.

Quezel, P., Barbero, M., 1982. Definition and characterization of Mediterranean-type ecosystems. Ecol Mediterr 7:15–29.

Raunkiaer, C., 1934. The life forms of plants and statistical plant geography, being the collected papers of C Raunkiaer. Clarendon, Oxford.

Reid, W.V., 2005. Millennium ecosystem assessment synthesis report. Island Press, Washington DC, USA.

Rodwell, J.S., Schaminee, J.H.J., Mucina, L., Pignatti, S., Dring, J., Moss, D., 2002. The Diversity of European Vegetation. An overview of phytosociological alliances and their relationships to EUNIS habitats. Ministry of agriculture nature management and fisheries, The Netherlands and European environmental agency, 168 pp.

Sheail, J., Bunce, R.G.H., 2003. The development and scientific principles of an environmental classification for strategic ecological survey in the United Kingdom. Environ. Conserv. 30 (2), 147-159.

Sitch, S., Smith, B., Prentice, I.C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J.O., Levis, S., Lucht, W., Sykes, M.T., Thonicke, K., Venevsky, S., 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. Glob. Change Biol. 9 (2), 161-185.

Skånes, H., 1996. Landscape change and grassland dynamics— retrospective studies based on aerial photographs and old cadastral maps during 200 years in south Sweden. The Department of Physical Geography, Stockholm University. Dissertation series, no. 8.

Vogelman, J.E., Howard, S.M., Yang, L., Larsen, C.R., Wylie, B.K., van Driel, 2001. Completion of the 1990s national hard cover data set for the conterminous United States from Landsat Thematic Mapper data and other sources. Photogramm. Eng. Remote Sens. 67:650–662.

Woodward, F.I., Rochefort, L., 1991. Sensitivity analysis of vegetation diversity to environmental change. Glob. Ecol. Biogeogr. Lett. 1:7–23.

Photo: A floodplain meadow with *Fritillaria meleagris* along river IJssel near Zwartsluis.

CHAPTER 7

Synthesis

7.1 Conclusions

The main objective of this thesis is to develop quantitative methodologies for spatial identification and monitoring of European landscapes and habitats. In a broader context, it concerns biodiversity monitoring, using an integrated approach based on Earth Observation data and geo-information tools derived from available European environmental data sets and field surveying techniques. Each of the chapters concentrates on answering one of the research questions as mentioned in Section 1.4, in order to meet the main objective of this thesis.

Question A: What is the added value of remote sensing for landscape ecology in Europe, with special emphasis on mapping and monitoring of habitats and landscapes? There is an increasing awareness that many high quality landscape components, e.g., habitats, are deteriorating and that they need to be protected and monitored in more comprehensive ways. First of all, a key element in nature conservation is the spatial identification of landscapes (where many components and processes interact) and their components as ecologically meaningful units. Chapter 2 provides examples of how remote sensing can contribute valuable information on landscape elements, habitats, landscapes and their spatial structure, because of its ability to capture repetitively synoptic landscape information in an abstraction-free manner (Groom et al., 2006). Most remotely sensed data sets are characterized by high levels of internal data standardization. Image data standardization is normally based upon fundamental physical properties, enabling the calculation or estimation of many land surface properties such as biomass and moisture content. Moreover, the pace of technical development of image sensors and platforms is more rapid now as ever before, and has considerable potential relevance for landscape ecology. The evolution in spatial resolution, data supply and classification methods (e.g., object-based classifications) are especially seen as important developments that have immediate impacts on the interface between landscape ecology and remote sensing (Groom et al., 2006). However, the pathway for the use of image data to meet the demands for landscape information capture is not always simple. Next to the successful applications of remote sensing in landscape ecology as shown by the seven examples in Chapter 2, there remain problems relating to recording frequency in cloud-free conditions, spatial resolution for large areas, classification accuracies and the fact that there is seldom a simple relationship between a habitat and an individual biophysical parameter. These limit the possibilities for direct mapping of habitats from satellite imagery (Groom et al., 2006). A spatial modelling approach is therefore appropriate for identifying the locations of specific habitats (Mücher et al., 2009a). Land cover, as derived from remote sensing, can act as a surrogate parameter between several sets of habitat types. Very high spatial resolution (VHRS) satellite imagery, e.g., IKONOS, provides many direct applications in landscape ecology. The use of a stereo model made from pairs of IKONOS images is an example, since it does not only provide topographical information but also much information about the vegetation structure which leads to a better recognition of landscape features such as vegetation types. However, on the short term, associated costs makes it unlikely to make it feasible in an operational way. In addition, the parameters for the automated mapping of landscape features from VHSR satellite imagery have not yet been fully developed (Mücher et al., 2003; Groom et al., 2006). Therefore, there is an obvious need for field surveying (Bunce et al., 2008), which complements remotely sensed information and improves the extraction of information from satellite imagery. Image data relate mainly to the geo-biophysical landscape, as is clearly evident from the examples in Chapter 2. However, many core landscape properties, social and cultural, as well as perceptual and aesthetic, are generally beyond the reach of remote sensing. However, they could be added as a separate layer, to be extracted from other information sources.

A specific rider to Question A was: do uses of remote sensing provide principles for classification within European landscape ecology? Remote sensing is a technique for information gathering and, in principle, any classification system should be designed to be independent on specific data sets or techniques to enable long-term information gathering (Groom et al., 2006). Chapter 2 shows that in practice classification, remote sensing, and landscape ecology interact in many different ad hoc ways which are not always unsuccessful or necessarily wrong (Groom et al., 2006). However, these relationships can cause semantic problems for regional and global applications. For this reason, with regard to land cover and habitat information, as examples, it is important to adopt and develop robust rules for the interpretation of satellite imagery and their translation within appropriate and accepted classification systems. However, to see the relationship between landscape ecology and remote sensing as one of information delivery, implies also a two-way process, engaging landscape ecologists and conservation people as active partners 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, and experimental data, interact with each other. The understanding and implementation of core information issues, such as, classification, semantics, accuracy assessment, error modelling and meta-information, are crucial for the success of remote sensing (Groom et al., 2006).

Question B: Is it possible to model the spatial distribution of European landscapes using remote sensing and additional spatial information? A quantitative methodology has been established for the spatial identification of European landscapes (Mücher et al., 2009b). As there are many regional differences in landscape properties, it is crucial to strike the right balance between reducing the inherent complexity and maintaining an adequate level of detail. Against this background the European landscape classification – LANMAP has been established making use of a data integration process of environmental data sets with a high spatial resolution in combination with segmentation and classification techniques. A conceptual framework was needed, since landscapes are complex and spatially heterogeneous with many properties and values. The developed conceptual framework (Mücher et al., 2003) was based upon an hierarchical approach of landscape components: abiotic, biotic and cultural aspects – with an increasing dependency. The developed concept determined the selection of data sources and the construction of the typology. A critical review of the availability of appropriate data sets was needed, which lead to a confrontation between the ideal and the attainable. Land cover, as derived from satellite imagery, was a crucial data information layer, next to climate, altitude and parent material (Mücher et al., 2006). The final result was a hierarchical landscape classification, containing 350 landscape types, at the most detailed level, distributed over 14,000 landscape units with a minimum mapping unit of 11 km^2 (Mücher and Wascher, 2007; Mücher et al., 2009b) The methodology concerned a transparent, flexible and user-friendly methodology to categorise landscapes. As shown in Chapter 3, a major part of the validation of the European Landscape classification LANMAP was developed from a geo-spatial cross-analysis of LANMAP with ten national landscape typologies and consultation with 15 environmental research institutes across Europe. Results varied greatly, and a major conclusion was that the techniques used to define national landscape typologies (Groom, 2005; Wascher et al., 2005) differed so much in spatial and thematic scales and methodology, that it was difficult to make meaningful comparisons (Kindler, 2005). The ELCAI (European Landscape Character Assessment Initiative – EU FP5 project) questionnaire concluded that LANMAP gives a consistent view across Europe and provides a common language and classification system, but it cannot replace any of the national landscape classifications (Kindler, 2005). However, it does provide a valuable European framework for these. In this role, LANMAP has already led to the re-evaluation of some of the national approaches (Mücher et al., 2009b). Although the methodology and the resulting LANMAP classification have their limitations (regional identity for example might be underestimated due to a lack of spatial information on cultural-historical aspects), it has already been used in a wide range of applications (Mücher and Wascher, 2007; Mücher et al., 2006, 2009b). Since the database can be downloaded from the internet (www.alterra.wur.nl/UK/research/Specialisation+Geo-Information/Projects/lanmap2), the range of applications has increased considerably and has been downloaded already from 20 European countries. Next to the fact that it is widely being used for educational purposes, the LANMAP classification, is being applied in studies related to visualisation, soils, habitats, spatial economics, epidemiology, leisure and biofuels (Mücher et al., 2009b).

Question C: Is it possible to model the spatial distribution of European habitats using remote sensing and additional spatial information? A quantitative methodology has been established for the spatial identification of habitats across Europe to enable the determination of their actual extent (Mücher et al., 2009a). Five methodological steps are involved: (1) appropriate spatial data sets need to be compiled, (2) knowledge rules are then defined on basis of the descriptions of Annex I habitat types, (3) additional ecological expert knowledge is gathered when needed, (4) the spatial models are implemented, and (5) validation is carried out. In this exercise, the use of remotely derived land cover information, combined with additional environmental data sets, has played a crucial role in the spatial identification of habitats across Europe (Mücher et al., 2004, 2005, 2009a). For restricted and local habitats the information on specific species in the Potential Natural Vegetation (PNV) database proved to be essential. Spatial distribution models were derived for 27 habitats representing the most significant ecosystems. Validation by using the Natura 2000 database with 13,405 sites across 12 European countries showed that the mapping accuracy depends on the habitat description available but also upon its spatial character (e.g., degree of fragmentation). Thus widespread habitats such as forests were accurately assessed whereas dispersed classes such as freshwater habitats were more difficult to determine. For example, priority habitat 4070 'bushes with *Pinus mugo* and *Rhodondendron hirsuta*' had the highest 'reliability' with 86.7%, while habitat 3130 'oligotrophic standing waters' received the lowest score with 5.1%. In total, 52% of all Natura 2000 sites that contained 10 hectares or more of one of the selected 27 habitats were properly identified by the proposed methodology (Mücher et al., 2009a). It can be concluded that the proposed methodology detects especially widespread European habitats with unprecedented accuracy. Habitats with a strongly restricted spatial distribution, e.g., habitat 5220 ‘arborescent matorral with *Zyziphus*’ require in-situ information. Local knowledge about their distribution should be incorporated in the knowledge rules.

Moreover, it should be noted that the validation concerned only areas within Natura 2000 sites, whereas, the whole methodology was developed to determine the spatial distribution of habitats across the whole of Europe (inside as well as outside protected sites). Uncertainties in the mapping results remain (Mücher et al., 2009a), especially in cases of poor habitat descriptions, spatial and thematic inaccuracies in the core data sets, and last but not least absence of spatial distribution maps of specific indicator species in the Atlas Flora Europaeae (AFE) or in the PNV database.

Question D: Since land cover information plays a crucial role in the spatial modelling of European landscapes and habitats, is it possible to monitor Europe’s land cover? The classification of satellite imagery, particularly when it is low resolution (e.g., NOAA-AVHRR satellite sensor) requires that data have been pre-processed to a high standards with acceptable radiometric, geometric and temporal quality. The proposed methodology of Chapter 5 (Mücher et al., 2000, 2001) takes full advantage of multi-spectral and multi-temporal NOAA-AVHRR imagery that requires a stratified approach for Pan-Europe and incorporates regional expert knowledge. In principle, the best classification results are obtained by supervised classification of several multi-spectral images well distributed over the growing season (spring/summer/autumn). However, this requires cloud-free conditions on specific dates (Mücher et al., 2001). Since this is not feasible for many European strata, use has been made of NDVI time series. Each classification (supervised or unsupervised) of the NDVI time-series resulted in a set of spectral distance files (minimum distance has been used as parametric rule). For each pixel the two smallest distances were retrieved and related signatures/cluster numbers were assigned to two image layers; i.e., pixels received a first and second ‘probability’ class number. The ratio between the first and second distance can be used as an indicator for the homogeneity of the specific pixel (Mücher et al., 2000, 2001). Due to limited accuracy of forest classification using NDVI time series, their identification was carried out on the basis of thresholding the synthesis of the visible reflectance of AVHRR band one (Champeaux et al., 2000; Mücher et al., 2001). In addition, urban areas and water bodies were masked on the basis of ancillary data sources.

Ancillary data sources, such as CORINE land cover, were crucial for training and defining the classification (Mücher et al., 2001). Accuracy assessment of the final PELCOM land cover database, on the basis of confidence sites across Europe with interpreted high resolution satellite imagery, indicated an overall accuracy of 69.2% (Mücher et al., 2001). This was considered a good result considering the mixed pixel and geo-referencing problems with AVHRR data. However, due to the limited spatial resolution and classification accuracies, the proposed methodology for land cover mapping is not suitable for monitoring land cover changes (Mücher et al., 2000). At the same time, it remains a prerequisite for applications of environmental monitoring that the land cover information can be easily updated. Therefore, the development of a change detection technique, based on the use of thematic fraction images derived by linear unmixing of satellite imagery, was proposed. Validation of the linear unmixing results, using the first four bands of an NOAA-AVHRR image acquired on 25th of July 1995 showed an overall accuracy of 82.0% for the following land cover types: grassland, arable land, forest and urban areas (Mücher et al., 2000). A direct comparison of fraction images, which can be regarded as continuous thematic data layers, calculated from satellite data recorded on different dates, makes it possible to highlight those areas where the proportion of the various land cover types has changed. The full potential of thematic fraction images for monitoring changes might be achieved with the use of newer sensors which have higher spatial and spectral resolutions, but are still able to cover large areas on a regular basis.

Question E: If it is possible to monitor European habitats using standardized procedures for field surveillance, can this be integrated with remote sensing to mitigate the latter's limitations? When recording habitats and biodiversity at the landscape level, it is always difficult to reconcile the observed complexity of points, lines and patches with recognizable categories that can be recorded consistently and repeatedly in the field and then converted into regional and national estimates. The method for the spatial modelling of habitats (Mücher et al., 2009a) described in Chapter 4 can be used for the spatial identification of widespread habitats but cannot be directly used for their monitoring, especially where it concerns gradual habitat changes in patches, next to point and line features. Moreover, the method proposed in Chapter 4 still lacks in-situ data across the European countryside for rigorous field validation and calibration of the modelling results. For all this reasons, a standardized procedure was developed for the surveillance and monitoring of European habitats in the field. In total, 130 General Habitat Categories (GHCs) were defined based on the classical plant life forms as defined by Raunkiaer (Raunkiaer, 1934; Bunce et al., 2008) and their combinations, next to 'super' categories 'Urban' and 'Crops'. It is widely recognized that, at continental scales (Woodward and Rochefort, 1991), biomes need to be defined in terms of the physiognomy and life forms of the dominant species, because individual species are too limited to encompass widely dispersed geographic locations. Further advantages of using life forms is that they provide direct links not only to dynamic global vegetation models, but also to the patterns present in satellite imagery, because of their relationship with vegetation structure. Sixteen life forms and five leaf retention divisions of scrubs and trees (e.g., evergreen) have been defined from the original enumeration of Raunkiaer (Bunce at al, 2005, 2008). The GHCs are enhanced by recording the global (e.g., % cover), environmental (e.g., soil moisture), site (e.g., moraine) and management qualifiers (e.g., cattle grazing) to enable flexible database interrogation. However, the provisional list of qualifiers needs further refinement and validation in pan-European field surveys. When the methodology is extended outside Europe, the list of qualifiers as well as the list of life form categories need to be expanded. The same categories are applied to areal, linear and point features to assist recording and subsequent interpretation at the landscape level. The field procedure was tested rigorously across sites in Europe and showed that the mapping rules are sufficiently robust and provide a basis for consistent baseline surveys (Bunce et al., 2005, 2008). However, only adequate field training for all surveyors will ensure that all terms are fully understood and interpreted in the same way. The field procedure was originally developed for 1 km squares at a scale of approximately 1:10,000, which is still seen as optimal for a European baseline survey (see also Appendix 1). The minimum mapping unit for patches is 400 m^2, for linear elements 30 m. Elements that are smaller than 400 m^2 and shorter than 30 m can be recorded as points (Bunce at al., 2008). Detrended Correspondence Analysis (DCA) of collected samples in Europe using the proposed methodology indicated that there is a good correspondence between the life forms and environmental gradients (Bunce et al., 2008). Since various life forms and dominant species per life form are also recorded by percentage coverage per mapping unit (vertical projection) it provides good links for the training and validation of satellite imagery by the rigorous description of the vegetation structure.

General conclusions: In relation to the main objective of this thesis, which was the development of quantitative methodologies for the spatial identification and monitoring of European landscapes and habitats, it can be concluded that; in combination with other environmental data sets; it is now possible to model quantitatively the spatial extent of widespread habitats and landscapes on the basis of remotely sensed land cover information derived from satellite imagery (Mücher et al., 2009a, 2009b). The lack of consistent cultural-historical digital data sets for Europe still is a major limitation in relation to the spatial modelling and characterization of European landscapes, and this might lead to the underestimation of regional identity (Mücher et al., 2009b). Although it is possible now to model the spatial extent of widespread European habitats, these patterns cannot be directly translated to area estimates of those habitats (Mücher et al., 2009a). This purpose requires validation and calibration with ground-truth sample sites across the European countryside as obtained from the field surveying methodology as proposed in Chapter 6 (Bunce at al., 2008). The retrieval of accurate land cover information is not only crucial for the spatial modelling of European landscapes and habitats, but also for their monitoring, since their destruction and degradation are mainly caused by changes in land management, which remains the most important driver of biodiversity loss. Operational remote sensing enables land cover characterization at various scales but the classification accuracies are still insufficient at continental and global scales for monitoring purposes (Mücher et al., 2000; Herold et al., 2008). The use of continuous thematic fraction layers, as derived from linear unmixing, provides a good basis for monitoring land cover changes of Europe's complex landscapes (Mücher et al., 2000). However, gradual or small changes in habitats and their quality are not easily detected by such images and therefore additional information from field surveying is needed. The field procedures developed for mapping patches as well as for linear and point habitats are sufficiently robust to provide a consistent baseline (Bunce et al., 2008). They also provide perspectives for further integration with remotely sensed information. However, cost dictates that field surveys always need to be implemented using a sampling framework in which the samples are limited to small areas, e.g., one square kilometre. Spatial modelling of habitats is therefore required to provide a synoptic overview of their spatial distribution (Mücher et al., 2009a).

7.2 Outlook

In this section the results of the scientific research are put in perspective and possible improvements and further directions of research are outlined. The outlook is divided into two sections:

- Spatial modelling of European landscapes and habitats
- Monitoring of European habitats

Spatial modelling of European landscapes and habitats: Until recently there were few quantitative approaches to European landscape classification. Those that were available for Europe as a whole (e.g., Meeus, 1995), were coarse in spatial resolution and were not based on modern data acquisition and analysis. The newly established European landscape classification LANMAP was a major breakthrough, because a consistent methodology was used to integrate various thematic layers. It therefore provides a consistent view across Europe as well as a common language and classification system (Mücher et al., 2009b). However, there is still enough room for improvement. Firstly, LANMAP includes no information on socio-economic and cultural-historical aspects and, particularly with regard to spatial information, it is not expected that much of these aspects will become available consistently across Europe with sufficient regional detail. Nevertheless, it has been shown that information on landscape patterns can be derived in a consistent way from satellite imagery by segmentation techniques (Mücher et al., 2007). Burnett and Blaschke (2003) have already shown the possibilities of multi-scale segmentation for landscape analysis. In the Austrian research project SINUS, Austrian cultural landscape types have been identified on the basis of segmentation of Landsat TM images (Peterseil et al., 2004). Landscape structure provides a good basis for many indicators that can link patterns to processes within landscapes (Wrbka et al, 2004). Obtaining consistent landscape structure information for the whole of Europe can become a reality, but needs a higher resolution than is provided by Landsat, e.g., by the use of current SPOT satellite imagery. It would be interesting to investigate the added value of landscape-based metrics such as landscape heterogeneity, as expressed by the information-entropy of the Shannon index as extra parameters, to identify and describe European landscapes as has been done by Van Eetvelde and Antrop (2009a, 2009b) for Belgium. Integration of LANMAP with socio-economic data also took place in the SENSOR (EU FP-6 project Sustainability Impact Assessment: Tools for Environmental, Social and Economic Effects of Multifunctional Land Use in European Regions) project (Renetzeder et al., 2008), but the selection of the appropriate parameters and their disaggregation to regional scales needs more research. Improvements are also needed in cases of specific landscape types (e.g., coastal dunes), by exploiting detailed digital elevation data within the coastal regions. Recently the landscape types in LANMAP have been described more extensively which was urgently needed (Van der Heijden, 2007). In the end, it will be important for national concepts to be nested within a hierarchy of scales that build upon each other. Regional, national and European units should therefore be part of the same methodological system and LANMAP should be able to provide such a framework at the highest level.

Until recently, spatial distribution maps of European habitats were not available. However, recent improved quantitative methologies have made it possible to model the spatial extent of widespread examples with unprecedented accuracy (Mücher et al., 2009a). Evans (2006) indicated that for the implementation of the Habitats Directive much information is still missing on habitat distribution. In this perspective, Evans indicated in October 2008 (pers. comm.) that a significant part of the habitat reports under Article 17 of the Habitats Directive provided limited or no information on a habitat’s area and its trends. Therefore, the developed methodology and resulting habitat distribution maps are not only crucial for the design of ecological networks in Europe, but could also support individual countries in the production of distribution maps and area estimates. However, it is only possible to estimate the likely occurrence of the habitats if all spatial information layers are available. In cases where crucial information is lacking, e.g., on water quality, the inclusion of geo-referenced vegetation relevés as an additional information source is a possible methodological improvement, which would also be useful in cases of local and dispersed habitats. Nevertheless, the distribution maps cannot be directly translated into area estimates (number of hectares) of the specific habitat. For this, interpolation is needed between the remotely sensed data and in-situ information across Europe, which is currently investigated in the European projects ECOCHANGE (Challenges in assessing and forecasting biodiversity and ecosystem changes in Europe- EU FP6 project) and EBONE (European Biodiversity Observation Network: Design of a plan for an integrated biodiversity observing – EU FP7 project) in collaboration with SynBioSys Europe (Schaminée et al., 2007). Precisely located geo-referenced vegetation relevés (point location) will provide suitable information for the further improvement of the knowledge rules with regard to site conditions. Due to the very limited surface of most vegetation relevés (much smaller than the spatial resolution of most sensors and more likely to represent a point than an area), they cannot be used easily to produce the confusion matrices that are needed to produce robust area estimates. Moreover, these vegetation relevés will miss most of the information on the presence of various landscape elements, like, hedgerows and small streams. The methodology for the field surveillance of habitats proposed in Chapter 6 provides a basis for robust ground-truth measurements. It gives useful information for the validation and calibration (correspondence analysis) of the habitat distribution maps, as obtained from the spatial modelling methodology as proposed in Chapter 4. This results in better area (stock) estimates of habitats than using land cover information alone. In the Flemish-Dutch project HABISTAT (A Classification Framework for Habitat Status Reporting with Remote Sensing Methods – STEREO II project) the proposed habitat recording methodology is currently being used for the training and validation of hyperspectral imagery (Haest et al., 2009). With regard to the input data for spatial models in this thesis there remains a serious shortage of validated European data sets on e.g. groundwater tables and water quality. The Atlas Florae Europaeae (AFE) should be expanded to include all European species.

In general, much work still remains to be done on the spatial and thematic improvements of the spatial input data sets and their accuracy assessments. For satellite sensors and derived products the CEOS (Committee on Earth Observation Satellites) working group on calibration & validation (WGCV) has an important role (Belward, 1999). However, environmental data sets that have not been derived from EO data need also standardized and robust accuracy assessements, which is unfortunately in many cases absent. Testing the range of uncertainties in the input data would be very valuable in relation to error propagation (Shi et al., 2005).

Higher spatial resolutions, especially of land cover information, elevation and soil data, would improve the modelling results to a large extent, because most European habitats are fragmented. The SRTM global elevation data set (Chen, 2005) already has a much higher spatial resolution (~ 90 m) than the GTOPO30 data set (~ 1 km) used in Chapter 3 and 4, but has too many internal distortions caused by its acquisition procedure and processing chain. Further, the development of the expert system approach, by combining local ecological knowledge with available spatial information, would improve the identification of European habitats (http://www.synbiosys.alterra.nl/ecochange/single classes.aspx).

To achieve public appreciation and acceptance, the landscape and habitat maps resulting from the spatial modelling require high quality cartographic presentation. This process needs further development on generalization of e.g. gridcell derived polygons and lines (Chen and Chen, 2005).

As has been demonstrated, when using remote sensing based methods for habitat classification in Europe, current satellites (or combinations of different satellites) do not provide measurements of the Earth surface at the typical length scale of the existing habitats and their fragmentation levels. It might be suggested that forthcoming satellite initiatives could be based on summarizing the typical temporal, spectral and geometric resolutions needed for European habitat inventories. In this case user driven requirements, e.g., adequate instruments and platforms, could be used for a Pan-European habitat mapping at unprecedented accuracy. Currently, as has been shown throughout this work, mapping is limited by the nature of existing instruments, which were primarily designed for different purposes, a deficiency that significantly influences the accuracy of this work.

Since there are many possibilities for improving spatial identification of European habitats and estimates of their area, a priority ranking should be given in the following order:

- completing a baseline field survey of European habitats to enable validation and calibration of the habitat distribution maps and associated area estimates;
- finishing the Atlas Florae Europaeae for all European plant species;
- collecting, harmonizing and making available existing geo-referenced European vegetation relevés with a high spatial precision (geo-referenced to a point and not to a grid);
- obtaining more detailed land cover and digital elevation models;
- making use of forthcoming satellite initiatives that might fulfil typical temporal, spectral and geometric needs for European habitat inventories;
- collecting additional validated environmental data sets, e.g., on water quality and groundwater tables;
- improved methods for the generalization of gridcell polygons and lines to provide better cartographic products.

Monitoring of European habitats: Accurate land cover information is crucial for monitoring as well as for spatial modelling of landscapes and habitats, whose destruction and modification are to a large extent caused by changes in land management. Monitoring is therefore essential for determining changes and trends in the extent and quality of a habitat. Land cover is the visual reflection of the land use at a certain moment in time and can be monitored very well by remote sensing. However, the use of remote sensing for monitoring is restricted by classification accuracies of only 70% maximum at continental and global scales. This limitation has two origins: the complexity of the legend of land cover that does not reflect a physical measurement (satellites measure radiance and not categorical classes such as land cover, so you must always translate). And second, the perfect spectral, temporal and spatial satellite configuration is not yet available for this task. Due to limited land cover classification accuracies, land cover monitoring requires specific approaches towards change detection such as in the CORINE land cover project (Perdigão and Annoni, 1997; Büttner et al., 2002; Feranec et al., 2007) or by thematic fraction techniques as proposed in Chapter 5. However, severe limitations remain. The CORINE land cover database still has a limited spatial resolution (scale 1:100,000 and minimum of 5 ha for change detection) and the use of fraction images limits the number of thematic classes. More recent trends show that the construction of land cover databases can be based on the automatic classification of high resolution satellite imagery, e.g., Landsat imagery with a 25m spatial resolution, for very large areas such as Europe (Pekkarinen et al., 2009). In this perspective, also a change detection method based on change vector analysis – decision tree classification (CVA-DTC method) of Xian et al. (2009) seems to be very promising. However, land cover change assessments in large areas still face many challenges, e.g., cost effectiveness, timely acquisition of data, minimizing inter- and intra-annual vegetation phenology variance, removal of image noises caused by atmospheric effects and the availability of appropriate analytical techniques (Coppin et al., 2004; Xian et al., 2009) A sampling approach, using statistically sound sample designs would be a solution that provides a methodology for land cover monitoring at such scales. A thorough knowledge of existing land cover conditions is also needed to be integrated with the remotely sensed change detection. A sampling approach also provides opportunities for using newer sensors which have high spatial and spectral resolutions, e.g., imaging spectrometers. At the same time it must be noted, when using much higher spatial resolution satellite data, the complexity of signal interpretation usually increases. This is due to the fact that shaded components increase in area fraction when striving for higher spatial resolution. Shaded parts of canopies can extend to more than 50% cover within a pixel rendering habitat classification approaches significantly worse that 50% accuracy. In general, a sampling approach can bridge scaling gaps, allowing spatial-temporal continuous sampling with limited discontinuities, using a multitude of sensors with varying spatial-temporal characteristics, in combination with solid and continuous ground observations (Schaepman et al., 2007). This requirement is also in line with the recently postulated complete observing system within the Global Earth Observation System of Systems (GEOSS). Sampling units for remotely sensed change detection can still be much larger than those used in most field surveys. In addition, once the objects are identified within the samples, remote sensing can provide excellent methods for the monitoring of specific bio-physical and bio-chemical parameters of objects, e.g., albedo, leaf area index, fractional cover, vegetation height, plant pigment and non-pigment retrieval at leaf or canopy level (Turner et al., 1999; Cohen et al., 2003; Schaepman-Strub et al., 2006; Zimmerman et al, 2007; Joshi et al., 2008; Ustin et al., 2009). Time-series analysis of satellite imagery as a special case of change detection is especially suited for the identification of trends in phenology (eg. length of the growing season), as White and Nemani (2006) have shown for real-time monitoring of land surface phenology; White at al. (2009) for the long-term changes in phenology in North-America and De Wit and Mücher (2009) for phenological trends in Europe. There are also improvements possible in thematic land cover, e.g., separation of evergreen from deciduous forests as different land cover types or plant functional groups (Vancutsem et al., 2009). However, remote sensing can not solve the whole information chain. Remote sensing will always require ground truth information, not only for training and calibration of the used methodology but also for validation, since, although it addresses spatial and temporal scales inaccessible to traditional field surveys, it cannot match the accuracy and detail of in-situ measurements (Gross et al., 2009). For field surveys involving estimates of the percentage cover of each life form and associated percentage of dominant species (both in vertical projection), efficient protocols in field recording, as presented in Chapter 6, are important for integration with remotely sensed information. Spatial accuracy and scale of the field measurements remain crucial for the integration with remote sensing (Zimmermann et al., 2007) and are important characteristics of the proposed field methodology (Bunce at al., 2008). Field surveys are indispensable because many changes in habitats are gradual shifts in habitat quality, such as changes in species abundance. Changes in land management such as adaptation to organic farming are also difficult to detect directly by remote sensing. While detailed vegetation records are not required for monitoring the habitat extent, such data are essential in determining habitat quality and condition, i.e. conservation status (Bunce et al., 2008). Nevertheless, measuring step-wise changes in habitat quality remains as important as measuring changes in habitat quantity. A good principle is the concept that is provided by the Natural Capital Index (Ten Brink and Tekelenburg, 2002).

As long as an appropriate sampling scheme is used, the methodology for field surveys proposed in Chapter 6 provides a robust baseline for monitoring changes in habitats, and although its cost may seem high, it is relatively low in comparison with the estimation of Lengyel et al. (2008) that 80 million Euro are spent annually on 123 national habitat monitoring schemes. A stratified random sampling of 1 km^2 sample units is proposed for Europe (see also Appendix 1). Much can be said about the sample size, but smaller sample sites are not suitable for the integration with satellite sensors having a range of spatial resolutions (from 0.5 m to 1000 m) and are not cost-efficient since travel time may become expensive. Larger samples sizes could be suitable, but then it is recommended to use more sample sites instead of larger samples to reduce the standard deviation of error, as discussed in Jongman et al. (2006).

Although design-based sampling is less flexible than model-based sampling (Gruijter et al., 2006), the former is preferred since assumptions can be limited and therefore more robust. Such a survey of habitats is essential in Europe as a baseline to compare the widely different national activities on habitat monitoring. Moreover, existing long-term (national) integrated monitoring programmes are difficult to harmonize and have been basically designed for national priorities. Failure to achieve an appropriate statistical structure for a monitoring programme will jeopardize the credibility of the results and support for the programme itself (Parr et al., 2002).

The methodology for field surveillance can provide suitable in-situ sites for the validation and calibration of the habitat distribution maps described above, but it can also be used to calibrate land cover changes, as detected by remotely sensed information, with the changes in habitats obtained from the field survey to produce, not only trends in habitats for Europe, but also to anticipate the implications of actual and future land cover changes.

Although the frequency of remote sensing measurements is usually higher than for field measurements, decisions have to be made about the frequency of recording from space and in the field. Landscapes and habitats differ widely in their dynamics and may therefore require different frequencies of recordings. However, in the case of sample sites across Europe, a fixed frequency is suggested, to avoid misleading conclusions. A six-year cycle, as required for reporting under Article 17 of the Habitat Directive, seems to be optimal. However, in many European regions, within a given year, three high-resolution satellite images may be required to interpret the highly seasonal vegetation cover. In terms of the habitat types and life forms as the basis for the GHCs it is recommended to investigate more the possibilities of Lidar data in combination with ESA’s Sentinel satellite family of optical and radar sensors (see also www.esa.int) to discriminate these classes.

Identified changes in land cover and associated habitats need to be analysed, summarised and reported at the different scales, e.g., by using the different levels of the European landscape classification (LANMAP) combined with possible driving forces that can be derived from e.g. socio-economic data and scenario studies (Mücher et al., 2008). Nowcasting (actual monitoring), as well as hindcasting (historical monitoring), e.g EU project BIOPRESS

(Linking pan-European land cover changes to pressures on biodiversity; Gerard et al., 2009) and forecasting (scenario building; Kok et al., 2007) are equally important. Knowledge of trends in land cover changes (land cover flows), not only *how much* but also *where* and *when* changes have occurred, can help land managers to identify key resource and ecosystem stressors, as well as prioritize management efforts (Wang et al., 2009). Unfortunately, within European programmes currently more effort and resources are invested in scenario building than in actual monitoring of land cover and habitats.

Further research is therefore necessary in the future in order to understand the interaction of changes at diffent scales in our landscapes, and to assess the uncertainties in measurements and their propagation in time and space. Robust biodiversity observation networks that exploit both remote sensing and field surveys, in combination with appropriate data infrastructures, are essential to facilitate operational monitoring, not only at the European level, but also at global scales. This is also anticipated by USA National Ecological Observatory Network (NEON), in which the observatory design (NRC, 2003) has the overarching goal to enable understanding and forecasting of the impacts of climate change, land use change and invasive species on continental-scale ecology by providing infrastructure, and incorporating long term observation sites to support research in these areas. The NEON observation sites unfortunately, do not follow the principles of a proper sampling design, which is the same problem for the European Long Term Ecological Research (LTER) sites. LTER-Europe is Europe's long-term ecosystem research and monitoring (LTER) network. It was formally launched in June 2007, as a result of ALTER-Net work to develop the network (http://www.alter-net.info). Therefore, next to these LTER sites, a baseline monitoring system of our habitats remains an urgent requirement next to LTER sites and national monitoring programmes. The approach requires organizational skills that can be facilitated by incorporation into international programmes such as GMES and GEO.

References

Belward, A. S., 1999. International co-operation in satellite sensor calibration; the role of the CEOS Working Group on Calibration and Validation. Adv. Space Res. 23 (8), 1443-1448.

Bunce, R.G.H., Groom, G.B., Jongman, R.H.G., Padoa-Schioppa, E. (Eds.), 2005. Handbook for surveillance and monitoring of European Habitats, 1st edn. Alterra report 1219, Wageningen.

Bunce, R.G.H., Metzger, M.J., Jongman, R.H.G., Brandt, J., De Blust, G., Elena-Rossello, R., Groom, G.B., Halada, L., Hofer, G., Howard, D. C., Ková, P., Mücher, C.A., Padoa-Schioppa, E., Paelinx, D., Palo, A., Perez-Soba, M., Ramos, I.L., Roche, P., Skånes, H., Wrbka, T., 2008. A standardized procedure for surveillance and monitoring European habitats and provision of spatial data. Landscape Ecol. 23 (1), 11-25.

Burnett, C., Blaschke, T., 2003. A multi-scale segmentation/object relationship modelling methodology for landscape analysis. Ecol. Model. 168 (3), 233-249.

Büttner, G., Feranec, J., Jaffrain G., 2002. Corine land cover update 2000: Technical guidelines. Technical report 89. EEA, Copenhagen, 2002, 56 pp.

Champeaux, J.L., Mücher, C.A., Steinnocher, K., Griguolo, S., Wester, K., Goutorbe, J.P., Kressler, F., Heunks, C., van Katwijk, V.F., 2000. PELCOM Project: A 1-km pan-European land cover database for environmental monitoring and use in meteorological models. Proceedings Int. Geosci. Remote Sens. (IGARSS), 5, pp. 1915-1917.

Chen, J., 2005. Quality evaluation of topographic data from SRTM3 and GTOPO30. Geomat. Inform. Sci. Wuhan Univ. 30 (11), 941-944.

Chen, C. F., Chen, M. H. 2005. Generalization of GIS polygon data using curvature-based approach. Int. Geosci. Remote Sens. (IGARSS), 5, 3498-3501.

Cohen, W. B., Maiersperger, T. K., Gower, S. T., Turner, D. P., 2003. An improved strategy for regression of biophysical variables and Landsat ETM+ data. Remote Sens. Environ. 84 (4), 561-571.

Coppin, P., Jonckheere, I., Nackaerts, K., Muys, B., Lambin, E., 2004. Digital change detection methods in ecosystem monitoring: A review. Int. J. Remote Sens. 25 (9), 1565-1596.

De Wit, A., Mücher, C.A., 2009. Satellite-derived trends in phenology over Europe: real trends or algorithmic effects. Poster presented at the General Assembly 2009 of the European Geosciences Union (EGU), from 19 – 24 April 2009 , Vienna, Austria.

Evans, D., 2006. "The habitats of the European union habitats directive. Proc. Royal Irish Acad.-Section B, Biol. Environ. 106 (3): 167-173.

Feranec, J., Hazeu, G., Christensen, S., Jaffrain, G., 2007. Corine land cover change detection in Europe (case studies of The Netherlands and Slovakia). Land Use Policy 24 (1), 234-247.

Gerard, F., Bugar, G., Gregor, M., Halada, L., Hazeu, G., Huitu, H., Köhler, R., Kolar, J., Luque, S., Mücher, C.A., Olschofsky, K., Petit, S., Pino, J., Smith, G., Thomson, A., Wachowicz, M., Bezák, P., Brown, N. M., Boltiziar, E., 2009. Determining Europe's land cover changes over the past 50 years using aerial photographs. Submitted to Journal of Land Use Science.

Groom, G., 2005. Methodological review of existing classifications, in: Wascher, D.M. (Ed.), European Landscape Character Areas – Typology, Cartography and Indicators for the Assessment of Sustainable Landscapes. Final ELCAI project report, Landscape Europe, pp. 32-45.

Groom, G., Mücher, C.A., Ihse, M., Wrbka, T., 2006. Remote sensing in landscape ecology: experiences and perspectives in a European context. Landscape Ecol. 21 (3 Spec. Iss.), 391-408.

Gross, J. E., Goetz, S. J., Cihlar, J., Application of remote sensing to parks and protected area monitoring: Introduction to the special issue. Remote Sens. Environ. DOI: 10.1016/j.rse.2008.12.013. In Press.

Gruijter, J. J., Bierkens, M. F. P., Brus, D. J., Knotters, M., 2006. Sampling for Natural Resource Monitoring. Berlin, Heidelberg, Springer-Verlag Berlin Heidelberg, 332 pp.

Haest, B., Kempeneers, P., Cheung-Wai Chan, J., Vanden Borre, J., Kooistra, L., Mücher, C.A., Deronde, B., 2009. Spectral comparison of Chris/Proba and AHS hyperspectral imagery in the framework of NATURA 2000 habitat monitoring. 6th EARSeL SIG IS workshop "Imaging Spectroscopy: Innovative tool for scientific and commercial environmental applications" Tel-Aviv, Israel, 16-19 March 2009.

Herold, M., Woodcock, C.E., Loveland, T.R., Townshend, J., Brady, M., Steenmans, C., Schmullius, C.C., 2008. Land-cover observations as part of a global earth observation system of systems (GEOSS): Progress, activities, and prospects. IEEE Systems Journal 2 (3), 414-423.

Jongman, R.H.G., Bunce, R.G.H., Metzger, M.J., Mücher, C.A., Howard, D.C., Mateus, V.L., 2006. Objectives and applications of a statistical environmental stratification of Europe. Landscape Ecol. 21 (3), 409-419.

Joshi, P. K., Gupta, B., Roy, P. S., 2008. Spectral evaluation of vegetation features using multi-satellite sensor system (Terra ASTER, Landsat ETM+ and IRS 1D LISS III) in man-made and natural landscape. Sensor Review 28 (1), 52-61.

Kindler, A., 2005. Geo-spatial Cross-Analysis of LANMAP and National Approaches, in: Wascher, D.M. (Ed.), European Landscape Character Areas – Typology, Cartography and Indicators for the Assessment of Sustainable Landscapes. Final ELCAI project report, Landscape Europe, pp. 46-87.

Kok, K., Verburg, P. H., Veldkamp, T., 2007. Integrated Assessment of the land system: The future of land use. Land Use Policy 24 (3), 517-520.

Lengyel, S., Déri, E., Varga, Z., Horváh, R., Tóthmérész, B., Henry, P. Y., Kobler, A., Kutnar, L., Babij, V., Seliskar, A., Christia, C., Papastergiadou, E., Gruber, B., Henle, K., 2008. Habitat monitoring in Europe: A description of current practices. Biodivers. Conserv. 17 (14), 3327-3339.

Meeus, J.H.A., 1995. Pan-European landscapes. Landscape Urban Plan. 31 (1-3), 57-79.

Mücher, C.A., Steinnocher, K.T., Kressler, F.P., Heunks, C., 2000. Land cover characterization and change detection for environmental monitoring of pan-Europe. Int. J. Remote Sens. 21 (6-7), 1159-1181.

Mücher, C.A., Champeaux, J.L., Steinnocher, K.T., Griguolo, S., Wester, K., Heunks, C., Winiwater, W., Kressler, F.P., Goutorbe, J.P., ten Brink, B., van Katwijk, V.F., Furberg, O., Perdigao, V., Nieuwenhuis, G.J.A., 2001. Development of a consistent methodology to derive land cover information on a European scale from remote sensing for environmental monitoring; the PELCOM report. Alterra-rapport 178, Wageningen, the Netherlands.

Mücher, C.A., Kramer, H. Thunnissen H.A.M., Clement, J., 2003. Monitoren van kleine landschapselementen met IKONOS satellietbeelden (Monitoring of small landscape elements using IKONOS satellite imagery). Alterra rapport 831, CGI rapport 03-008, Alterra, Wageningen, 96 pp.

Mücher, C.A., Hennekens, S.M., Bunce, R.G.H., Schaminée, J.H.J., 2004. Mapping European habitats to support the design and implementation of a pan-European ecological network; the PEENHAB-project. Alterra report 952, Wageningen, the Netherlands.

Mücher, C.A., S.M. Hennekens, R.G.H. Bunce and J.H.J. Schaminée, 2005. Spatial identification of European habitats to support the design and implementation of a Pan-European Ecological Network, in McCollin. D., Jackson J.I. (Eds.), Planning, People and Practice. The landscape ecology of sustainable landscapes. Proceeding of the 13th Annual IALE(UK) Conference held at the University of Northampton, 2005, pp. 217-225.

Mücher, C.A., Wascher, D.M, Klijn, J.A., Koomen, A.J.M., Jongman, R.H.G., 2006. A new European Landscape Map as an integrative framework for landscape character assessment. In: Bunce R.G.H., Jongman, R.H.G. (Eds.), Landscape Ecology in the Mediterranean: inside and outside approaches, 2006. Proceedings of the European IALE Conference 29 March – 2 April 2005 Faro, Portugal. IALE Publication Series 3, pp. 233-243.

Mücher, C.A., Vos, C.C., Renetzeder, C., Wrbka, T., Kiers, M.A., van Eupen, M., Bugter, R. J.F., 2007. The application of satellite imagery to identify landscape structure. Proceedings of the IALE 2007 World Congress July 8th - 12th , Wageningen, the Netherlands, Wageningen, IALE, pp. 590-591.

Mücher, C. A., Wascher, D. M. 2007. European Landscape Characteracterization, in: Pedroli, B., van Doorn, A., de Blust, G., Paracchini, M.L., Wascher, D., Bunce, F. (Eds.), Europe's Living Landscapes. KNNV Publishing in cooperation with Landscape Europe, Zeist, pp. 37-43.

Mücher, C.A., Hazeu, G.W., Swetnam, R., Pino, J., Halada, L., Gerard, F., 2008. Historic land cover changes at Natura 2000 sites and their associated landscapes across Europe. Proceedings 28th EARSeL Symposium: Remote Sensing for a Changing Europe, Istanbul, Turkey, 2 - 7 June 2008, Istanbul, Turkey, pp. 226-231.

Mücher, C.A., Hennekens, S.M., Bunce, R.G.H., Schaminée J.H.J., Schaepman, M.E., 2009a. Modelling the spatial distribution of Natura 2000 habitats across Europe. Landscape Urban Plan. 92 (2), 148-159.

Mücher, C.A., Klijn, J.A., Wascher, D.M., Schaminée, J.H.J., 2009. A new European Landscape Classification (LANMAP): A transparent, flexible and user-oriented methodology to distinguish landscapes. Ecol. Indicat., doi:10.1016/j.ecolind.2009.03.018. In Press.

NRC (National Research Council), 2003. NEON: Addressing the Nation's Environmental Challenges. Washington DC: National Academies Press.

Parr, T. W., Ferretti, M., Simpson, I. C., Forsius, M., Kovács-Láng, E., 2002. Towards a long-term integrated monitoring programme in Europe: Network design in theory and practice. Environ. Monit. Assess. 78 (3), 253-290.

Pekkarinen, A., Reithmaier, L., Strobl, P., 2009. Pan-European forest/non-forest mapping with Landsat ETM+ and CORINE Land Cover 2000 data. ISPRS J. Photogramm. 64 (2), 171-183.

Perdigão, V., Annoni, A., 1997. Technical and methodological guide for updating CORINE land cover database, Joint Research Centre, Ispra.

Peterseil, J., Wrbka, T., Plutzar, C., Schmitzberger, I., Kiss, A., Szerencsits, E., Reiter, K., Schneider, W., Suppan, F., Beissmann, H., 2004. Evaluating the ecological sustainability of Austrian agricultural landscapes-the SINUS approach. Land Use Policy 21 (3), 307-320.

Renetzeder, C., van Eupen, M., Mücher, C.A., Wrbka, T., 2008. A Spatial Regional Reference Framework for Sustainability Assessment in Europe, in: Helming, K., Perez-Soba, M., Tabbush, P. (Eds.), Sustainability Impact Assessment of Land Use Changes. Springer, Berlin Heidelberg New York, ISBN 978-3-540-78647-4, pp 249- 268.

Raunkiaer, C., 1934. The life forms of plants and statistical plant geography, being the collected papers of C Raunkiaer. Clarendon, Oxford.

Schaminée, J.H.J., Hennekens, S.M., Ozinga, W.A., 2007. Use of the ecological information system SynBioSys for the analysis of large datasets. J. Veg. Sci. 18, 463-470.

Schaepman, M.E., Malenovsky, Z., Mücher, C.A., Kooistra, L., Thullier, W., 2007. Bridging Scaling Gaps for the Assessment of Biodiversity from Space. In: The Full Picture. A publication for the GEO Ministerial Summit, 'Earth Observation for Sustainable Growth and Development' Cape Town, 30 November 2007. Editor GEO Secretariat, Geneva (CH),. Tudor Rose, pp. 258-161.

Schaepman-Strub, G., Schaepman, M. E., Martonchik, J., Schaaf, C. 2006. What's in a satellite albedo product? Int. Geosci. Remote Sens. (IGARSS), 2848-2851.

Shi, W. Z., Ehlers, M., Molenaar, M., 2005. Uncertainties in integrated remote sensing and GIS. Int. J. Remote Sens. 26 (14), 2911-2915.

Ten Brink, B.J.E., T. Tekelenburg (2002). Biodiversity: how much is left? The Natural Capital Index framework (NCI).RIVM report 402001014. Bilthoven.

Turner, D. P., Cohen, W. B., Kennedy, R. E., Fassnacht, K. S., Briggs, J. M., 1999. Relationships between leaf area index and Landsat TM spectral vegetation indices across three temperate zone sites. Remote Sens. Environ. 70 (1), 52-68.

Ustin, S., Gitelson, A.A., Jacquemoud, S., Schaepman, M.E., Asner, G., Gamon, J.A., & Zarco-Tejada, P., 2009. Retrieval of Foliar Information about Plant Pigment Systems from High Resolution Spectroscopy. Remote Sensing of Environment. In Press.

Vancutsem, C., Pekel, J. F., Evrard, C., Malaisse, F., Defourny, P., 2009. Mapping and characterizing the vegetation types of the Democratic Republic of Congo using SPOT VEGETATION time series. International Journal of Applied Earth Observation and Geoinformation 11 (1), 62-76.

Van Eetvelde, V., Antrop, M., 2009a. Indicators for assessing changing landscape character of cultural landscapes in Flanders (Belgium). Land Use Policy 26 (4), 901-910.

Van Eetvelde, V., Antrop, M., 2009b. A stepwise multi-scaled landscape typology and characterisation for trans-regional integration, applied on the federal state of Belgium. Landscape Urban Plan. In Press.

Van der Heijden, R.B.J., 2007. Characterization of European Landscapes and analysis of their dynamics. Internal CGI Report, Alterra, Wageningen, the Netherlands, pp 1370.

Wascher, D.M., Groom, G.B., Mücher, C.A., Kindler, A., 2005. Recent developments in Mapping Europe's landscapes, in Wascher, D.M. (Ed.), European Landscape Character Areas. Typologies, Cartography and Indicators for the Assessment of Sustainable Landscapes. Final ELCAI Project Report (ELCAI-EVK2-CT-2002-80021).

Wang, Y., Mitchell, B. R., Nugranad-Marzilli, J., Bonynge, G., Zhou, Y., Shriver, G., 2009. Remote sensing of land-cover change and landscape context of the National Parks: A case study of the Northeast Temperate Network. Remote Sens. Environ. DOI: 10.1016/j.rse.2008.09.017. In Press.

White, M. A., Nemani, R. R., 2006. Real-time monitoring and short-term forecasting of land surface phenology. Remote Sens. Environ. 104 (1), 43-49.

White, M. A., de Beurs, K.M., Didan, K., Inouye, D.W., Richarson, A.D., Jensen, O.P. et al., 2009. Intercomparison, interpretation, and assessment of spring phenology in North America estimated from remote sensing for 1982–2006. Global Change Biology (2009), doi: 10.1111/j.1365-2486.2009.01910.x. In Press.

Woodward, F.I., Rochefort, L., 1991. Sensitivity analysis of vegetation diversity to environmental change. Glob. Ecol. Biogeogr. Lett. 1:7-23.

Wrbka, T., Erb, K.H., Schulz, N.B., Peterseil, J., Hahn, C., Haberl, H., 2004. Linking pattern and process in cultural landscapes. An empirical study based on spatially explicit indicators. Land Use Policy 21 (3), 289-306.

Xian, G., Homer, C., Fry, J., 2009. Updating the 2001 National Land Cover Database land cover classification to 2006 by using Landsat imagery change detection methods. Remote Sens. Environ. 113 (6), 1133-1147.

Zimmermann, N.E., Washington-Allen, R.A., Ramsey, R.D., Schaepman, M.E., Mathys, L., Kötz, B., Kneubühler, M., Edwards, T.C., 2007. Modern remote sensing for environmental monitoring of landscape states and trajectories, in: Kienast, F., Wildi, O., Ghosh, S (Eds.), A Changing World: Challenges for Landscape Research. Published by Springer, Dordrecht, pp.65 - 91.

Appendix I

Sampling framework and strategy for monitoring of European habitats

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Joint position paper of the EU projects BIOHAB (EVK2-CT-2002-20018) and BIOPRESS (EVK2-CT-2002-00178). The contribution of C.A. Mücher to this work is: 35 % design paper, 20% development of methodology and 20% writing.

A.1 Objectives

The objective of this position paper is to provide a recommendation on the design of a sampling and monitoring strategy of European habitats to provide statically reliable European estimates on the extent of habitats and their associated changes. The habitat methodology that is recommended for a European monitoring system are the General Habitat Categories (GHC's) of the BIOHAB project which are the lowest common denominator for linking existing classifications and are pragmatic for field surveys in Europe. It is recognised to provide a basis for policy formulation that enables to collect information on EUNIS habitat categories (EEA) or Natura 2000 habitat categories (Habitat Directive). It is suggested to record these typologies in the field were possible. This position paper has the flexibility to choose between one or more habitat typologies but focuses especially on the stratification and sampling design.

Box 1. Development of a method:

- *To consistently collect and update information on European habitats both from inside and outside protected areas from each country and to assess impacts on biodiversity.*

- *To contribute to a unified dataset for habitats and eventually biodiversity across national borders recognising individual national interests.*

- *To support European biodiversity policy.*

A.2 Background

A.2.1 Mandate

A.2.1.1 Both the BIOHAB and BIOPRESS research communities were posed the same question (by EEA and DG Research) i.e. in which way and with how many samples could the rich variety of European habitats be best monitored based on the project experiences. Hereafter, a collaboration started between both European funded projects to discuss the appropriate scheme for monitoring scheme and how many samples would approximately being needed. The two projects are directly complementary as BIOHAB provides rules for collecting in-situ data and a sampling framework whereas BIOPRESS provides a methodology based on Earth Observation data for (historical) land cover changes linked to pressures. The result of this discussion is this position paper.

A2.1.2 The primary objective of the BioHab project was to describe a methodology appropriate for coordinating information on habitats in order to obtain statistically robust estimates of their extent and associated changes in biodiversity. The BioHab methodology is a system for consistent field recording of habitats and for subsequent monitoring. It is based on tried and trusted existing procedures which have been proven in practice in the field over several decades, the first handbook being produced for the GB woodland survey in 1971. The recording procedure involves disaggregated data which can then be combined in a flexible way for specific objectives using standard database management techniques. The current handbook for surveillance and monitoring of European habitats is the main BIOHAB product. For more information see their homepage: www.biohab.alterra.nl .

A2.1.3 BIOPRESS is a project funded in the framework of the dedicated call under EC-FP5 for research to support GMES ‘Global Monitoring for Environment and Security’. It is the only GMES project under the priority theme "Land cover change in Europe”. The BIOPRESS aims to provide the EU-user community with quantitative information on how changes in land cover and land use have affected the environment and biodiversity in Europe. The major stakeholder is the European Environment Agency, through its Topic Centres on Biological Diversity (ETC-BD) and Land Use and Spatial Information (ETC-LUSI). Other potential users are DG Environment, DG Regional Policy, the GMES project LADAMER, National conservation agencies and regional and local authorities responsible for Natura-2000 sites. The project is currently producing consistent and coherent sets of historical (1950 – 1990 – 2000) land cover change information in and around more than 100 Natura-2000 sites located from the boreal to the Mediterranean, and from the Atlantic to the continental zones of Europe. For more information see their homepage: http://www.creaf.uab.es/biopress/.

A2.2 The Policy Problem

A.2.2.1 In Europe the biodiversity in cultural landscapes (which form the major part of Europe's countryside) is under threat. Due to modern management techniques in agriculture and forestry and increased impact of urban and transport infrastructure, the extent and the quality of habitats across Europe decreased dramatically. These trends are recognized widely and are forcing national and international bodies to adapt their current nature conservation policies in order to support well established habitat networks and to improve environmental and spatial conditions suitable to maintain regionally specific biodiversity. The Natura 2000 network is the best known in this respect for the protection of primary nature conservation areas. This instrument is undoubtedly successful, but at the same time, it is generally understood that it does not guarantee the preservation of biodiversity in the wider countryside

A.2.2.2 Biodiversity of the countryside and the environmental conditions that sustain it, are of importance for a number of reasons, e.g.:

- Many species have their primary habitat in protected areas but also depend on the wider countryside in one way or another (e.g., during migration, dispersion, foraging);
- Due to geophysical factors, e.g., groundwater level, acting at the landscape scale, the environmental pressures influencing biodiversity of the rural areas may also affect habitat quality inside the protected areas;
- There is a demand by society to have biodiversity within ready access, in everyday countryside, as well as in designated nature areas.

A.2.2.3 As a result, there is a need to develop appropriate policy instruments for nature conservation outside protected areas, equal with those applied for the protected areas. Although recognized as such and adopted as a general objective by EU policy (see e.g., the reform of the CAP, Rural Development Regulations and re-organisation of agri-environment schemes), the elaboration and implementation of such instruments proceeds slowly. A major reason for that is the lack of a strategic framework to link national programmes or to provide

European figures for the extent of habitats and biodiversity. However, the production of such figures is fundamental for policy formulation for the maintenance and enhancement of biodiversity across Europe. Thus, the European Commission states that it is necessary to identify the conservation status and trends of components of biodiversity as well as to identify relevant pressures and threats together with their causes on components of biodiversity. The Topic Centre on Nature Conservation and the European Environment Agency (EEA) are probably the most appropriate institutions to compile these data as a base for a European conservation policy outside designated areas. Having the disposal of common data is also a concern for OECD (Organisation for Economic Co-operation and Development), who -during an expert meeting November 2001 in Zürich- expressed the urgent need for well established agri-biodiversity indicators to assess and monitor the impact of agriculture on biodiversity in their member states. Thus, it seems that the interest and the political will are there, only a common methodology that can provide reliable data and a strategic and international framework are missing.

A.3 Principle requirements for European habitat monitoring

A3.1 Data collected for habitats in Europe are using a multiplicity of procedures. Those that are collected systematically for habitats can enable statistically reliable conclusions to be drawn. For Europe-wide monitoring and reporting such data are essential for policy support. Other descriptive information and individually selected sites cannot be used for statistical analysis of representativeness although they are useful in other ways, such as lists of habitats in a given site. So far, no consistent estimates of the extent of habitats in Europe have been produced and therefore no measures of change. By contrast, data from individual species such as birds and butterflies are now available because they can be recognised without rules and partly because of a massive contribution from volunteers.

A.3.2 The present position paper shows how this widely recognised gap can be filled and what time and costs are involved. Any proposal for habitat monitoring must include three main target groups:

1. Natura 2000 sites.

2. Twinned stratified random samples chosen from outside Natura 2000 sites.

3. Long-term monitoring sites, eg. Alternet sites.

It may also be necessary to target rare habitats in all three groups. The main topics concerning these requirements are as follows:

1. Natura 2000 sites. They differ in size, frequency and selection procedure between countries. To obtain a fully coordinated database would require major reserves but undoubtedly some common ground could be found. There is no doubt however that there is a major demand for getting the national data from the sites onto a common basis. Discussions are continuing in relation to the Dutch sites and the state of other national databases also needs to be assessed. Within Natura 2000 sites, these categories of habitats need to be considered:

    a) Widespread habitats that will be picked up by random sampling e.g., Species-rich Nardus grasslands (6230)

    b) Habitats of restricted distribution in Natura 2000 sites, which will have to be targeted e.g., Arborescent matorral with Juniperus spp (5210)

    c) Very rare habitats where a small site has been identified specifically for that habitat, e.g., Palm groves of Phoenix (9370).

    Thereafter, additional samples may needed to be included based on specific requirements. These considerations will require complex analysis (eg. the need to take into account national differences in the approach to Natura 2000 site designation)

2. Twinned stratified samples. There is no doubt that it is essential to have a common reference data set against which Natura 2000 sites can be compared and to review the impact of conservation policies. Data gathering from such a series of sites could proceed independently of the analysis of

Natura 2000 sites, as shown in Fig. A.1, but would need subsequent additional sites to ensure the twinning was as efficient as possible. The comparison of profile of Natura 2000 sites with non designated areas will reveal much about protection policy, e.g., in England most high quality calcareous grass and lowland heath is already protected whereas riverside vegetation is mainly outside such area. Targetting of very rare habitats will also need careful attention.

3. Long-term monitoring sites (LTER sites eg. Alternet sites for detailed monitoring). There has been little attention paid as to how sites in which a detailed intensive monitoring of parameters such as SO2 and NOx can be related to the wider population. These sites are essential in explaining the mechanisms behind widely occurring or extensive changes, e.g., the detailed site analysis of pH change of the Forestry Commission in Alice Holt was able to explain the widely observed increase in pH in British woodlands. A combination of using the BioHab habitat categories (GHC's) together with the European Environmental Stratification is a way forward to provide a common European Framework.

A.3.3 The BioHab mapping procedure is based on the recording of General Habitat Categories, which are defined by plant life forms. These life forms reflect the structure of vegetation and enable the main series of European habitats to be defined consistently. Thus at one extreme there are the evergreen forests of southern Spain and at the other the open dwarf heaths of the high mountains and arctic environment. In the BioHab project strict rules have been developed for recording habitats consistently throughout Europe and the procedure has been validated in the field for all Environmental Zones in Europe.

A.3.4 As the entire land surface must be mapped, there are also General Habitat Categories for "urban", "crops" and "sparsely vegetated land". For each polygon, information regarding global, site and management qualifiers is added in a standardised way. Detailed life form composition and dominant species are also recorded as well as basic information on biodiversity. Areal elements (> 400 m^2) are mapped separately from linear (> 30m) and point elements. Explicit definitions are provided for life forms and qualifiers and strict rules for mapping, so that the problem of subjective interpretation is kept to a minimum (for an example see Annex 1).

A.3.5 A systematic monitoring approach for Europe must consist of several steps and every action for collection of new data will first have to consider what existing data are available and how they can be used and interpreted. For example, there are several European datasets that can deliver supporting data (e.g., on soil, geomorphology and hydrology). Also several national initiatives exist, which deliver nation-wide samples on (selected) habitats (such as the UK Countryside survey, Spain (Sispares) and the Swedish Environmental mapping project NILS).

A.3.6 The BIOPRESS project has developed a EO methodology to detect historical changes linked to pressures. The linking of this approach to in-situ recording would not only provide hard evidence but also to vital long-term information on countryside changes.

A.3.7 Developing an approach for European habitat monitoring requires inclusion of these data of existing data and a system that delivers data that can be used as a comparable set for all Europe. For monitoring of habitats the 25 members of the European Union are considered as the basis of the system. However calculations on time and costs can be made for a wider frame including also eastern neighbours and accession countries. The contrast between rates of changes between countries are not only of great scientific interest but would also be fundamental to policy formulation.

A.3.8 The Biohab project has concluded that the way forward is to measure habitat diversity as a proxy for biodiversity on the basis plant life forms but also including information on environmental variation in humidity and trophic level using a stratified random sampling system dispersed on a grid. The monitoring system should consist of a baseline monitoring system combined with selected sites for intensive sampling in conservation sites (NATURA 2000) and sites for intensive ecological monitoring. These three systems deliver ground truth for general observation, information on conservation policy measurements and in depth information on ecological (and socio-economic) development.

A.4 Baseline monitoring

A. 4.1 Site selection

A.4.1.1 For an EU baseline on habitats and land use it is important to make a site selection for habitat recording related to existing systems. This can be done by using a grid such as the LUCAS structure combined with a stratified random sample over Europe. This baseline therefore should consist of 1 km^2 sample units that are representative for a region. The fewer squares are needed the more cost efficient the method will be. Therefore sample reduction and representativeness of samples are important for determining a sample set for Europe. For the interpretation of the samples the costs can be partly reduced by starting with interpretation of very high resolution satellite images or aerial photographs as has been done within the BIOPRESS project.

A.4.1.2 This EU baseline data can be validated and integrated with other datasets such as CORINE land cover, the Alternet LTER sites (long term ecological research sites, LTER), national monitoring databases (Countryside Survey (UK), SISPARES (ES), Swedish monitoring system (SE) and others (Fig.A.1).

Fig. A.1 shows the extent of the monitoring databases which are now available and how they need to be processed to optimise overall performance of the available statistics. However, whilst this exercise is technically feasible if linked through the stratification system described below, the costs will be very high and will take many years of work. The diagram shows that the present proposal is separate from this complex analysis and could proceed within a short time without duplicating any of the work which would be needed to obtain a completely integrated data analysis. The independent figures produced for habitat extent would not only support all the projects within Fig. A.1, but would also provide a basis for monitoring.

A4.1.3 A baseline series can be linked to monitoring in NATURA 2000 sites to show the links between the wider countryside and protected areas (favourable conservation status) and interpreted on changes in the cultural landscape. The combination of EO observation, baseline monitoring, Natura 2000 and LTER sites allows for national and international comparative studies and generalisations at the lowest possible costs and with statistical rigour needed for reliable reporting.

A4.1.4 Baseline monitoring should be linked with monitoring in NATURA 2000 sites to show the contrasts between the baseline and protected areas (favourable conservation status) and assist interpretation of changes in the cultural landscape. Only then can the effectiveness conservation measures be determined. The combination of EO observation, baseline monitoring, Natura 2000 and LTER sites allow for national and international comparative studies and generalisations at the lowest possible costs and with statistical rigour needed for reliable reporting.

A.4.2 Stratification

A 4.2.1 Strata such as those from the European Environmental Strata (Metzger et al., 2005) are essential for surveillance and monitoring as they are independent of land cover and land use which can change over time. The Ens has 84 strata. When excluding northern Africa and Turkey 81 strata remain.

A 4.2.2 The stratification uses 1 km^2 as the basic unit which is the most widely used scale for such strategic inventories. Subdivision of the EnS strata in altitudinal bands (AEnS) improves correlation with PELCOM landcover in all cases. For estimating ecological resources spreading the sample units across the AEnS will reduce standard errors in estimates. This advantage will be greatest in mountain regions and therefore a subdivision has been made using AEnS strata for the strata with mean altitudes > 500m. For Europe there are 81 EnS strata of which 32 have a mean altitude > 500m. When using the AEnS strata the combination of strata and substrata results in 145 strata. Statistical studies within the context of the BioHab project have shown that if use is made of a European stratification 15 squares per stratum or substratum are sufficient to obtain an overall picture of the relative extent of European General Habitat Categories (GHC). The selection of the sample data should be based on a European Environmental Zones (Metzger et al., 2005) or on the European

Landscape Classification (Mucher et al., 2009).

A 4.2.3 The estimate of sample size per stratum and the total sample for European with associated standard errors can be calculated using standard statistical procedures. In a case study for Portugal it has been shown, that even a small sample of relatively homogeneous environmental subclasses can provide sufficient estimates of land cover (Fig. A.2). Increasing the number of samples will not change the estimate, but mainly reduce the Coefficient of Variation i.e. the proportion of error.

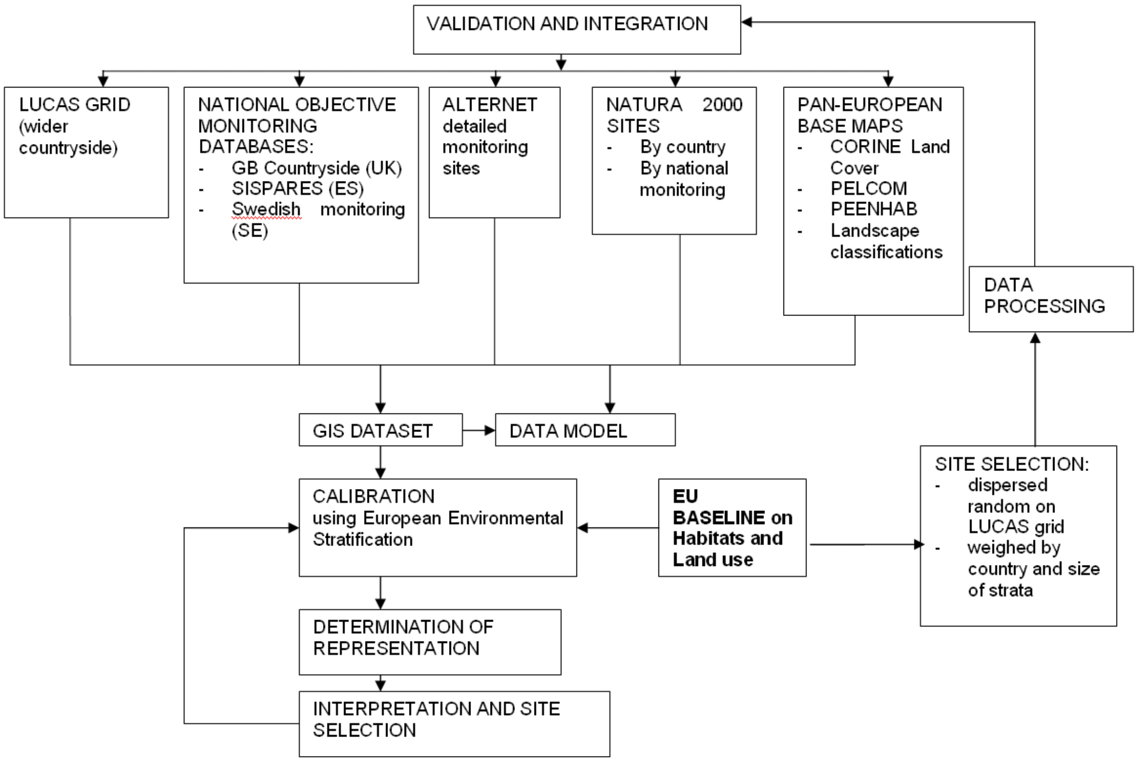

Fig. A.1 Structure for integrating field survey with current available databases.

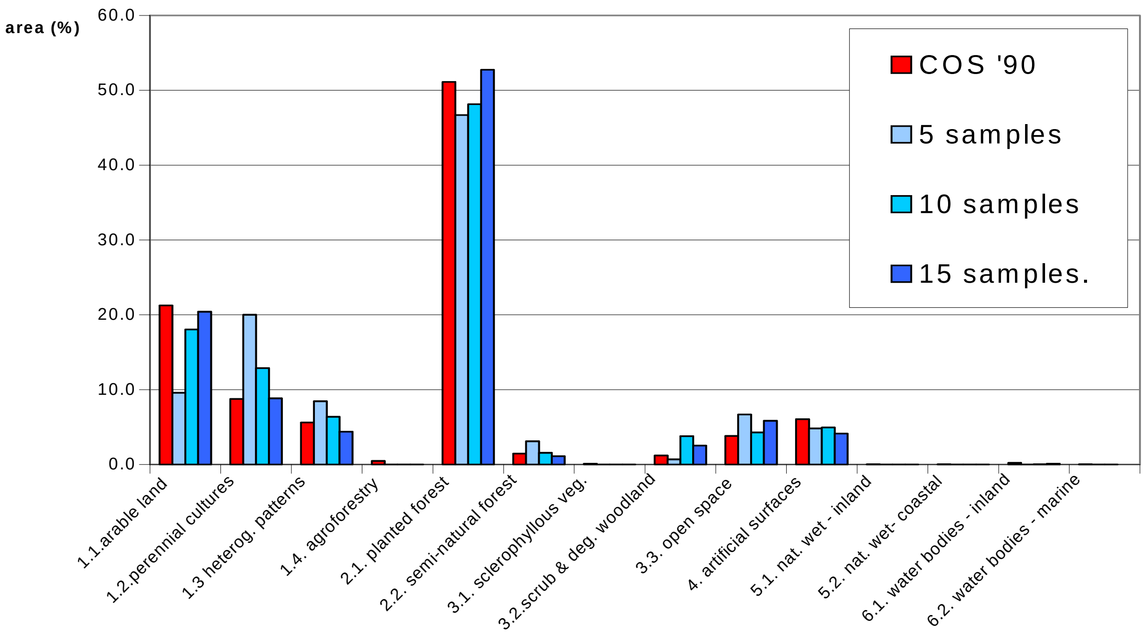

Fig. A.2 Comparison of the Portuguese land cover data base (COS) and estimates of 5, 10 and 15 samples (Jongman et al., 2006).

A.4.3 Time and costs for sampling and processing

A.4.3.1 Within the 145 strata sampling squares need to be selected and experience shows that 15 squares will be sufficient for a reliable estimate of habitats to obtain sound European estimates (Jongman et al. 2005). The would result in 2175 samples. For comparison of NATURA 2000 sites with areas outside the number of squares can be extended by eight giving a total of 23 squares per stratum. This would result in a total number of samples of 3335.

A4.3.2 It is recognised that rare habitats need a different approach. Reliable information on such habitats is often available, although usually of a descriptive nature. As long as this information is spatially referenced it could be linked to statistical estimates using the environmental strata, as has been done in Great Britain.

A4.3.2 Experience in the FP5 BioHab project, the GB Countryside Survey and the Spanish SISPARES project make it possible to estimate time required for field survey, data processing and data analysis. The estimates based on these projects are given in Table A.1. The field work time includes access time to the square. In high mountain areas this might be more than the recording time as often the habitats in these areas are simple. In lowland situations the access time is mostly less, but the complexity of a square often requires longer recording time.

A4.3.3 However, the dates of the survey need to be carefully coordinated at a regional level e.g., the higher Mediterranean mountains would need to be recorded later than southern Spain.

A.4.3.4 The average number of squares for baseline recording is 15 per stratum and the number of total squares is 23 squares including Natura 2000 sites. The squares can be dispersed on a grid or stratified random. The total number of squares is 23 for 145 AEnS in the EU25 equals 3335 km^2. A more or less equal number of squares per stratum is required, because statistical representation is important.

A4.3.5 The stratified random sample will automatically be weighted according to the relative areas of the Natura 2000 sites. If it is needed to specifically sample these sites the sample number can be increased to for example 30 (weighted it means 20 outside and 10 inside Natura 2000 sites). The details of sample size and unit size are discussed in details in Bunce et al (1996).when small numbers are taken for each stratum than an equal number is appropriate. Further samples can be added to strata that are more variable following the analysis of the initial survey data.

A4.3.6 If surveillance is carried out based on the above sample of 3325 km^2 then this requires for general habitats + linear features 3325 days. If a working year in Europe consists of 212 days then the total workload for the fieldwork in all Europe is 15.7 working years. The data processing and analysis will include 360 days for processing and 60 days for the analysis.

Table A.1 Estimates of time required for sampling and processing habitat data.

	General habitat categories Areal and linear	General habitat [a] + all qualifiers
Preparation field work + at office AP/VHRSI interpretations	1 day per sample	1 day per sample
Field work	1 km^2/day	0.5 km^2/day
Processing time/km^2	10km^2/day	10km^2/day
Analysis data set	30 days	60 days
Training of surveyors	7 days*	12 days*
Quality control	30 days	40 days
Reporting	20 days	50 days
Coordination	140 days	140 days

[a] assuming basic ecological knowledge

A.4.4 The interpretation of samples

A.4.4.1 The interpretation of samples is a combination of developed methods from Biopress and Biohab. Because of data accessibility and comparability, a very high resolution satellite imagery (VHRSI) like QuickBird, IKONOS or SPOT-5 should be considered next to the use of traditional aerial photography. However, at the moment costs of these VHRSI products are much higher than the use of AP. The average costs of aerial photography (contact prints) in Europe per square kilometre is approximately 3 euro (ask Jan Kolar to estimate exact figures)

A 4.4.2 Steps of interpretation:

1. First the site and its surrounding (size of sample site around the 1km² core area may vary with respect to landscape diversity) will be mapped by the land cover interpretation developed by BIOPRESS (so far for structures up to 0,5 hectares MMU).
2. Land cover polygons are subdivided, for the core area, by the method of BIOHAB.
3. Detected habitats, that can not be classified clearly or habitats with very high variability need to be confirmed in a field survey.

A 4.4.3 If from the sample interpretations and analysis it becomes clear that there is a correlation between the available land cover information and the habitat information this correlation can be used for extrapolation.

A 4.4.4 The cost per sample will depend on the costs for image purchasing, costs for image interpretation and field survey. By the use of so far existing sites, models and projects results, the real number of samples needed for pan-European monitoring of habitats and the related costs could be estimated in a small precursor project.

A.4.4.5 Tests of quality assurance in the Countryside Survey using random stratified repeat samples by independent surveyors have shown 95% accuracy for enclosed land (fields) and 75% for open moorlands.

A.4.5 Training of surveyors:

A.4.5.1 Surveyors must be trained for consistent performance throughout Europe and to ensure reliable recording that can traced back for validation and repeat survey to individual surveyors. This require for each group of Environmental Zones 10 working days of training. For training purposes the Environmental Zones can be divided into four major groups over the continent. In total the time required for training in habitat monitoring is 40 days for all surveyors. If there are 4 surveyors on average for each EU member state then there 160 days of training + 40 days for the trainers are required. In total this is 200 working days.

A 4.5.2 Strata groups:

- Alpine north, Boreal, Nemoral (Sweden, Norway, Finland, Lithuania, Latvia, Estonia
- Continental, Alpine south, Pannonian (Poland, Czech Republic, Germany, Slovakia, Hungary, Austria, Switzerland, Slovenia)
- Atlantic north, Atlantic south, Lusitanian (UK, Ireland, Netherlands, Denmark, Belgium, Luxemburg, France, Portugal)
- Mediterranean north, Mediterranean south, Mediterranean mountains, (Spain, Greece, Italy, Malta, Cyprus)

A.4.6 Use of a field computer

A4.6.1 For repeated and spatially consistent surveying as well as to reduce costs of data processing the use of a field computer is recommended.

A.4.7 Total costs

A4.7.1 There are two basic options, but each of these can vary between countries both in terms of travel and subsistence and in wages. Costs can be calculated based on hours to be invested for the EU as a whole. The options for costing are:

- EU 25 per AEnS, 23 squares per class (including NATURA 2000)
- Reduced monitoring, only areal features
- Additionally extra modules for vegetation
- Additionally extra module for other species.

The aspects that determine costs for field work are:

- Aerial photography and / or satellite imagery
- Processing and Interpretation Aerial photography and / or satellite imagery
- Field survey
- Data processing and analysis
- Coordination
- Training
- Development of Field computer
- Acquiring field computers
- Travel and subsistence costs

The days needed for field work and analysis is given in Table A.2.

A.4.7.2 The time needed can be more if every country if every country requires a full set of data that is applicable for the country itself instead of the environmental class. This is not costed in this note. Publication costs and the website to support the project are not yet in the time calculation but are part of the calculation of costs (Table A.3).

A.4.7.3 Field workers are estimated to cost €100 - €300 per day including overheads depending on country and expertise. For the present calculation an average of € 200 is taken. Field workers have to work in pairs for reasons of mutual control, consulting and for safety. This is included in the days needed for field work (Table A.2) and the related costs (Table A.3).

- Coordinator costs are calculated using estimated labour costs on an average of € 800 daily
- The trainers costs are calculated using estimated costs of € 600 daily
- The data processing and analysis is supposed to € 600 daily.
- The costs for quality control will be € 800 daily
- Travel and subsistence for the field is estimated at € 100 daily
- Development of the field computer costs is estimated at € 164.000
- The costs of buying 100 field computers is estimated as € 100.000.

The total costs for a European project are calculated in Table A.3. The project costs for a habitat surveillance project without environmental qualifiers and including reporting is estimated to be about 3.2 million Euro. A full habitat survey with all qualifiers is calculated to cost 5.3 M. As laid down in the BioHab project the key issue in the monitoring of European habitats is cooperation consistency between and within countries. The monitoring should be carried out by national teams having had the same training as other national teams. Training is a key issue as it is the basis for consistent recording.

No inclusion of national recording objectives has been taken into account as these may vary between countries and are subject to national objectives and national priorities.

Table A.2 Working days for stratified sampling of European habitats based on 23 km^2 per environmental stratum.

EU25, total days for habitat surveillance for 23 squares per stratum	General habitat categories (Areal and linear), no Qualifiers	General Habitat Categories with qualifiers
Aerial photography and / or satellite imagery		
Processing and Interpretation Aerial photography and / or satellite imagery		
Field work	6670	13340
Processing	334	334
Analysis data set	30	60
Trainer of surveyors	28	48
Surveyors training	700	1200
Development field computer	163	163
Coordination	140	140
Quality control	400	400
report and dissemination	40	60
Total	8505	15745

Table A.3 Costs for four different packages of habitat recording. The first approach is a simple habitat recording scheme; the second column is the BioHab recording scheme including all qualifiers and the last two are BioHab recording schemes including a vegetation module and terrestrial species recording respectively.

EU25, total days for habitat surveillance for 23 squares per stratum	General Habitat Categories (areal and linear) without Qualifiers	General Habitat Categories with qualifiers
Field work	€ 1,334,000	€ 2,668,000
Processing	€ 200,400	€ 200,400
Analysis data set	€ 18,000	€ 36,000
Trainer of surveyors	€ 16,800	€ 16,800
Surveyors training	€ 140,000	€ 240,000
Development field computer	€ 164,000	€ 164,000
Coordination	€ 112,000	€ 112,000
Quality control	€ 320,000	€ 320,000
Acquiring field computers	€ 100,000	€ 100,000
Travel and subsistence	€ 727,000	€ 1,394,000
report and dissemination	€ 52,000	€ 68,000
Unforeseen	€ 30,000	€ 30,000
Total Project costs	€ 3,214,200	€ 5,349,200

A.5 Extent data linkage

A.5.1 There are two broad types that need to be considered:

1. Natura 2000 data. The BioHab categories can be used to link existing data from different countries. Each country would need its own reference table and the extent of the resources for carrying out the analyses. Basically each country maintains its own habitat classes, but reports to the EU via the BioHab categories.

2. Extent data bases

a. Quantitative comparison can be made with relational data bases

b. Quantitative comparison can be made where disaggregated data bases (e.g., Countryside survey) or 1:1 relationships are available

c.Phytosociological data have great potential for the assessment of vegetation change but require careful screening.

A.6 Estimating Change

A.6.1 The ultimate objective of monitoring habitats in Europe is to detect change. Past change can be estimated by comparison of aerial photographs as has been shown by many projects e.g., monitoring change in Great Britain, the Clateres project on monitoring change in habitats in Spain and more recently in BioPress. It would therefore be necessary to obtain historical photographs. It is suggested that a subset of the LUCAS project aerial photographs could be used for detecting change as well as the use national archives of air photographs as has been exploited in the BIOPRESS project. It is however clear, that not all changes can be detected by using aerial photographs. Changes in species richness and between management regimes have to be detected through field surveys.

A.6.2 Field validation is therefore essential but the use of aerial photography or satellite Images can improve the efficiency of the field survey to a large extent. Future change can be optimally tracking by repeating the field surveys every three to six years, depending on objectives and budget. Requirements are the use the same procedure, comparable seasons to prevent distortion through differences in growth and vitality. Whilst the technology is proven, monitoring the costs of monitoring is important for future work. It seems a powerful tool for environmental reporting on the European environment. Bias on the availability of aerial photographs also has to be assessed when analyzing past changes.

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References

Bunce, R.G.H., Barr C.J., Clark, R.T., Howard, D.C., Lane, A.M.J., 1996. Land classification for strategic ecological survey. J. Environ. Manage. 47:37–60

Bunce, R.G.H., Smart, S.M., Vna de Poll, H.M., Watkins, J.W., Scott, W.A., 1999. Measuring Change in British Vegetation. NERC-CEH, ECOFACT Volume 2.

Bunce R.G.H., Carey, P.D., Elena Roselló, R. Orr, J., Watkins, J.W., Fuller, R., 2002. A comparison of different biogeographical classifications of Europe, Great Britain and Spain. J. Environ. Manage., 65, 121-134.

Bunce, R.G.H., Groom, G.B., Jongman, R.H.G., Padoa-Schioppa, E. (Eds.), 2005. Handbook for Surveillance and Monitoring of European Habitats. First Edition. Alterra-rapport 1219, ISNN 1566-7197.

Jongman, R.H.G., Bunce, R.G.H., Metzger, M.J., Mücher, C.A., Howard, D.C., Mateus, V.L., 2006. Objectives and applications of a statistical environmental stratification of Europe. Landscape Ecol. 21 (3), 409-419.

Metzger, M.J., Bunce, R.G.H., Jongman, R.H.G., Mücher, C.A., Watkins, J.W., 2005. A climatic stratification of the environment of Europe. Glob. Ecol. Biogeogr. 14 (6), 549-563.

Mücher, C.A., Klijn, J.A., Wascher, D.M., Schaminée, J.H.J., 2009. A new European Landscape Classification (LANMAP): A transparent, flexible and user-oriented methodology to distinguish landscapes. Ecol. Indicat. , doi:10.1016/j.ecolind.2009.03.018. In Press.

Wascher, 2003. Identification and Characterisation of Environments and Landscapes in Europe. Alterra rapport 832, Alterra, Wageningen.

Summary

During the last two centuries in particular, the world population grew rapidly, in conjunction with technological developments, which led to a significant expansion of industrialisation, urbanisation and agricultural activity. As a result, land use and associated land cover changed at an increasing rate, intensifying the pressures on habitats and landscapes, and biodiversity in general. The increasing deterioration of these habitats and landscapes demonstrates that these need to be protected and monitored in a more comprehensive fashion, ranging from regional to global scales. The loss of biodiversity, indeed, has a global dimension. The United Nations Conference on Environment and Development in Rio de Janeiro in 1992 led to the Rio Declaration, confirming the need to work towards international agreements to protect the integrity of the global environment. The associated Convention on Biological Diversity (CBD) draws attention to the need to identify and monitor ecosystems, habitats, species, communities, genomes and genes. All CBD parties have committed themselves in achieving the 2010 Biodiversity Target: to protect and restore habitats and natural systems and halt the loss of biodiversity by 2010. The pan-European initiative, Streamlining European Biodiversity Indicators 2010 (SEBI 2010), is aiming to develop and implement indicators to monitor and promote progress towards the achievement of the 2010 target.

All these policies require quantitative figures on the extent of habitats and their degree of fragmentation. The development of the series of Natura 2000 sites based on the Habitats and Birds Directives is the major EU initiative for the protection of primary nature conservation areas. However at the same time, these sites do not guarantee the maintenance of biodiversity in the wider countryside, because inevitably many habitats and species occur outside protected areas. Therefore, there is a need to develop additional policy instruments for nature conservation outside protected areas that are equally appropriate to those applied within. The development of a Pan-European Ecological Network (PEEN) is the most significant tool in the implementation of the Pan-European Biological and Landscape Diversity Strategy (PEBLDS). Information about the spatial distribution of species is already being collected by many international organisations, but quantitative methodologies for spatial modelling of European habitats and landscapes need to be developed. Therefore, the main objective of this thesis is to develop quantitative methodologies for the spatial identification and monitoring of European landscapes and their habitats, which is urgently needed. The study area concerns

Pan-Europe; the area from Iceland in the north-west to Azerbaijan in the south-east and from Gibraltar in the south-west to Nova Zembla in the north-east, which covers an area of approximately 11 million km^2.

In a broader context, it concerns biodiversity monitoring using Earth Observation data and methods as well as geo-information tools integrated with available European environmental data sets and field surveying techniques. Remote sensing provides excellent methods towards this objective, especially with regard to large areas such as Pan-Europe or the globe as a whole. These methods have merits, but also limitations, especially when considering small and fragmented habitats and gradual changes within them. Therefore it is additionally necessary to monitor the components of European landscapes, by the use of standardised procedures for the surveillance of habitats, in order to enable habitat changes to be assessed. Although field surveys can provide habitat information with a much higher spatial and thematic resolution, their coverage and frequency of recording is often limited. Therefore, field surveying techniques and remote sensing methods are complementary and should be integrated to a much larger extent than is presently the case in biodiversity monitoring schemes.

Chapter 1 outlines the significance of quantitative methodologies for the spatial identification and monitoring of European landscapes and habitats by considering the potentials and limitations of remote sensing and GIS methods in combination with in-situ measurements and digitally available European environmental data sets. The chapter ends with the most important research objectives and questions.

Chapter 2 highlights experiences and perspectives of remote sensing within European landscape ecology. It provides examples of how remote sensing can contribute valuable information on landscape elements, habitats, landscapes and their spatial structure, because of its ability to capture repetitively synoptic landscape information in an abstraction-free manner. However, next to the successful applications of remote sensing in landscape ecology, there are also clear limitations related to e.g., thematic details and classification accuracies, asking for additional field surveys. Satellite imagery mainly relates to the geo-biophysical landscape, while many core landscape properties, social and cultural, as well as perceptual and aesthetic, are generally beyond the reach of remote sensing.

Chapter 3 concerns a quantitative methodology for the spatial identification of European landscapes, resulting in a new hierarchical European landscape classification, called

LANMAP. It concerns a transparent, flexible and user-oriented methodology to categorise landscapes. Because there are many regional differences in landscape properties, it is crucial to strike the balance between reducing the inherent complexity and maintaining an adequate level of detail. LANMAP has been established, against this background, making use of available segmentation and classification techniques using high resolution Pan-European environmental data sets. Validation was mainly based on a geo-spatial cross-analysis of LANMAP with ten national landscape typologies and a European questionnaire. It was concluded that LANMAP gives a consistent view across Europe and provides a common language and classification system, but it cannot replace any of the national landscape classifications, although it does provide a valuable European framework for these.

Chapter 4 concerns the geo-spatial modelling of European habitats. The methodology identifies the spatial distribution of habitats across Europe so that their actual extent can be determined. Spatial distribution models were derived for 27 Natura 2000 habitats representing the most significant European ecosystems, but can easily be extended to other habitats. Validation by using the Natura 2000 database showed that the mapping accuracy depends on the habitat description available as well as on their spatial character. Widespread habitats such as forests were accurately assessed, whereas dispersed classes such as freshwater habitats, were more difficult to determine. Uncertainties in the mapping results remain, especially in cases of poor habitat descriptions, spatial and thematic inaccuracies in the core data sets, and last but not least absence of spatial distribution maps of specific indicator species.

While Chapters 3 and 4 concentrate on the geo-spatial modelling of European landscapes and habitats, Chapters 5 and 6 deal with monitoring issues of habitats and associated land cover across European landscapes, using both remote sensing and field surveying techniques.

Chapter 5 concerns European land cover characterization and change detection, using NOAA-AVHRR satellite imagery. A methodology was designed that resulted in the establishment of a Pan-European land cover database, called PELCOM, with a 1 km spatial resolution. Accuracy assessment of the PELCOM land cover database indicated an overall accuracy of 69.2% Since the proposed methodology for land cover mapping has limitations for monitoring changes, due to the low spatial resolution and limited classification accuracies, a change-detection methodology is proposed on the basis of linear unmixing techniques. Validation of the linear unmixing results using the first four bands of an NOAA-AVHRR image acquired on 25th of July 1995 showed an overall accuracy of 82.0% for the following land cover types: grassland, arable, forest and urban areas. The use of thematic continuous

fraction images can highlight those areas where the proportions of the various land cover types have changed.

Chapter 6 concerns standardized field surveys for the monitoring of European habitats and the provision of spatial data. Rigorous survey rules are needed to provide consistent data on changes in European habitats. The field procedure was tested rigorously across sites in Europe. It is shown that the mapping rules are sufficiently robust and provide a good basis for a consistent a baseline survey on European habitats. Field surveys can only be implemented on a sample basis, and a good sampling framework is a prerequisite, as discussed in Appendix I. Although such a baseline can provide good area estimates on European habitats and excellent data for the validation and calibration of remotely sensed information, spatial modelling of habitats on the basis of disaggregation of remotely sensed land cover information remains necessary to provide a synoptic overview of their spatial distribution across Europe.

Chapter 7 comprises the main conclusions and the outlook for possible improvements in future research. The main contribution of this thesis are quantitative methods for the spatial identification of habitats and their monitoring across European landscapes. Remote sensing provides excellent methods for monitoring land cover changes, but the study shows that habitat changes should be monitored on basis of field surveys using a stratified sampling approach. Such samples across the European countryside are also needed for the validation and calibration of the habitat distribution maps resulting from geo-spatial models. The provided methods provide a good basis for the future monitoring of European habitats and associated landscapes on the basis of quantitative methods that integrate remotely-sensed and in-situ data.

Samenvatting

De wereldbevolking is in de afgelopen twee eeuwen exponentieel toegenomen dat in combinatie met belangrijke technische ontwikkelingen heeft geleid tot een enorme expansie van de landbouw, steden en industrie. Hierdoor zijn veranderingen in landgebruik steeds sneller gegaan met als gevolg dat de milieudruk op habitats en landschappen, en de biodiversiteit in het algemeen, enorm is toegenomen. De in kwantiteit en kwaliteit degraderende habitats en landschappen zouden beter beschermd en gemonitord moeten worden van lokaal niveau tot op wereldschaal. Inmiddels is het inderdaad gemeengoed dat het verlies aan biodiversiteit een probleem op wereldschaal is. Een belangrijke politieke stap werd in 1992 in Rio de Janeiro genomen op de Conferentie van de Verenigde Naties over milieu en ontwikkeling resulterend in de Rio Declaratie. Deze declaratie bevestigde de noodzaak om meer internationale afspraken te maken voor een betere bescherming van het mondiale milieu. Het hieruit voorkomende Verdrag inzake Biologische Diversiteit (CBD) vestigt de aandacht op het inventariseren en monitoren van biodiversiteit op het niveau van ecosystemen, habitats, soorten, genomen en genen. Alle CBD partijen hebben zich gecommitteerd tot het bereiken van de 2010 Biodiversiteitdoelen, te weten de bescherming en het herstel van habitats en natuurlijke systemen en het tot een halt roepen van het verlies aan biodiversiteit in 2010. Het hieraan gekoppelde Europese initiatief, ‘Stroomlijning van Europese Biodiversiteit Indicatoren’ (SEBI 2010), is gericht op het ontwikkelen en toepassen van biodiversiteits-indicatoren om beter toezicht te kunnen houden en hiermee ook de vooruitgang te bevorderen tot de verwezenlijking van de 2010 doelstellingen.

Al deze beleidsmaatregelen vereisen “harde” cijfers over de omvang van de habitats en hun fragmentatie. De aanwijzing en het beheer van Natura 2000-gebieden in het kader van de Habitatrichtlijn en de Vogelrichtlijn is het belangrijkste EU-initiatief voor de bescherming van de primaire natuurgebieden. Maar deze gebieden zijn nog geen garantie voor het behoud van de biodiversiteit op het (semi-natuurlijke) platteland, waar ook vele habitats en soorten buiten de beschermde gebieden voorkomen en dus van het platteland afhankelijk zijn. Daarom is er behoefte om aanvullende beleidsinstrumenten voor natuurbehoud te ontwikkelen buiten de beschermde Natura 2000-gebieden om. Zo is de ontwikkeling van een Pan-Europees Ecologisch Netwerk (PEEN) het belangrijkste instrument voor de uitvoering van de Pan-Europese Biologische en Landschappelijke Diversiteit Strategie (PEBLDS). Voor deze ontwikkeling is het noodzakelijk om informatie te hebben over de ruimtelijke verspreiding van habitats en soorten. Informatie over de verspreiding van soorten wordt al verzameld door veel internationale organisaties, maar methoden om de ruimtelijke verspreiding en omvang van Europese habitats en landschappen te kwantificeren ontbreken nog. Daarom is de belangrijkste doelstelling van dit proefschrift het ontwikkelen van methoden voor het kwantificeren van de ruimtelijke verspreiding en omvang van Europese landschappen en habitats en hun monitoring. Zulke methodieken zijn namelijk dringend nodig. Het studiegebied betreft Pan-Europa. Dit is het gebied van IJsland in het noordwesten tot aan Azerbeidzjan in het zuidoosten en van Gibraltar in het zuidwesten tot Nova Zembla in het noordoosten. Het gebied heeft een oppervlakte van ongeveer 11 miljoen km2.

In een bredere context gaat het om monitoring van de biodiversiteit met behulp van remote sensing bestaande uit het analyseren van satellietbeelden en gebruikmakend van additionele Europese digitale milieubestanden, GIS technieken en veldgegevens. Remote sensing technieken en methoden lenen zich goed voor dit doel, met name voor grote gebieden zoals Europa. Deze methoden zijn verdienstelijk, maar hebben ook beperkingen vooral bij het karteren van kleine en gefragmenteerde habitats en het monitoren van geleidelijke veranderingen daarin. Daarom is het gebruik van additionele en gestandaardiseerde veldmethodieken noodzakelijk om verschillende componenten van Europese landschappen te monitoren. Alleen op deze manier kunnen ook graduele veranderingen van habitats worden bewaakt. Maar hoewel veldinventarisaties habitatinformatie kunnen verstrekken met een veel hogere ruimtelijk en thematisch detailniveau, is het aantal en de frequentie van de veldopnamen vaak beperkt. Daarom zijn veldinventarisaties en remote sensing methoden vaak complementair voor biodiversiteit monitoring en moeten zij geïntegreerd worden in een grotere mate dan nu het geval is.

Hoofdstuk 1 beschrijft de uitdagingen van kwantitatieve methoden voor de ruimtelijke kartering en monitoring van Europese landschappen en habitats door te kijken naar de mogelijkheden en beperkingen van remote sensing en GIS-methoden in combinatie met veldwaarnemingen en beschikbare Europese milieubestanden. Het hoofdstuk eindigt met de belangrijkste vragen en doelstellingen van het onderzoek.

Hoofdstuk 2 licht de ervaringen en de perspectieven van remote sensing in de Europese landschapsecologie toe. Het geeft aan hoe remote sensing waardevolle informatie over landschapselementen, habitats, landschappen en hun ruimtelijke structuur kan leveren, door haar vermogen om herhaaldelijk synoptische landschapsinformatie te leveren op een objectieve manier. Echter, naast de succesvolle toepassingen van remote sensing in de landschapsecologie, zijn er ook duidelijke beperkingen, o.a. het ruimtelijke en thematisch detailniveau en de classificatienauwkeurigheid, die additionele veldinventarisaties onontbeerlijk maken. Satellietbeelden zien voornamelijk het biofysische landschap, terwijl veel kernwaarden van het landschap, zoals cultuurhistorische eigenschappen, zowel als perceptuele en esthetische kenmerken, zich in het algemeen buiten het bereik van de remote sensing begeven.

Hoofdstuk 3 beschrijft een kwantitatieve methode voor de ruimtelijke identificatie van Europese landschappen, wat geresulteerd heeft in een nieuwe Europese hiërarchische landschapsclassificatie, genaamd LANMAP. Dit betreft een transparante, reproduceerbare, flexibele en gebruiksvriendelijke methode om landschappen te karteren en in te delen in verschillende klassen. Omdat er veel regionale verschillen in landschappen bestaan, is het van cruciaal belang om de juiste balans te vinden tussen het verminderen van de inherente complexiteit en het behoud van een adequaat detailniveau. Tegen deze achtergrond is LANMAP opgezet, gebruikmakend van beschikbare segmentatie- en classificatietechnieken en hoge-resolutie digitale pan-Europese milieubestanden. Validatie van LANMAP is uitgevoerd door de vergelijking met tien nationale geogerefereerde landschapsclassificaties en een enquête onder Europese milieu - en onderzoeksinstituten. Een belangrijke conclusie was dat LANMAP een consistent beeld geeft voor heel Europa en daarmee een gemeenschappelijke classificatie- en communicatietool biedt. Echter het kan de nationale landschapsclassificaties zeker niet vervangen, die vaak meer informatie bezitten over regionale verschillen. In andere woorden, LANMAP biedt vooral een waardevol Europees kader.

Hoofdstuk 4 beschrijft een kwantitatieve methode voor de ruimtelijke modellering van Europese habitats. De methode identificeert de ruimtelijke verspreiding van Europese habitats, zodat hun werkelijke distributie kan worden bepaald. Ruimtelijke verspreidingsmodellen zijn opgesteld voor een selectie van 27 Natura 2000-habitattypen die de belangrijkste Europese ecosystemen vertegenwoordigen. Echter de methode kan ook gemakkelijk worden toegepast op andere habitattypen. Validatie die is uitgevoerd met behulp van de Natura 2000-database toont aan dat de classificatienauwkeurigheid sterk afhangt van de beschikbare habitatbeschrijving, alsmede van de ruimtelijke aspecten (bijv. mate van fragmentatie) van het habitattype. Wijdverspreide habitattypen zoals bossen konden nauwkeurig worden geclassificeerd, terwijl sterk gefragmenteerde of lokale habitattypen, zoals zoetwater habitats, veel moeilijker te karteren zijn. Onzekerheden blijven helaas vaak bestaan in de classificatieresultaten, vooral in gevallen van slechte habitatbeschrijvingen, geometrische en thematische onnauwkeurigheden in de onderliggende bestanden en het vaker ontbreken van specifieke informatie, zoals informatie over waterkwaliteit of specifieke indicatorsoorten.

Terwijl hoofdstukken 3 en 4 zich concentreerden zich op de ruimtelijke modellering van Europese landschappen en habitats, richten hoofdstukken 5 en 6 zich vooral op de monitoring van de habitats en daarmee samenhangende landbedekking, waarbij zowel remote sensing als veldinventarisatie-methodieken een rol spelen.

Hoofdstuk 5 heeft betrekking op de kartering van de Europese land- of bodembedekking en het detecteren van veranderingen daarin met behulp van NOAA-AVHRR satellietbeelden. Een classificatiemethodiek werd ontworpen die resulteerde in een pan-Europese landbedekkingsdatabase, genaamd PELCOM. Validatie gaf een algehele classificatie-nauwkeurigheid van 69,2% aan. Aangezien de voorgestelde classificatiemethode beperkingen heeft om veranderingen in landbedekking te detecteren, mede bepaalt door de relatief lage ruimtelijke resolutie (1 km) in combinatie met een beperkte classificatienauwkeurigheid, wordt er een aparte methode voorgesteld om veranderingen te detecteren op basis van lineaire unmixing technieken. Validatie van de lineaire unmixing resultaten die zijn verkregen met een NOAA-AVHRR satellietbeeld van 25 juli 1995 geven een algehele classificatie-nauwkeurigheid van 82,0% voor de volgende klassen: grasland, bouwland, bos- en stedelijke gebieden. Temporele vergelijking van thematische continue fractiebeelden kunnen die hotspots markeren waar de verhoudingen van de verschillende klassen zijn veranderd.

Hoofdstuk 6 beschrijft een gestandaardiseerde veldmethodiek voor de kartering en monitoring van Europese habitats. Strikte regels voor veldopnames zijn nodig om consistente gegevens te verkrijgen over veranderingen in de omvang en kwaliteit van Europese habitats. De veldprocedures zijn getest op vele locaties in Europa. Er is hiermee aangetoond dat de karteringsregels voldoende solide zijn en bieden daardoor een goede basis voor het verkrijgen van consistente en coherente basisinformatie over Europese habitats. Veldkarteringen kunnen echter alleen worden uitgevoerd voor beperkte oppervlakten en vereisen daarom een goede steekproefopzet om uiteindelijk tot Europese uitspraken te kunnen komen, zie ook bijlage I. Hoewel een dergelijke baseline kan zorgen voor goede areaalschattingen en tegelijkertijd uitstekende data kan leveren voor de training en validatie van remote sensing beelden, blijft ruimtelijke modellering van habitats op basis van de in hoofdstuk 4 voorgesteld methodiek nodig om een synoptisch overzicht te verkrijgen van hun ruimtelijke verspreiding over Europa.

Hoofdstuk 7 beschrijft de belangrijkste conclusies en de vooruitzichten voor mogelijke verbeteringen in nader onderzoek. De belangrijkste bijdrage van dit proefschrift zijn kwantitatieve methoden voor de ruimtelijke modellering van Europese habitats en landschappen en de monitoring daarvan. Remote sensing biedt uitstekende methoden voor de monitoring van veranderingen in landbedekking, maar graduele veranderingen in habitats moeten worden eerder gemonitord op basis van uit veldonderzoek verkregen samples die met behulp van een gestratificeerde steekproef zijn verkregen. Zulke gestratificeerde samples zijn ook nodig voor de validatie en kalibratie van de habitatverspreidingskaarten zoals die verkregen zijn in hoofdstuk 4. De ontwikkelde methoden leveren een goede basis voor de toekomstige monitoring van Europese landschappen en de daarmee samenhangende habitats op basis van kwantitatieve methoden die remote sensing – en veldgegevens integreren.

Resumen

En los siglos XIX y XX la población mundial creció mucho más rápidamente que en los siglos precedentes. Este fuerte crecimiento demográfico coincidió con una gran desarrollo tecnológico, dando lugar a una expansión significante de la actividad agrícola, la urbanización y la industrialización. La consecuencia de estos procesos es un cambio creciente del uso de la tierra y correspondiente cobertura del suelo, que han resultado en una intensificación de la presión sobre los paisajes, hábitats y la biodiversidad en general. El creciente deterioro de hábitats y paisajes implica que estos deben ser protegidos y controlados a una escala mayor, que cubra desde el nivel regional al global. La pérdida de la biodiversidad ha adquirido una dimensión mundial. En la Conferencia de las Naciones Unidas sobre el Medio Ambiente y el Desarrollo celebrada en Río de Janeiro en 1992 se tomaron decisiones políticas importantes que resultaron en la 'Declaración de Río'. Esta declaración confirma la necesidad de trabajar en pro de los acuerdos internacionales para proteger la integridad del medio ambiente mundial. La Convención sobre Diversidad Biológica (CDB) llama la atención sobre la necesidad de identificar y monitorear los ecosistemas, hábitats, especies, comunidades, genomas y genes. Todos los miembros del CDB se han comprometido a lograr la meta de Biodiversidad 2010, para proteger y restaurar hábitats y sistemas naturales y detener la pérdida de biodiversidad antes del 2010. La iniciativa Europea en apoyo de CDB incluye, la racionalización de los indicadores de biodiversidad 2010 (SEBI 2010), y tiene como objetivo desarrollar y aplicar indicadores para vigilar y promover el progreso para conseguir alcanzar el objetivo en el 2010.

Todas estas políticas requieren datos cuantitativos sobre la extensión de los hábitats y su grado de fragmentación. El desarrollo de la red Natura 2000 basada en las Directivas de Hábitats y Aves, es una iniciativa importante de la UE para la protección de áreas de conservación de la naturaleza primaria. Sin embargo, esta protección no garantiza el mantenimiento de la biodiversidad en el resto de las zonas rurales circundantes porque, inevitablemente, muchos hábitats y especies se encuentran fuera de las áreas protegidas. Por lo tanto, es urgente el desarrollo de instrumentos políticos adicionales para la conservación de la naturaleza fuera de las áreas protegidas. El desarrollo de una Red del continente Europeo Ecológica (Pan-European Ecological Network, PEEN) es la herramienta más importante en la aplicación de la Estrategia del continente Europeo para la Diversidad Biológica y el Paisaje (PEBLDS). Muchas organizaciones internacionales están ya recogiendo datos sobre la

distribución espacial de la especies, pero las metodologías cuantitativas para identificar la extensión de los hábitats y los paisajes europeos todavía no están desarrolladas. Por lo tanto, el objetivo principal de esta tesis doctoral es desarrollar metodologías cuantitativas para la identificación espacial y la vigilancia de los paisajes europeos y de sus hábitats.. El área de estudio es el continente Europeo, desde Islandia en el extremo Noroeste, hasta Azerbaiyán en el Sudeste, y de Gibraltar en el extremo Suroeste, hasta Nueva Zembla en el Nordeste. El área total cubre aproximadamente 11 millones de km^2.

La investigación presentada se centra en vigilar la biodiversidad utilizando técnicas de teledetección y de Sistemas de Información Geográfica (SIG) integradas con información de datos digitales del medio ambiente y técnicas de recogida de datos de campo. La teledetección proporciona métodos excelentes para lograr este objetivo, especialmente con respecto a las áreas grandes, tales como el continente Europeo. Estos métodos tienen ventajas pero también limitaciones, especialmente en lo que se refiere a la identificación de los hábitats de áreas pequeños y fragmentadas y a los cambios graduales. Por lo tanto, es también necesario al estudiar los componentes de los paisajes con trabajo de campo. Los estudios de campo pueden facilitar información sobre los hábitats con una resolución espacial y temática mucho mayor. Sin embargo , su cobertura y la frecuencia de recogida de datos es a menudo limitada. Por lo tanto, las técnicas de campo y los métodos de teledetección son complementarios y deben ser integrados en mayor medida que en los sistemas actuales de monitoreo de la biodiversidad.

El capítulo 1 revisa la importancia de las metodologías cuantitativas para la identificación espacial y el monitoreo de los paisajes y sus hábitats, considerando las ventajas y limitaciones de los métodos de tele-observación y SIG, en combinación con datos ambientales y mediciones *in situ*. Finalmente incluye los objetivos y cuestiones de esta tesis doctoral.

El capítulo 2 presenta las experiencias y perspectivas del uso de la teledetección en la ecología del paisaje en Europa. El capitulo da ejemplos de cómo la teledetección puede aportar información valiosa sobre los elementos del paisaje, hábitats, y la estructura de los paisajes, debido a su capacidad para capturar información sinóptico repetitiva sobre los paisajes en una forma objetivo. También presenta las limitaciones de la técnica relacionadas, por ejemplo, con los detalles y precisiones de la clasificación temática, que resaltan la necesidad de estudios complementarios de campo. Las imágenes de satélite describen principalmente el paisaje biofísico, pero no cubren muchas propiedades fundamentales socio-culturales y de percepción y estética de los paisajes.

El capítulo 3 describe una metodología cuantitativa nueva para la identificación espacial de los paisajes europeos, que resulta en una nueva clasificación jerárquica de los paisajes europeos llamada LANMAP. Se trata de una metodología transparente, flexible y fácil de utilizar para clasificar los paisajes. Debido a que hay muchas diferencias regionales en las propiedades del paisaje, es crucial lograr un equilibrio entre la reducción de la complejidad inherente y mantener un adecuado nivel de detalle. En este contexto, LANMAP se ha establecido, aplicando las técnicas de segmentación y de clasificación disponibles y utilizando los datos ambientales de alta resolución Europeos. La validación de los resultados se basa en un análisis comparativo espacial de LANMAP con diez clasificaciones de paisaje nacionales y un cuestionario enviado a institutos de medio ambiente en Europa. Se concluye que LANMAP ofrece una visión coherente en toda Europa y proporciona un lenguaje común y un sistema de clasificación común, pero no puede sustituir las clasificaciones del paisaje nacional, aunque sí ofrece un marco europeo de gran valor para estos.

El capítulo 4 presenta la elaboración de modelos geo-espaciales de los hábitats europeos. La metodología sirve para identificar la distribución espacial de los hábitats en toda Europa, de manera que se puede determinar su extensión real. En total, se han elaborado 27 modelos de distribución espacial de los Natura 2000 hábitats , que representan los ecosistemas europeos más importantes. Estos modelos se pueden aplicar fácilmente a otros hábitats. La validación realizada utilizando la base de datos de la red Natura 2000 indica que la precisión de los resultados depende de la descripción del hábitat, así como de su carácter espacial. Los hábitats que están distribuidos de forma general en el espacio, como los bosques, se pueden evaluar con exactitud, mientras que aquellos hábitats con una distribución muy local, como muchos hábitats de agua dulce, son más difíciles de determinar. Los imprecisiones en los resultados de la cartografía se deben, sobre todo en los casos de pobre descripciones de los hábitats, falta de precisión espacial y temática en los de datos básicos y, por último pero no menos importante la ausencia de mapas de distribución espacial de las especies indicadoras específicas.

Mientras que los capítulos 3 y 4 se centran en la elaboración de modelos geo-espaciales de los paisajes y de los hábitats europeos, los capítulos 5 y 6 tratan de cuestiones de monitoreo de los hábitats y de sus correspondientes usos de suelos en los paisajes europeos, utilizando las técnicas de teledetección y de investigación de campo.

El capítulo 5 presenta la caracterización y detección de cambios en la cobertura de los suelos, usando imágenes de satélite de NOAA-AVHRR. Para ello se diseñó una clasificación metodológica que resultó en la creación de una base de datos de cobertura de suelos para el continente Europeo, llamada PELCOM, con una resolución espacial de 1 km. La precisión de la base de datos PELCOM es de 69,2%. La metodología propuesta para la cartografía de la cobertura del suelo tiene limitaciones para el estudio de los cambios, debido a la baja resolución espacial y precisión limitada de la clasificación. Por eso se propone.una metodología para detección de los cambios, basada en la utilización de técnicas lineales sin mezcla (linear unmixing techniques). La validación de los resultados de ‘unmixing lineal’ usando una imagen NOAA-AVHRR del 25 de julio 1995, mostró una precisión global de 82.0% para los siguientes tipos de cobertura de la tierra: pastizales, tierras de cultivo, bosques y zonas urbanas. El uso de imágenes con fracciones temáticas contínuas permiten identificar las áreas (hot spots) donde las proporciones de los diferentes tipos de cobertura de la tierra han cambiado.

El capítulo 6 se refiere a los estudios de campo estandardizados para el monitoreo de los hábitats europeos y el suministro de datos espaciales. Para ello se aplican reglas rigurosas que ayudan a obtener datos consistentes sobre los cambios en los hábitats europeos. El procedimiento de campo se puso a prueba de una forma rigurosa en distintos sitios en Europa. Se demostró que las reglas de identificación de hábitats son suficientemente sólidas y ofrecen una buena base para estudiar de forma consistente los hábitats europeos. Los estudios de campo sólo se puede aplicar sobre una parte de la muestra, y por ello es un requisito esencial el tener un buen marco de muestreo, tal como se discute en el Apéndice I. Esta información básica puede proporcionar estimaciones de los hábitats europeos a nivel de hectáreas y provee excelentes datos para validar y calibrar las imágenes de tele-observación. Sin embargo la modelización espacial de los hábitats basada en la información desagregada obtenida por tele-observación de la cobertura de la tierra (capítulo 4), sigue siendo necesaria para ofrecer una visión sinóptica de su distribución espacial en toda Europa.

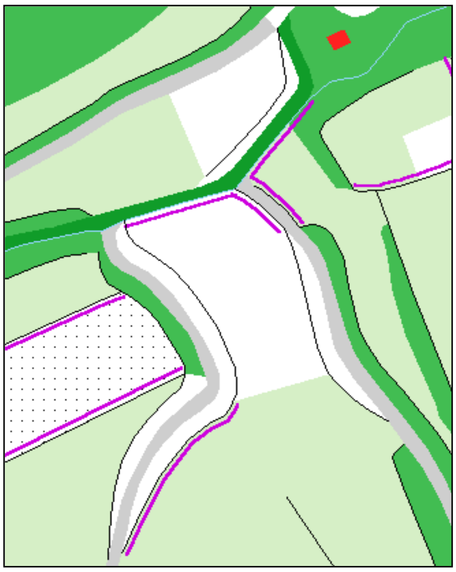
El capítulo 7 incluye las conclusiones principales y el análisis de las perspectivas para mejoras en futuras investigaciones. La principal aportación científica de esta tesis son los métodos cuantitativos para la identificación espacial de los hábitats y su seguimiento temporal en los paisajes europeos. La teledetección proporciona excelentes métodos para vigilar los cambios de la cobertura de la tierra, pero el estudio demuestra que es necesario controlar los cambios de hábitat con estudios de campo, utilizando un método de muestras estratificado.

Estos muestreos en los estudios de campo distribuidos en Europa también son necesarios para la validación y calibración de los mapas de la distribución de los hábitats (capítulo 4). Esta tesis demuestra que sólo a través de la integración de los métodos cuantitativos con las imágenes de satélites y datos in situ, se obtiene una buena base científica para la vigilancia de los paisajes europeos y de los hábitats asociados.

Colour Plates

(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)

Fig. 2.2. 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).

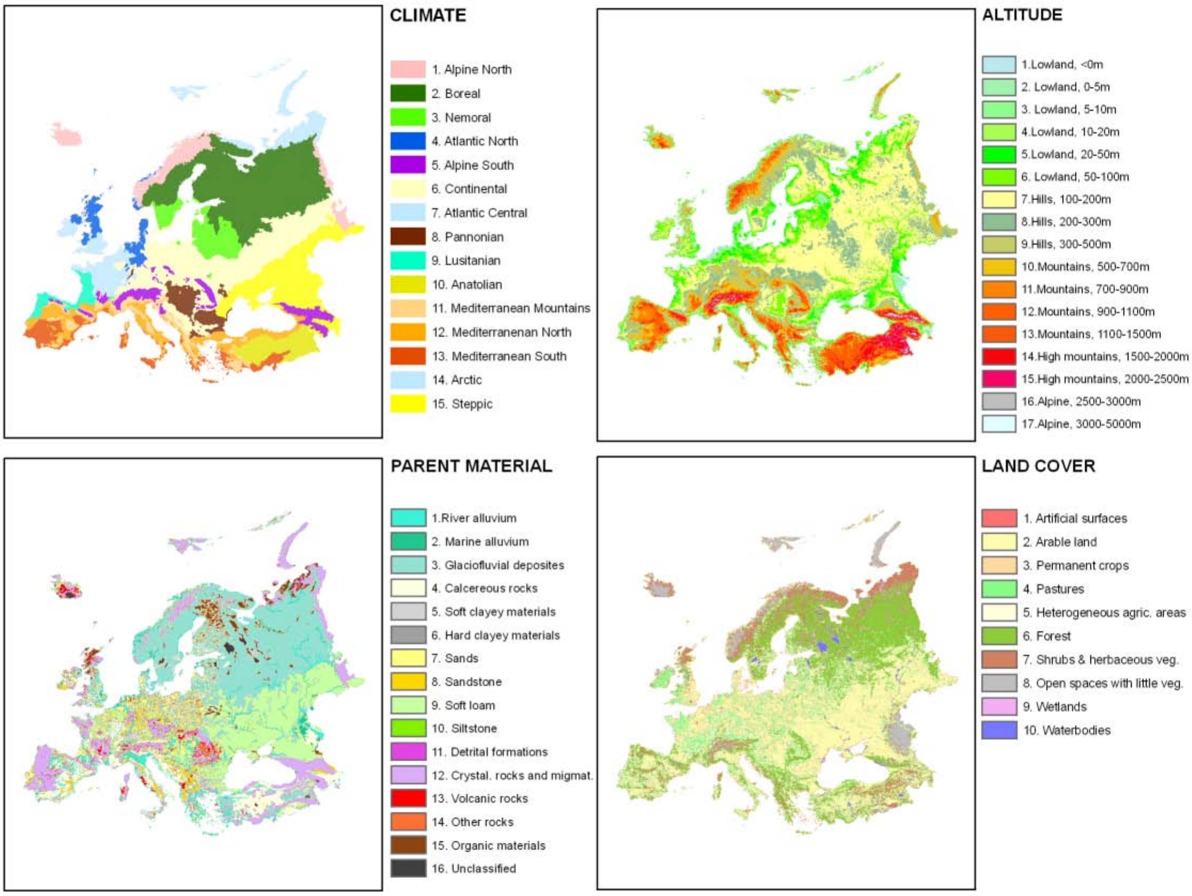


Fig. 3.1 Fig. 3.1a shows the first data layer Climate (C), which was obtained by integration of the European Environmental Stratification (Metzger et al. 2005) and the Biogeographical Regions Map of Europe (Roekaerts, 2002). Fig. 3.1b, above right, shows the second data layer Altitude (A) derived from the Digital Elevation Model GTOPO30. Fig. 3.1c, below left, shows the third data layer Parent material (P), which was obtained by integration of the European Soil Database (CEC, 1985), and the FAO Soil Map of the World (FAO, 1991). Fig. 3.1d, below right, shows the fourth data layer Land cover (LC) , which was obtained by integration of the following land cover databases CORINE (CEC, 1994), GLC2000 global land cover database (Fritz et al., 2003) and PELCOM (Mücher, 2001).

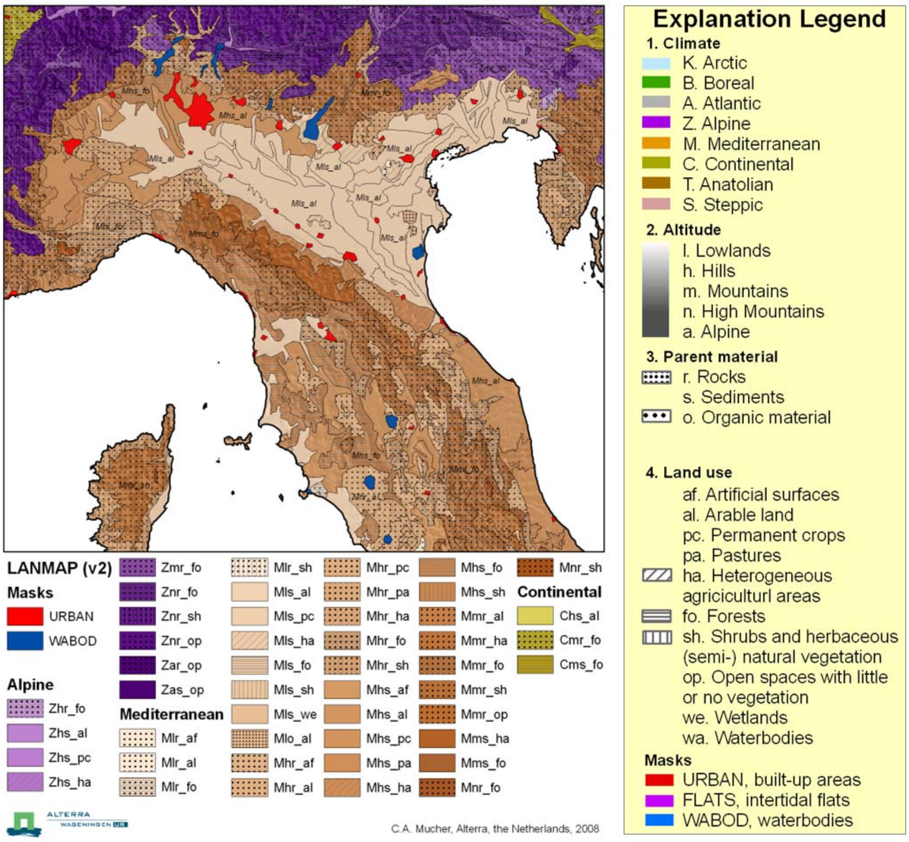


Fig. 3.4 Detail of the European Landscape Classification for Northern Italy and direct surroundings.

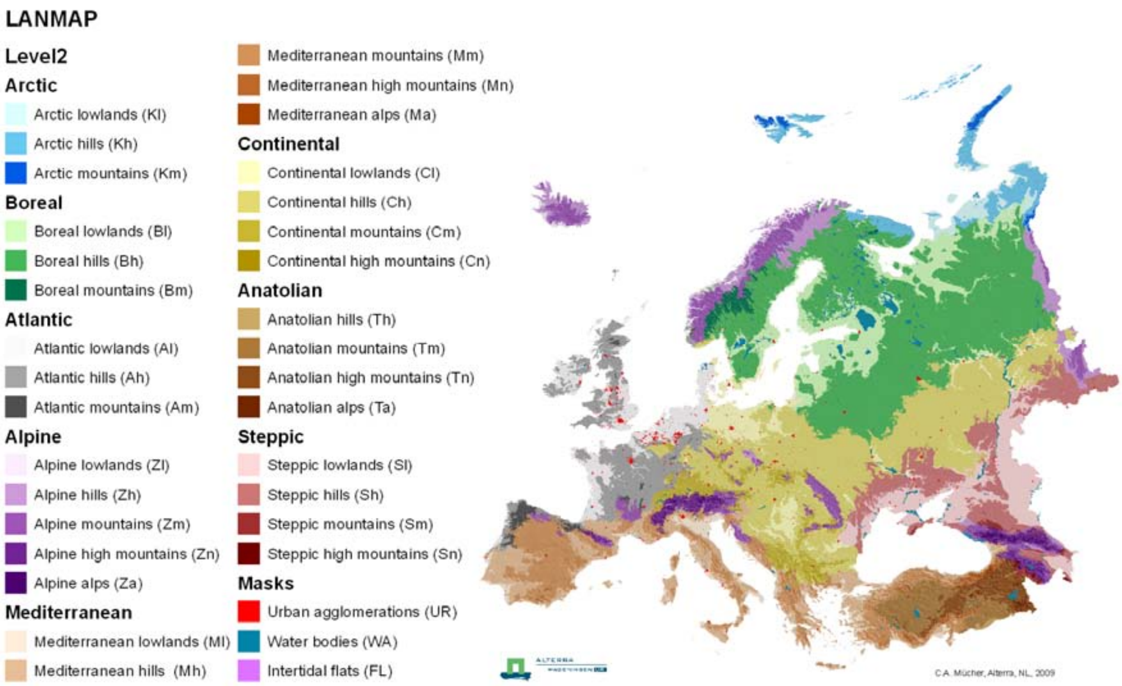


Fig. 3.5 LANMAP, a newly established European Landscape Classification based on high-resolution spatial-explicit digital information. Level 2 of LANMAP is shown in this figure.

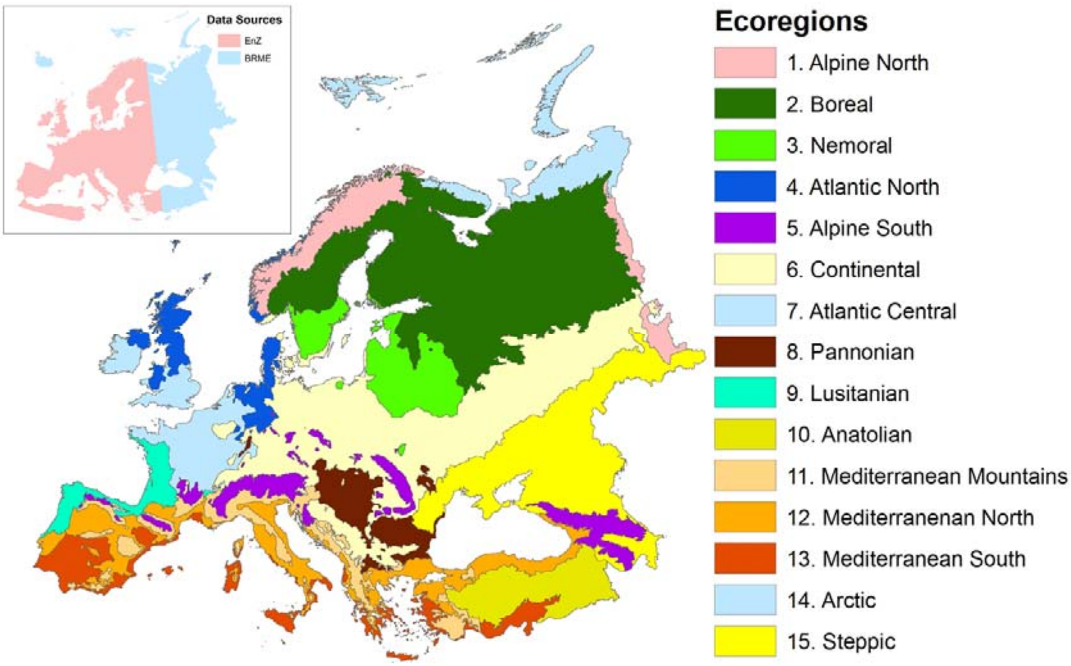


Fig. 4.1 Ecoregions of Europe based on the integration of the Environmental Zones (source: Wageningen UR) and the Biogeographical Regions Map of Europe (source: EEA)

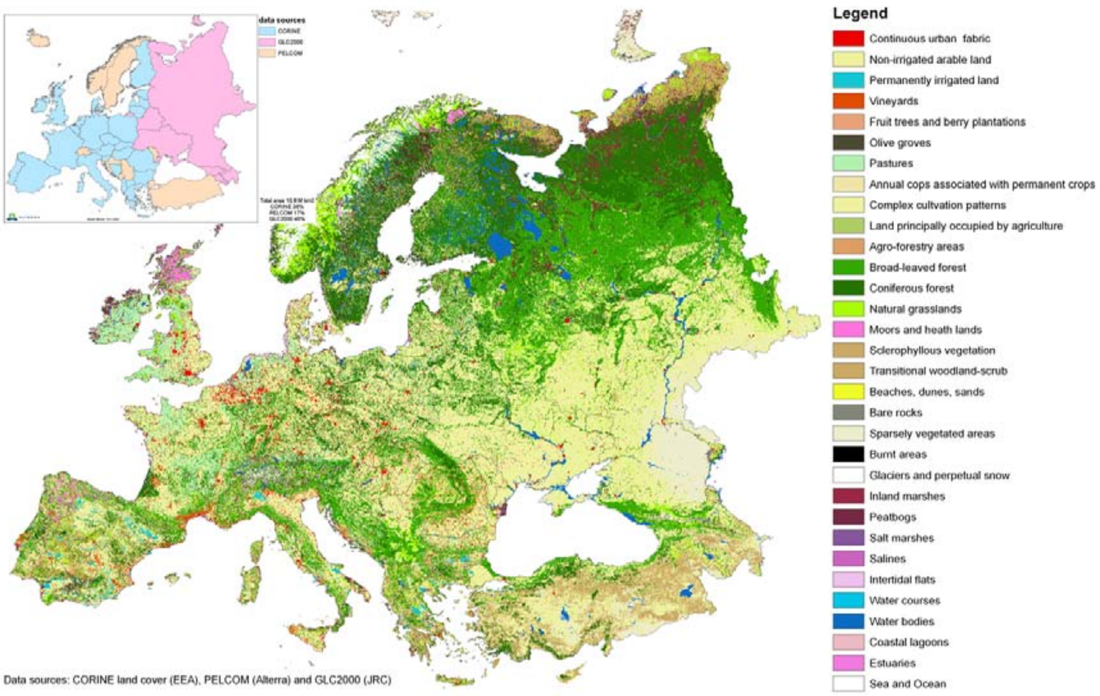


Fig. 4.2 Pan-European land cover database with a spatial resolution of 250 m based on integration of CORINE land cover (source: EEA), GLC2000 (source: JRC) and PELCOM (source: Alterra).

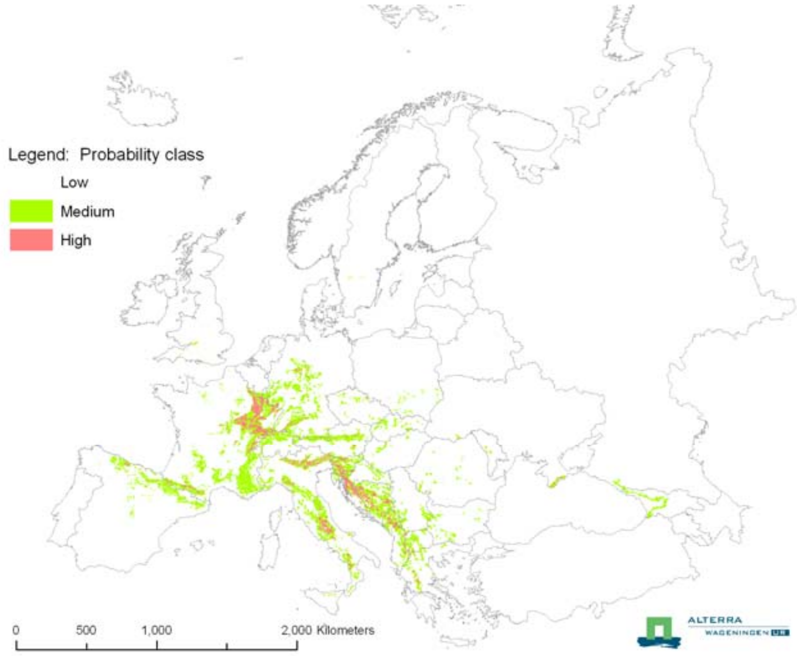
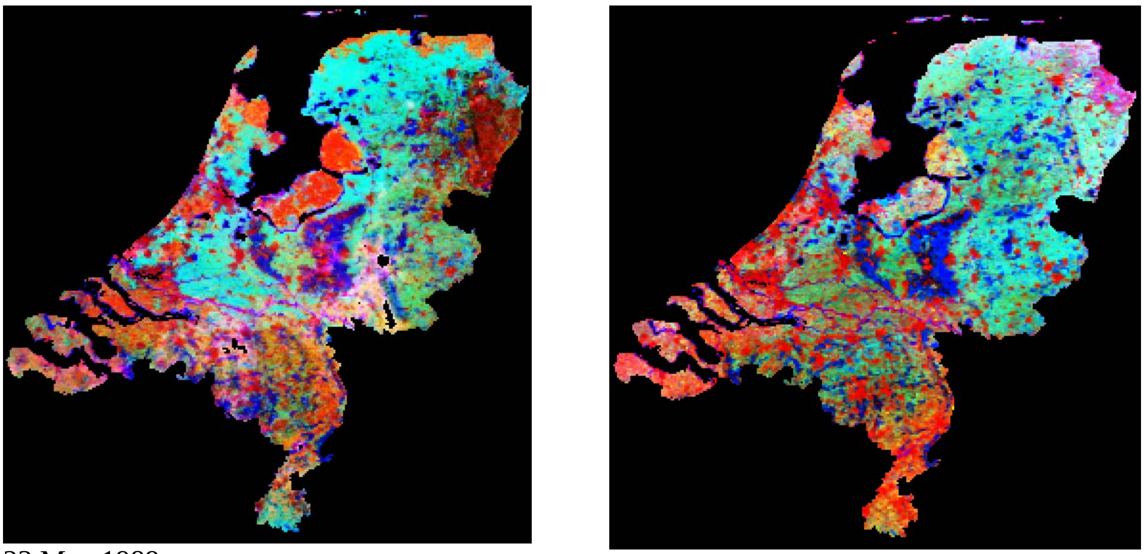


Fig. 4.6 Final result of the proposed methodology. This example concerns Annex I Habitat Type 9150 “Medio-European limestone beech forest of the Cephalanthero-Fagion”. The resulting habitat map has a spatial resolution of 250 m and is divided into three probability classes.



23 May 1989 5 July 1989

Fig. 5.1 Figure on the left shows an AVHRR multi-spectral colour composite acquired on 23 May 1989 (RGB: 1/2/3). At this time period most arable land is still bare. Orange/red colours indicate arable land or urban area. Dark blue colours indicate forest and light green colours indicate grassland. Figure on the right shows an AVHRR multi-spectral colour composite acquired on 5 July 1989 (RGB: 1/2/3). At this time period all arable crops cover the surface completely. There is no spectral difference between grassland and arable land. All urban areas can now be detected.

Acknowledgements

This thesis is in fact the result of my work over the last ten years at Alterra. Actually, my career at Alterra started already in 1993, when Gerard Nieuwenhuis offered me a position in his Remote Sensing team at the Winand Staring Centre in Wageningen. Alterra was created in 2000 from a merger between the DLO institutes Winand Staring Center and the Institute for Forestry and Nature Conservation. This merger created for me the opportunity to work with experts from both the abiotic and biotic world, and was also for me a personal milestone. Increasingly I became involved in many European and national activities with a strong accent on land cover, landscape, and habitat mapping and monitoring. The European dimension has always been a strong component in my research and started already in the early nineties. For example, I worked in several NRSP (National Remote Sensing Programme) projects in the field of environmental monitoring together with RIVM (National Institute for Public Health and the Environment). In fact, it was Rob van de Velde who asked me if we could improve their European land use database, mainly derived from national statistics, with information derived from remote sensing. This collaboration led to many new projects in the field of European land use and land cover monitoring using remote sensing, amongst others in several NWO projects on agricultural land use monitoring in Russia together with Jan Clevers.

In collaboration with the Landscape Centre of Alterra (Irene Bouwma, Jan Klijn, Rob Jongman and Rien Reijnen) I started in 2002 to work on the design of a Pan-European Ecological Network (PEEN) which required information on the spatial distribution of habitats. It was especially Bob Bunce who triggered my interests in European habitats. On many European field visits, e.g. at the ECOLAND meetings (a IALE working group functioning as a pan-European forum for countryside and landscape monitoring) with amongst others Berien Elbersen, Marta Pérez-Soba, Hubert Gulinck, Geert de Blust and Desiré Paelinckx, it was Bob who tested always my knowledge (which was not much concerning European plant species; but I made some progress since that time). Soon after, I was invited by Joop Schaminée to participate in the PKN (the Dutch Society of Plant Sociology) excursions from which I am learning every year a lot. Because of my enthusiasm, it was especially Jan Klijn and Bob Bunce who triggered me to think about writing a PhD thesis in my field of expertise. But thinking about doing a PhD thesis is something else than really writing one. It was Michael Schaepman who became the right person at the right time to provide me a framework for doing so at our Centre for Geo-Information. But writing a PhD thesis next to all the project (co-ordination) activities is not always easy and sometimes slowed down the process of writing one. Actually, it was my sabbatical at the Nature Conservation and Plant Ecology Group (the group of Frank Berendse) at Wageningen University, organized by Michael Schaepman and Joop Schaminée in collaboration with Alterra (Auke de Bruin), which made it possible to finish my PhD thesis.

In this voyage, that led to the completion of my PhD thesis, I have to thank a lot of people with whom I have been working. First of all, I would like to thank my supervisors Michael Schaepman, Joop Schaminée and Bob Bunce for their friendship, scientific feedback and for setting realistic goals to finish my thesis. Gerard Nieuwenhuis, I would like to thank especially for giving me all the freedom to exploit my scientific interests at our Centre for Geo-Information (CGI). From our CGI centre I have to thank all my colleagues with whom it has been always a pleasure to work. Above all, I would like to thank Henk Kramer and Allard de Wit for their patience to solve all my technical software problems and keeping me updated with new technological developments. Anne Schmidt for giving her clear views and always being able to create a good atmosphere. Gerard Hazeu and Marta Perez-Soba with whom it was always a pleasure to travel and work in European projects. And Gerard, thanks for all the squash matches, which kept me a little bit in shape; they were always relaxing (at least for me). My former room mates, Annette Willemen, Monica Wachowicz, JanDirk Bulens and now John Stuiver for their friendship. I have to thank also our cartographers Rini Schuiling, Herman Gijsbertse, Gert Dortland and Theo Spek for preparing many data sets for me and their good company at many occasions. Of my GIRS colleagues (university part of CGI) I would like to thank, especially Jan Clevers, Harm Bartholomeus, Lammert Kooistra, Sytze de Bruin, Ron van Lammeren and Arnold Bregt who always provided me with good suggestions when needed. Other Alterra colleagues I would like to thank for their always pleasant collaboration in projects and friendship are amongst others Stephan Hennekens, Jan Klijn, Berrien Elbersen, Irene Bouwma, Marlies Sanders, John Janssen, Michiel van Eupen, Rob Jongman and Dirk Wascher.

I owe also special thanks to all my NCP colleagues who made my sabbatical very pleasant: Liesje Mommer, Frank Berendse, Joop Schaminee, Juul Limpens, Marleen Pierik, Jasper van Ruijven, Arina Schrier, Daan Blok, Elmar Veenendaal, Karle Sykora, Dick van der Hoek, Monique Heijmans, Flavia Geiger, Maurits Gleichman, Veronique Vos, Mink Zijlstra, Jan van Walsem, Frans Moller, Miriam Bakker and Petra Kloppenburg.

Besides my colleagues, I have to thank especially my family for their continuous support. Without their support it would have been impossible to finish my PhD thesis. Quela and Camila, thanks for always bringing my back to reality ‘waar zit je met je gedachte’. I want to thank my parents, Thea and Herman, for their never-ending support and always keeping interested in my work.

Last but not least, I would like to thank once more all the people, next to my supervisors, who helped me in the last stage of my thesis, amongst others, Freda Bunce, Anne Schmidt, Lammert Kooistra, Jan Clevers, Harm Bartholomeus, Lucia Yanez, Geoff Groom, Henny Michel, Sylvia Kuster, Martin Jansen and, of course, my two paranymphs John Stuiver and Gerard Hazeu.

Glossary

AEnS	EnS strata in altitudinal bands
AFE	Atlas Flora Europaeae
AIS	Area Information System
ALMASS	Animal, Landscape and Man Simulation System (http://www.dmu.dk/International/AnimalsPlants/ALMaSS/)
ALTERNET	A Long-Term Biodiversity, Ecosystem and Awareness Research Network (http://www.alter-net.info/)
AVHRR	Advanced Very High Resolution Radiometer onboard of NOAA polar-orbiting satellite series (http://noaasis.noaa.gov/NOAASIS/ml/ avhrr.html)
BIOHAB	A framework for the coordination of Biodiversity and Habitats. EU FP5 project (EVK2-CT-2002-20018).
BIOPRESS	Linking pan-European land cover changes to pressures on biodiversity. EU FP5 project (EVK2-CT-2002-00178), (http://www.biopress.ceh.ac.uk/)
BRME	Biogeographical Regions Map of Europe (http://dataservice.eea.europa.eu/atlas/viewdata/viewpub.asp?id=221)
CAP	Common Agricultural Policy (http://ec.europa.eu/agriculture/publi/capexplained/cap_en.pdf)
CBD	Convention on Biological Diversity (http://www.cbd.int/)
CEC	Commission of the European Communities
CEOS	Committee on Earth Observation Satellites (http://www.ceos.org/)
CWHM	Coastal Water Mapping Project (http://cmst.curtin.edu.au/brochures/cwhm_crc_flyer_72crop.pdf)
CIR	Colour InfraRed aerial photography
CLC2000	Corine Land cover of the reference year 2000
CLT	Cultural Landscape Type
CORINE	Coordination of Information on the Environment by the EEA, e.g., CORINE biotopes (http://dataservice.eea.europa.eu) and land cover (http://etc-lusi.eionet.europa.eu/CLC2000)

CRU	Climate Research Unit at the University of East Anglia (http://www.cru.uea.ac.uk/)
CS	Countryside Survey (http://www.countrysidesurvey.org.uk)
CVA	Change Vector Analysis
DCA	Detrended Correspondence Analysis
DCW	Digital Chart of the World (http://www.maproom.psu.edu/dcw/)
DG	Directorate General of the European Commission, e.g., DG Environment (http://ec.europa.eu/dgs/environment/index_en.htm)
DTC	Decision Tree Classification
EBONE	European Biodiversity Observation Network: Design of a plan for an integrated biodiversity observing – EU FP7 project (FP7-212322)
EC	European Commission (http://ec.europa.eu/)
ECNC	European Centre for Nature Conservation (http://www.ecnc.org/)
ECOCHANGE	Challenges in assessing and forecasting biodiversity and ecosystem changes in Europe – EU FP6 project (FP6-036866)
EEA	European Environment Agency (http://www.eea.europa.eu/)
ELCAI	European Landscape Character Assessment Initiative – EU FP5 project (EVK2-CT-2002-80021)
ELU-1	Ten-minute pan-European land use database of RIVM
EnS	Environmental Stratification of Europe (Metzger et al., 2005)
EnZ	Environmental Zones of Europe (Metzger et al., 2005)
ENVIP-Nature	Landscape typology and indicators for nature protection. This study contract was framed within the Eurolandscape project of JRC (http://ivfl.boku.ac.at/Projekte/envip/home.html)
EO	Earth Observation
EPA	United States Environmental Protection Agency (http://www.epa.gov/)
ESA	European Space Agency (http://www.esa.int)
ETC-BD	European Topic Centre on Biological Diversity (http://biodiversity.eionet.europa.eu/)

ETC-LUSI	The European Topic Centre Land Use and Spatial Information ETC-LUSI (http://etc-lusi.eionet.europa.eu/)
EU	European Union
EUNIS	European Nature Information System of the EEA (http://eunis.eea.europa.eu)
EVS	European Vegetation Survey (http://www.iavs.org/part_groups_euroveg.asp)
GB	Great Britain
GCP	Ground Control Point
GEOSS	Global Earth Observation System of Systems (http://www.earthobservations.org/geoss.shtml)
GHC	General Habitat Categories
GIS	Geographic Information System
GLC2000	Global Land Cover data for the year 2000 (http://www-gvm.jrc.it/glc2000/)
GLOBCOVER	Global land cover database with a 300 meter spatial resolution based on MERIS satellite imagery (http://postel.mediasfrance.org/en/PROJECTS/Preoperational-GMES/GLOBCOVER/)
GMES	Global Monitoring for Environment and Security. GMES is a European programme for the implementation a European capacity for Earth observation (http://www.gmes.info/)
GTOPO30	GTOPO30 is a global Digital Elevation Model (DEM) resulting from a collaborative effort led by the U.S. Geological Survey's EROS Data Center in Sioux Falls, South Dakota (see also http://edc.usgs.gov/products/elevation/gtopo30/gtopo30.html). The elevations are given in meters and are regularly spaced at 30-arc seconds (approximately 1 km)
HABISTAT	A Classification Framework for Habitat Status Reporting with Remote Sensing Methods. Flemish Research Programme For Earth Observation – STEREO II (Contract Nr SR/00/103)
HPDM	Hierarchical Patch Dynamics Model
IALE	International Association for Landscape Ecology (http://www.landscape-ecology.org/)
IGBP-DIS	International Geosphere and Biosphere Programme’s Data and Information System (http://www.igbp.net/)

IGBP DISCover	Global land cover database with a 1km spatial resolution based on NOAA-AVHRR satellite imagery (http://edcdaac.usgs.gov/glcc/glcc.asp)
IKONOS	Commercial satellite sensor with a very high spatial resolution of Satellite Imaging Corporation (http://www.satimagingcorp.com/)
IRS	Indian Remote Sensing satellites. One such satellite is IRS-LISS-III (Linear Imaging Self-Scanning) with spatial resolutions of 24 meters (http://www.nrsa.gov.in/satellites/IRS_satellites.html)
JRC	Joint Research Centre of the European Commission, Ispra, Italy (http://ec.europa.eu/dgs/jrc/index.cfm)
LANDSAT	The Landsat Programme is a series of Earth-observing satellite missions jointly managed by NASA and the U.S. Geological Survey. Landsat TM is the Landsat Thematic Mapper, a sensor carrier onboard on Landsats 4 and 5. The Landsat Enhanced Thematic Mapper (Landsat ETM+) was introduced with Landsat 7 (http://landsat.gsfc.nasa.gov/)
LANDSAT-MSS	Landsat Multispectral Scanner. The Landsat Multispectral Scanner (MSS) was a sensor onboard Landsats 1 through 5 and acquired images of the Earth nearly continuously from July 1972 to October 1992 (http://edc.usgs.gov/products/satellite/mss.php)
LANMAP	A newly established Pan-European Landscape Classification. The database can be downloaded from (http://www.alterra.wur.nl/UK/research/Specialisation+Geo-Information/Projects/lanmap2)
LC	Land Cover
LGN	Dutch National land cover database (http://www.lgn.nl/)
LTER-Europe	European Long Term Ecological Research. LTER-Europe is Europe's long-term ecosystem research and monitoring (LTER) network
LUCAS	Land Use/Land Cover Area Frame Survey. LUCAS is being co-ordinated by EUROSTAT.
LULC	Land use and Land Cover
MARS	Monitoring Agriculture by Remote Sensing
MERIS	Medium Resolution Imaging Spectrometer. The MERIS instrument is onboard of the ENVISAT satellite platform of ESA (http://envisat.esa.int/instruments/meris/)

MHW	Mean High Water
MISR	Multi-angle Imaging SpectroRadiometer. MISR was built for NASA by the Jet Propulsion Laboratory in Pasadena, California, and is one of five instruments launched into polar orbit aboard NASA's Terra spacecraft in August 1999 (http://www-misr.jpl.nasa.gov/)
MME	Minimum Mappable Element
MML	Minimum Mappable Length
MODIS	Moderate Resolution Imaging Spectroradiometer is a key instrument aboard the Terra (EOS AM) and Aqua (EOS PM) satellites with spatial resolution up to 250 meter (http://modis.gsfc.nasa.gov/)
MVC	Maximum Value Composite
NALC	North American Landscape Characterisation program (http://eros.usgs.gov/products/satellite/nalc.php)
NCI	Natural Capital Index (http://www.mnp.nl/mnc/i-en-1119.html)
NDVI	Normalized Difference Vegetation Index
NEON	USA National Ecological Observatory Network. The National Ecological Observatory Network (NEON) is a continental-scale research platform for discovering and understanding the impacts of climate change, land-use change, and invasive species on ecology h(ttp://www.neoninc.org/).
NOAA	National Oceanic and Atmospheric Administration of the United States (http://www.noaa.gov/satellites.html)
NRSP	Dutch National Remote sensing Programme. This programme has finished and it got a follow-up in the GO programme. (http://www.nivr.nl/go-regeling-291.html)
NUTS	Nomenclature d'Unite´s Territoriales Statistiques. It concerns the division into administrative regions (http://ec.europa.eu/eurostat/ramon/nuts/basicnuts_regions_en.html)
OECD	Organisation for Economic Co-operation and Development (http://www.oecd.org)
Pan-Europe	Pan-Europe, the western extension of Eurasia. Pan-Europe is the area from Iceland in the Northwest to Azerbaijan in the Southeast and from Gibraltar in

	the Southwest to Nova Zembla in the Northeast and covers an area of approximately 11 million km2.
PEEN	Pan-European Ecological Network (http://www.countdown2010.net/ archive/paneuropean.html)
PEENHAB	Pan-European Habitat mapping project (http://www.kennisonline.wur.nl/BO/BO-01/431/009/beschrijving.htm)
PELBDS	Pan-European Biological and Landscape Diversity Strategy (http://www.peblds.org/)
PELCOM	Pan-European Land Use and Land Cover Monitoring. Development of a consistent methodology to derive land cover information on a European scale from remote sensing for environmental monitoring. EU-FP4 project. The European land cover database PELCOM can be downloaded from http://www.geo-nformatie.nl/projects/pelcom/public /index.htm
PNV	Potential Natural Vegetation database (http://www.synbiosys.alterra.nl/ pnv/)
QUICKBIRD	QuickBird is a commercial high resolution satellite owned and operated by DigitalGlobe. It is able to offer sub-meter (60 cm) resolution imagery (http://www.digitalglobe.com/index.php/85/QuickBird)
RGB	Red, Green and Blue. RGB is a device-dependent colour space. Typical RGB input devices are image scanners, digital cameras and color TV
RIVM	Dutch National Institute for Public Health and the Environment (http://www.rivm.nl/)
SAC	Special Areas for Conservation. SACs are strictly protected sites designated under the EC Habitats Directive.
SAI-JRC	Space Applications Institute of the Joint Research Centre in Ispra, Italy. SAI is now part of the Institute for Environment and Sustainability (IES) of JRC (http://ies.jrc.ec.europa.eu/)
SMART	Smoothing AVHRR Reflectance Technique
SEBI2010	Streamlining European Biodiversity Indicators 2010(http://biodiversity-chm.eea.europa.eu/ information/indicator/F1090245995)
SENSOR	Sustainability Impact Assessment: Tools for Environmental, Social and Economic Effects of Multifunctional Land Use in European Regions – EU FP6 project (FP6-003874)

SINUS	The aim of this research project was to design an integrative approach to identify and visualise landscapes with sustainable land use (http://131.130.59.133/projekte/sinus/en/kap06_en.htm).
SISPARES	Sistema para el Seguimiento de los Paisajes Rurales Españoles (http://www.chavales.net/sigparesweb_005.htm)
SPACE	Software for Processing AVHRR data for the Communities of Europe
SPOT	Satellite Pour l'Observation de la Terre. It concerns a series of high-resolution satellite sensors of Spot Image, Toulouse, France (http://www.spotimage.fr/)
SRRF	Spatial Regional Reference Framework (Renetzeder et al., 2008)
SRTM	Shuttle Radar Topography Mission. SRTM data is being used to generate a digital topographic map of the Earth's land surface (http://eros.usgs.gov/products/elevation/srtmbil.php)
SWOT	Strengths-Weaknesses-Opportunities-Threats (analysis)
SynBioSys Europe	SynBioSys Europe, an initiative of the European Vegetation Survey, is an information system for the evaluation and management of biodiversity among plant species, vegetation types and landscapes. The project is coordinated from Alterra at Wageningen, The Netherlands, and will function as a network of distributed databases related through a web-server (http://www.synbiosys.alterra.nl/eu/).
UNCED	The United Nations Conference on Environment and Development. In 1992 in Rio de Janeiro this led to the Rio Declaration, confirming the need to work towards international agreements to protect the integrity of the global environment (http://www.un.org/geninfo/bp/enviro.html)
UNEP	United Nations Environment Programme (www.unep.org)
VHRS	Very High Spatial Resolution
WCMC	World Conservation Monitoring Centre (http://www.unep-wcmc.org/)
WGCV	Working Group on Calibration & Validation of CEOS (http://wgcv.ceos.org/)

Curriculum Vitae

Personal information:

Family name	Mücher
First names	Caspar Alexander (Sander)
Date of birth	August 2, 1967
Place of birth	Amsterdam
Nationality	Dutch
Contact	sander.mucher@wur.nl

Education:

1986 – 1992	MSc degree in Tropical Crop Science, Wageningen University, the Netherlands. Major subjects: Tropical Crop Science, Soil Science and Geo-Information.
1989 – 1990	Intensive course in Rural and Land Ecology Survey at the International Institute for Aerospace Survey and Earth Sciences (ITC), Enschede.

Work experience:

1992 – 1993	FAO commissioned desktop study. Result: a proposal for a global land use classification in cooperation with Wageningen University (Wageningen), ITC (Enschede) and FAO (Rome).
1994 – present	Researcher in Remote Sensing and GIS at Alterra, Wageningen University and Research Centre (WUR), the Netherlands. Research interests: Remote Sensing, GIS and surveying techniques in the field of landscape ecology and vegetation science.
2002	FAO mission to Dhaka, Bangladesh. Major objective was to determine the need and national support for establishing a national FIVIMS (Food Insecurity and Vulnerability Information and Mapping System).

List of Publications

Peer reviewed journals:

Bunce, R.G.H., Metzger, M.J., Jongman, R.H.G., Brandt, J., De Blust, G., Elena-Rossello, R., Groom, G.B., Halada, L., Hofer, G., Howard, D. C., Ková, P., **Mücher, C.A.**, Padoa-Schioppa, E., Paelinx, D., Palo, A., Perez-Soba, M., Ramos, I.L., Roche, P., Skånes, H., Wrbka, T., 2008. A standardized procedure for surveillance and monitoring European habitats and provision of spatial data. Landscape Ecol. 23 (1), 11-25.

Clevers, J.G.P.W., Schaepman, M. E., **Mücher, C.A.**, de Wit, A.J.W., Zurita-Milla, R., Bartholomeus, H. M., 2007. Using MERIS on Envisat for land cover mapping in the Netherlands. Int. J. Remote Sens. 28 (3-4), 637-652.

Gerard, F., Bugar, G., Gregor, M., Halada, L., Hazeu, G., Huitu, H., Köhler, R., Kolar, J., Luque, S., **Mücher, C.A.**, Olschofsky, K., Petit, S., Pino, J., Smith, G., Thomson, A., Wachowicz, M., Bezák, P., Brown, N. M., Boltiziar, E., 2009. Determining Europe's land cover changes over the past 50 years using aerial photographs. J. Land Use Sci., submitted.

Groom, G., **Mücher, C.A.**, Ihse, M., Wrbka, T., 2006. Remote sensing in landscape ecology: experiences and perspectives in a European context. Landscape Ecol. 21 (3 Spec. Iss.), 391-408.

Jongman, R.H.G., Bunce, R.G.H., Metzger, M.J., **Mücher, C.A.**, Howard, D.C., Mateus, V.L., 2006. Objectives and applications of a statistical environmental stratification of Europe. Landscape Ecol. 21 (3), 409-419.

Metzger, M.J., Bunce, R.G.H., Jongman, R.H.G., **Mücher, C.A.**, Watkins, J.W., 2005. A climatic stratification of the environment of Europe. Glob. Ecol. Biogeogr. 14 (6), 549-563.

Mücher, C.A., Hennekens, S.M., Bunce, R.G.H., Schaminée J.H.J., Schaepman, M.E., 2009. Modelling the spatial distribution of Natura 2000 habitats across Europe. Landscape Urban Plan. 92 (2), 148-159.

Mücher, C.A., Klijn, J.A., Wascher, D.M., Schaminée, J.H.J., 2009. A new European Landscape Classification (LANMAP): A transparent, flexible and user-oriented methodology to distinguish landscapes. Ecol. Indicat. , doi:10.1016/j.ecolind.2009.03.018. In Press.

Mücher, C.A., Steinnocher, K.T., Kressler, F.P., Heunks, C., 2000. Land cover characterization and change detection for environmental monitoring of pan-Europe. Int. J. Remote Sens. 21 (6-7), 1159-1181.

Renetzeder, C., van Eupen, M., **Mücher, C.A.**, Wrbka, T., Paula Turetta, A., Coutinho, H.L., Meirelles, M.S., Fistarol, G.O., Schlindwein, S., Zhen, L., Wie, Y., Tscherning, K., Sieber, S., 2009. Spatial Regionalisation in Europe, MERCOSUR and China for Sustainability Impact Assessment. Environmental Science & Policy, submitted.

Renetzeder, C., Schindler, S., Peterseil., J., Prinz, M.A., **Mücher, C.A.**, Wrbka, T, 2009. Can we measure ecological sustainability? Landscape pattern as an indicator for naturalness and land use intensity at regional, national and European level. Landscape Urban Plan., submitted.

Stomph, T.J., **Mücher, C.A.**, Fresco, L.O., 1997. Environmental impact of land use: a new basis for analysis. The Land: (1.2), 29-142.

Book chapters:

Clevers, J.G.P.W., **Mücher, C.A.**, Popov, V.P., Vandysheva, N.M., Vassilenko, G.I., 1999. Agricultural land cover monitoring in Russia using remote sensing, in: Nieuwenhuis, G.J.A., Vaughan, R.A., Molenaar, M. (Eds.), Operational remote sensing for sustainable development. Rotterdam, Balkema, 1999, pp. 81-88.

Gerard, F., Thompson, A., Manchester, S., Smith, G., Wadsworth, R., Swetnam, S., Petit, S., Gregor, M., Luque, S., Huitu, H., Köhler, H.R., Olschofsky, K., Hazeu, G.W., **Mücher, C.A.**, Halada, L., Bugár, G., Pino, J. 2006. Aerial photo interpretation and derived statistics from 59 samples distributed across Europe, in: Köhler, R., Olschofsky, K., Gerard, F. 2006 (Eds.), Land Cover Change in Europe from the 1950'ies to 2000. Arial photo interpretation and derived statistics from 59 samples distributed across Europe. University of Hamburg, World Forestry Institute, Hamburg.

Mücher, C. A., Wascher, D. M., 2007. European Landscape Characteracterization, in: Pedroli, B., van Doorn, A., de Blust, G., Paracchini, M.L., Wascher, D., Bunce, F. (Eds.), Europe's Living Landscapes. KNNV Publishing in cooperation with Landscape Europe, Zeist, pp. 37-43.

Mücher, C.A., Wascher, D.M, Klijn, J.A., Koomen, A.J.M., Jongman, R.H.G., 2006. A new European Landscape Map as an integrative framework for landscape character assessment. In: Bunce R.G.H., Jongman, R.H.G. (Eds.), Landscape Ecology in the Mediterranean: inside and outside approaches, 2006. Proceedings of the European IALE Conference 29 March – 2 April 2005 Faro, Portugal. IALE Publication Series 3, pp. 233-243.

Mücher, C.A., S.M. Hennekens, R.G.H. Bunce and J.H.J. Schaminée, 2005. Spatial identification of European habitats to support the design and implementation of a Pan-European Ecological Network, in McCollin. D., Jackson J.I. (Eds.), Planning, People and Practice. The landscape ecology of sustainable landscapes. Proceeding of the 13th Annual IALE(UK) Conference held at the University of Northampton, 2005, pp. 217-225.

Mücher, C.A., Steinnocher, K., Champeaux, J.L., Griguolo, S., Wester, K., Loudjani, P., 1999. Land cover characterization for environmental monitoring of pan-Europe, in: Nieuwenhuis, G.J.A., Vaughan, R.A., Molenaar, M. (Eds.), Operational remote sensing for sustainable development. Rotterdam, Balkema, 1999, pp. 107-111.

Kramer, H., **Mücher, C.A.**, 2001. The role of remote sensing techniques for European land use database construction, in: Stillwell J., Scholten, H. (Eds.), Land use simulation for Europe. Dordrecht, Kluwer Academic Publishers, pp. 83-99.

Renetzeder, C., Eupen, M. v., **Mücher, C. A.**, Wrbka, T., 2008. A Spatial Regional Reference Framework for Sustainability Assessment in Europe, in: Helming, K., Perez-Soba, M., Tabbush, P. (Eds.), Sustainability Impact Assessment of Land Use Changes. Springer, Berlin Heidelberg New York, pp. 249-268.

Schaepman, M. E., Malenovsky, Z., **Mücher, C.A.**, Kooistra, L., Thullier, W., 2007. Bridging scaling gaps for the assessment of biodiversity from space, in: GEO Secretariat (Ed.), The full picture. A publication for the GEO Ministerial Summit, 'Earth Observation for Sustainable Growth and Development' Cape Town, 30 November 2007. Tudor Rose / GEO, Geneva (Switzerland), pp. 258-261.

Conference and other scientific contributions:

Bunce, R.G.H., Pérez-Soba, M., **Mücher, C.A.**, Elbersen, B.S., Jongman, R.H.G., 2003. BioHab: a consistent methodology linking habitats with land use. International conference on framing land use dynamics; integrating knowledge on spatial dynamics in socio-economic and environmental systems for spatial planning in western urbanised countries, 16-18 April 2003, Utrecht University, the Netherlands, pp. 196-197.

Champeaux, J.L., **Mücher, C.A.**, Steinnocher, K., Griguolo, S., Wester, K., Goutorbe, J.P., Kressler, F., Heunks, C., van Katwijk, V.F., 2000. PELCOM Project: A 1-km pan-European land cover database for environmental monitoring and use in meteorological models. Proceedings Int. Geosci. Remote Sens. (IGARSS), 5, pp. 1915-1917.

Defourny, P., Schouten, L., Bartalev, S., Bontemps, S., Cacetta P., de Wit, A.J.W., di Bella, C., Gérard, B., Giri, C., Gond, V., Hazeu, G.W., Heinimann, A., Herold, M., Jaffrain, G., Latifovic, R., Lin, H., Mayaux, P., **Mücher, C.A.**, Nonguierma, A., Stibig, HJ., Van Bogaer,t E., Vancutsem C., Bicheron P., Leroy M., Arino O., 2009. Accuracy Assessment of a 300 m Global Land Cover

Map: the GlobCover Experience. 33rd International Symposium on Remote Sensing of Environment (ISRSE), May 4-8.2009, Stresa, Italy.

De Wit, A., **Mücher, C.A.**, 2009. Satellite-derived trends in phenology over Europe: real trends or algorithmic effects. Poster presented at the General Assembly 2009 of the European Geosciences Union (EGU), from 19 – 24 April 2009 , Vienna, Austria.

Fritz, S., Bartholomé, E., Belward, A., Hartley, A., Stibig, H.J., Eva, H., Mayaux, P., Bartalev, S., Latifovic, R., Kolmert, S., Partha Sarathi, R., Agrawal, S., Wu, B., Xu, W., Ledwith, M., Pekel, J.F., Giri, C., **Mücher, C.A.**, de Badts, E., Tateishi, R., Champeaux, J.L., Defourny, P., 2003. Harmonisation, mosaicing and production of the Global Land Cover 2000 database. European Commission, EUR 20489, Joint Research Centre (JRC), Ispra.

Groom, G., Wascher, D.M., **Mücher, C.A.**, 2007. Comparative review of European national and international landscape classifications with regard to future applications. Proceedings IALE 2007 World Congress, Wageningen, the Netherlands, 8 - 12 July, 2007, Wageningen, IALE, 568-569.

Groom, G., **Mücher, C.A.**, Ihse, M., Wrbke, T., 2003. Landscape level habitat mapping and monitoring: image data and information. Proceeding IALE 2003 World Congress of the International Association for Landscape Ecology, 13-17th July 2003, Darwin, Australia, Darwin, IALE, pp. 53-54.

Haest, B., Kempeneers, P., Cheung-Wai Chan, J., Vanden Borre, J., Kooistra, L., **Mücher, C.A.**, Deronde, B., 2009. Spectral comparison of Chris/Proba and AHS hyperspectral imagery in the framework of NATURA 2000 habitat monitoring. 6th EARSeL SIG IS workshop "Imaging Spectroscopy: Innovative tool for scientific and commercial environmental applications" Tel-Aviv, Israel, 16-19 March 2009.

Hazeu, G. W., **Mücher, C.A.**, Kramer, H., Kienast, F., 2008. Compilation and Assessment of Pan-European Land Cover Changes. Proceedings 28th EARSeL Symposium: Remote Sensing for a Changing Europe, Istanbul, Turkey, 2 - 7 June, 2008, Istanbul, Turkey, pp. 220-225.

Hazeu, G. W., **Mücher, C.A.**, 2005. Historic land use dynamics in and around Natura2000 sites as indicators for impact on biodiversity; Phase 1 of the BIOPRESS project for the Netherlands. Alterra Report 1077, Wageningen, the Netherlands.

Janssen, J.A.M., **Mücher, C.A.**, 2009. A quick method for mapping EU habitat types. Poster presented at 18th I.A.V.S. Workshop for the European Vegetation Survey Working Group, March 25- 28, Rome, Italy.

Kooistra, L., **Mücher, C.A.**, Chan, J., Borre, J. V., Haest, B., 2009. Use of spectral mixture analysis for characterisation of function and structure of heathland habitat types. Poster presented at 6th

EARSeL SIG IS workshop "Imaging Spectroscopy: Innovative tool for scientific and commercial environmental applications" Tel-Aviv, Israel, 16-19 March 2009.

Kramer, H., **Mücher, C.A.**, 2006. Land use from the days before the satellites. Proceedings of the second workshop of the EARSeL SIG on remote sensing of land use & land cover; application & development, Bonn (Germany), September 28-30, 2006, Bonn (Germany), EARSeL, pp. 316-322.

Mücher, C.A., Hazeu, G.W., Swetnam, R., Pino, J., Halada, L., Gerard, F., 2008. Historic land cover changes at Natura 2000 sites and their associated landscapes across Europe. Proceedings 28th EARSeL Symposium: Remote Sensing for a Changing Europe, Istanbul, Turkey, 2 - 7 June 2008, Istanbul, Turkey, pp. 226-231.

Mücher, C.A., Vos, C.C., Renetzeder, C., Wrbka, T., Kiers, M.A., van Eupen, M., Bugter, R. J.F., 2007. The application of satellite imagery to identify landscape structure. Proceedings of the IALE 2007 World Congress July 8th - 12th , Wageningen, the Netherlands, Wageningen, IALE, pp. 590-591.

Mücher, C.A., Gerard, F., Olschofsky, K., Hazeu, G. W., Luque, S., Pino, J., Gregor, M., Wachowicz, M., Halada, L., Tompo, E., Kohler, R., Petit, S., Smith, G., Kolar, J., 2006. Spatial impact of conservation sites (Natura 2000) on land cover changes. Proceedings of the second workshop of the EARSeL SIG on remote sensing of land use & land cover; application & development, Bonn (Germany), September 28-30, 2006, Bonn (Germany), pp. 386-393.

Mücher, C.A., Hennekens, S.M., Bunce, R.G.H., Schaminée, J.H.J., 2004. Mapping European habitats to support the design and implementation of a pan-European ecological network; the PEENHAB-project. Alterra report 952, Wageningen, the Netherlands.

Mücher, C.A., Bunce, R.G.H., Jongman, R.H.G., Klijn, J.A., Koomen, A.J.M., Metzger, M.J., Wascher, D.M., 2003. Identification and characterisation of environments and landscapes in Europe. Alterra rapport 832, Alterra, Wageningen.

Mücher, C.A., Kramer, H., Thunnissen, H.A.M., Clement, J., 2003. Monitoren van kleine landschapselementen met IKONOS satellietbeelden. Alterra rapport 831, Wageningen, the Netherlands.

Mücher, C.A., Remm, K., 2002. The pan-European ecological network habitat map, in Bouwma, I.M., Jongman R.H.G., Butovsky, R.O. (Eds.), The indicative map of the Pan-European Ecological Network for Central and Eastern Europe; technical background document. ECNC report, Tilburg, pp 43-52.

Mücher, C.A., Champeaux, J.L., Steinnocher, K.T., Griguolo, S., Wester, K., Heunks, C., Winiwater, W., Kressler, F.P., Goutorbe, J.P., ten Brink, B., van Katwijk, V.F., Furberg, O., Perdigao, V., Nieuwenhuis, G.J.A., 2001. Development of a consistent methodology to derive land cover information on a European scale from remote sensing for environmental monitoring; the PELCOM report. Alterra-rapport 178, Wageningen, the Netherlands.

Mücher, C.A., Steinnocher, K., Champeaux, J. L., Griguolo, S., Wester, K., Heunks, C., van Katwijk, V., 2000. Establishment of a 1-km pan-European land cover database for environmental monitoring. Proceedings XIXth congress of the International Society for Photogrammetry and Remote Sensing (ISPRS), ITC, 2000. Int. Arch. Photogramm. Remote Sens. Vol. 33, Part B7/3, pp. 702-709.

Mücher, C.A., Veldkamp, J.G., van Katwijk, V.F., Nieuwenhuis, G.J.A., van de Velde, R.J., 1996. Applicability of NOAA-AVHRR 1-km data for land cover based environmental monitoring in Europe. Final Report Part 1. SC-DLO Report 128, Wageningen, the Netherlands.

Roerink, G. J., de Wit, A.J.W., Pelgrum, H., **Mücher, C.A.**, 2001. Remote sensing mapping of carbon and energy fluxes over forests. Alterra Report 179, Wageningen, the Netherlands.

Sanders, M.E., **Mücher, C.A.**, Haveman, R., 2007. Monitoring Natuurdoelen. Achtergronden bij de Natuurbalans 2005. MNP Rapport nr. 408763008, Bilthoven, the Netherlands.

Wascher, D.M., Groom, G.B., **Mücher, C.A.**, Kindler, A., 2005. Recent developments in Mapping Europe’s landscapes, in Wascher, D.M. (Ed.), European Landscape Character Areas. Typologies, Cartography and Indicators for the Assessment of Sustainable Landscapes. Final ELCAI Project Report (ELCAI-EVK2-CT-2002-80021).

PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of Literature (4.2 ECTS)

- Remote sensing in landscape ecology: experiments and perspectives in a European context (2006)
- Comparative review of European national and international landscape classifications with regard to future applications (2007)

Writing of Project Proposal (6 ECTS)

- ECOCHANGE. Challenges in assessing and forecasting biodiversity and ecosystem changes in Europe (2007)

Laboratory Training and Working Visits (5.1 ECTS)

- Historic land use changes; CEMAGREF, Grenoble, France (2006)
- Landscape metrics and landscape elements; University Vienna, Vienna, Austria (2007)
- Challenges in assessing and forecasting biodiversity and ecosystem change in Europe; Institutul de Cercetari Biologice (IBRC, Cluj Napoca) (2008)
- Land use scenarios and associated habitats; University of Edinburgh (UEDIN), UK (2008)
- Landscape fragmentation; Eidgenössische Forschungsanstalt WSL, Switzerland (2008)

Post-Graduate Courses (2.8 ECTS)

- Sampling for natural resource monitoring; WUR (2008)
- 2nd HYPER-I-NET Summer school; PE&RC (2008)

Deficiency, Refresh, Brush-up Courses (2.4 ECTS)

- ENVI-IDL Seminar “Application Development for Remote Sensing”; CREASC (2006)
- IDL (Interactive Data Language) programming; D. Fanning (2008)

Competence Strengthening / Skills Courses (1.4 ECTS)

- Working with EndNote; Wageningen UR Library (2004)
- Techniques for writing and presenting a scientific paper; M. Grossman, Wageningen Business School (2005)

Discussion Groups / Local Seminars and Other Scientific Meetings (7.9 ECTS)

- Member GIN (Geo-Informatie Nederland) Voorheen Kring Remote Sensing (1998-2008)
- Member Plantensociologische Kring Nederland (PKN) (2004-present)
- Jaarcongres Kennisbasis Thema 1 Groene en Blauwe Ruimte (2006 and 2007 and 2008)

PE&RC Annual Meetings, Seminars and the PE&RC Weekend (2.8 ECTS)

- LUCAS Expert workshop “Multi-dimensional cross-analysis of LUCAS” ; Brussels (2007)
- Seminar remote sensing & vegetatiekatering; C. de Vries, Roeterseiland complex van de UvA (2007)
- SEAMLESS Seminar; WUR (2008)
- PE&RC Day on ‘Scaling from Molecules to Ecosystems’ with 2nd HYPER-I-NET summer school (2008)
- Remote sensing of the environment; WUR (2009)

International Symposia, Workshops and Conferences (9.6 ECTS)

- IALE Conference “Landscape Ecology in the Mediterranean: Inside and Outside Approaches”; Faro, Portugal (2006)
- IALE World congress; Wageningen, the Netherlands (2007)
- 28th EARSEL Symposium “Remote Sensing for a Changing Europe”; Istanbul, Turkey (2008)

- International conference "Impact Assessment of Land Use Changes"; Humboldt University, Berlin (2008)

Courses in Which the PhD Candidate has worked as a teacher

- European Landscape Characterization; Faculty of Spatial Sciences, Groningen ; ½ day
- Modelling spatial distribution of habitats across Europe-disaggregating remotely sensed land cover information into ecological relevant classes; Remote Sensing Course, Alterra, Wageningen; ½ day

Supervision of MSc Students (42 days; 7 students)

- Change detection in Europe's land cover by means of medium resolution satellite images; MSc thesis Petra D'Odorico ; Geo-Information, WUR (2005)
- Comparison of MODIS and MERIS data for land cover mapping in the Netherlands; MSc thesis Hailu Shiferaw, Geo-Information, WUR (2005)
- Spatio-temporal identification of *Quercus suber L.* forests with high and medium resolution imagery; MSc thesis Javier Chico Zamanillo, Geo-Information, WUR (2006)
- Monitoring habitats by remote sensing data; MSc thesis Ana Belén Ruiz Sánchez, Geo-Information, WUR (2006)
- Characterization of European landscapes and analysis of their dynamics. Landscape descriptions; Internship MSc course Geo-Information, Rick van der Heijden (2007)
- Reconstruction of heathland management for the Edese and Ginkelse Heide using aerial photographs. Internship MSc course Geo-Information, Adriana Niewiadomska (2007)
- Mapping heathland habitat types using multi-angular CHRIS PROBA data. Internship MSc Course Geo-Information, Beatus Jacob Chuma (2008)