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Change trajectories and key biotopes—Assessing landscape dynamics and sustainability

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Abstract

This paper presents a methodological synthesis of two congruent approaches into a common landscape change trajectory analysis and the assessment of landscape dynamics and sustainability. The emphasis of the analysis is on the retrospective relationship between the past and the present-day landscape patterns and associated key biotopes. The example key biotopes, oak woodlands and grasslands, represent valuable habitats in the hemiboreal landscapes of Finland and Sweden. The paper presents a conceptual stepwise approach for change trajectory analysis utilising multiple spatio-temporal data and techniques available in image processing and geographical information systems (GIS) including the following steps: (I) specification of spatio-temporal data and their representation of target objects, (II) the choice of direct or indirect change trajectory analysis, (III) hierarchical structuring of landscape information, (IV) compilation of landscape information into a GIS database, and (V) identification of paths for landscape change trajectory analysis. In this case study, we have focused on three interlinked trajectory analysis approaches, and their role in the assessment of landscape sustainability from a potential biodiversity perspective. We conclude that proposed landscape change trajectory analysis can improve the assessment of the key biotopes as well as present-day landscape characteristics, in maintaining biodiversity and related ecological values by providing information on landscape stability, continuity, change processes and boundary dynamics. This approach can be useful in the assessment of natural capital, but requires data-specific and context sensitive data processing and analysis solutions. The results should be interpreted as an approximation and generalisation of the spatio-temporal complexity of landscape reality and therefore be used in conjunction with additional habitat function measures.

Keywords: Landscape change; Oak woodlands; Grasslands; Spatio-temporal data; Hierarchical classification; Retrospective GIS; Multiple landscape values

1. Introduction

A distinguishing feature of landscapes and ecosystems is constant change and evolution. Whatever actions we intend to perform on landscapes inescapably target dynamic systems, which possess both spatial and temporal complexity and chaotic behaviour (Antrop, 1998; Haines-Young, 2000). While landscapes hold intriguing spatial and functional properties in situ, their dynamic character obstructs our ability to predict and control their future development (Bartel, 2000). Fur-

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thermore, there are enormous gaps in our knowledge about the nature of landscapes and these uncertainties which, by necessity shifts the analysis focus from spatially driven (species–landscape patches interactions) to more dynamic, process-oriented courses (Antrop, 1998). One of the implications of these dynamic approaches is *landscape change trajectory analysis* or LCTA, where the emphasis is on identifying the ways in which landscapes transform through time. In this paper we explore how such analyses can be made.

This approach focuses on change processes instead of the arbitrary information of landscape patterns at any random occasion in time. Additionally, change trajectory analyses often consider what might be the driving forces behind changes and the main consequences of these processes.

Indisputably, landscape systems are challenging to study. Complex interactions of environmental factors and driving forces continuously alter species compositions, and these dynamics are reflected on different landscape patterns (Fry, 1998; Lambin et al., 2001). Landscape patterns, on the other hand, are scale- and observation-dependent (Delcourt et al., 1983; Turner et al., 1989) and tend to respond by successions in different directions and with varied time lags to changing environmental conditions (Löfvenhaft et al., 2002, 2004). Pattern and scale are therefore central issues within landscape ecology that require appropriate geographical analyses. Due to multiple values attached to the landscape (e.g. ecological, economical, amenity) it also acts as a valuable surface upon which to implement planning and management actions. Decisions concerning preservation and management of, for example, valuable biotopes are made within a cultural, social, political and economic setting, and increasingly at the landscape level, where different research problems and social values can be addressed, both in theory and in practice (Wiens, 1989; Council of Europe, 2000; Haines-Young, 2000; Gulinck et al., 2001).

There is a growing awareness in ecological sciences of the need to study phenomena at a wide range of spatial, temporal and organisational levels (Levins, 1992; Godron, 1994; Klijn and Udo de Haes, 1994). The framework necessary to organise this research is provided by a hierarchical structure in which a sequence of small subsets, applicable at different dimensions, such as time, space, ecological levels and thematic resolution, are studied (Delcourt et al., 1983; Urban et al., 1987).

One of the main ideas of landscape change trajectory analyses is the promotion of qualitative, spatio-temporal aspects of landscapes and hence seeking possible relationships between the present-day landscape and its past, underlying change dynamics and patterns (Skånes, 1996a; Vuorela and Toivonen, 2003). As the present approach is retrospective, the emphasis is set on past landscape patterns and processes but primarily in the context of the present-day landscape and related values. Retrospective analysis can be used to relate the past to the present state and dynamics of the landscape and therefore, compose one type of re-evaluation method of landscape-related ecological, social or economic values. Thus, retrospective landscape change analysis can be crucial, for example, when supplementing our knowledge about the present-day variation and future trends of key landscape elements and biotopes and associated biodiversity and amenity values (Fry, 1998; Burke, 2000; Haines-Young, 2000).

Recent discussions concerning the properties of landscapes and how they should be analysed have emphasised two issues. Firstly, as pointed out by several authors, there is a need for transdisciplinary landscape research, due to the complexity of landscapes and on limited understanding of the driving forces behind the changes. Secondly, new approaches for landscape analysis have been adopted under the sustainable landscapes and natural capital paradigm where landscape properties or functions are evaluated as goods and services for people (Haines-Young, 2000; de Groot et al., 2002; Potschin and Haines-Young, 2003). Both issues are crucial when considering the ways in which landscape change analyses are carried out and especially how the value of such analyses are determined.

This challenges landscape change trajectory analysis in several respects. Firstly, the primary focus of change trajectory analysis needs to be justified. This refers in particular to the hypotheses and expectations we have of the possible links between the present-day landscape and its past and ongoing dynamics. Secondly, there needs to be a clear vision of how change trajectory analysis is carried out in practice. What types of techniques and methods can be used and how are these implemented in relation to the primary hypotheses? Thirdly, how can the information from trajectory analysis be applied when assessing different functions of landscape? In this study, we have focused on the biodiversity implications of the landscape change trajectory analysis both from the perspective of potential biodiversity and management and conservation of biodiversity. This paper addresses these three challenges by synthesising concepts and results from two landscape change trajectory case studies from Finland and Sweden. The implemented analyses were based on the idea that the relationships between the key biotopes (oak woodlands and grasslands), and landscape change trajectories can be used in assessing landscape and key biotope dynamics and their sustainability, mainly as sources of potential biodiversity. It must be emphasised that biodiversity cannot be measured in absolute figures when using retrospective analysis extending over centuries. Still, a retrospective method that analyses the spatial prerequisites and major conditions for biodiversity enables an approximation of what we call potential biodiversity to be made. This is possible by using the attributes visual in spatial data, mainly structure and composition (Skånes, 1997). The landscape perspective used in these case study was primarily a combination of a geobotanical and an ecological–geographical approach, with the main interest on the relationship between the present-day landscape patterns, their past development, and land use/land cover continuity and dynamics.

2. Case studies and key landscape elements

2.1. Ruissalo Island in South-western Finland

The island of Ruissalo (9 km^2) immediately offshore the city of Turku is characterised by features typical of the hemiboreal coastal archipelago of southwest Finland (Fig. 1). There are cultivated fields, numerous summer residences and woodlands ranging from dry and rugged to mesic and rich deciduous woodlands (Vuorela, 2001). However, the abundance of pedunculate oak (*Quercus robur*) woodlands of Ruissalo is atypical in Finland. Oak and other hardwoods dominate approximately one third of the woodland coverage here, while regionally in Finland the equivalent figure is approximately 1% (Ympäristöministeriö, 1994; Alanen et al., 1995). Several long-term environmental processes have influenced the general characteristics of the topography and the edaphic site conditions of the island. These include shear zones of bedrock, glacial erosion and isostatic uplift (Fogelberg, 1986). Although the general nature of the landscape can be considered typical of the region, the landscape of Ruissalo consists of exceptional land use and land ownership changes and patterns: the island was a Royal hunting park during the 16th century, a wage-farm of the regional governors from the 17th to 18th centuries, and a summer housing area of the merchants of the town during the 19th century (Vuorela, 2000). During the past 150 years Ruissalo has become an important biodiversity and conservation site in Finland with several threatened invertebrate species, the largest oak woodlands in the country and a valuable cultural landscape. This reflects the range of both natural and human induced environmental changes (Ympäristöministeriö, 1992).

2.2. Virestad in southern Sweden

Virestad Parish (298 km^2), Kronoberg County, is situated in the central parts of the Götaland Forest Region within the hemiboreal region (Fig. 1). The topography of Virestad is relatively flat, within the range of 131–188 m a.s.l. The geology is dominated by Precambrian acid gneiss, resulting in poor soils. The Quaternary deposits are dominated by till with an abundance of peat. Apart from till and peat there are, in conjunction with the lakes, occasional narrow veins of glaciofluvial sediments, mainly clay and sand. The entire study area is situated above the highest marine coastline after the latest deglaciation. Due to this, the soils were never washed out during deglaciation and still hold substantial proportions of silt and fine sand. This preserved a relatively high capacity to hold nutrients and water, making the land worth cultivating. The area had a Medieval agricultural colonisation. Although the till is generally rich in boulders and therefore hard to cultivate, these soils still constituted the main arable land type in areas above the highest marine coastline before the drainage projects of the turn of the 20th century. However, with the modern demands on high yields, the number of active farms decreased and the dominant agricultural production is livestock. The Virestad area is representative of major parts of the Götaland Forest region (Skånes, 1996a).

2.3. Oak woodlands and grasslands

Key biotopes are generally considered to support greater biodiversity than other biotopes, either directly

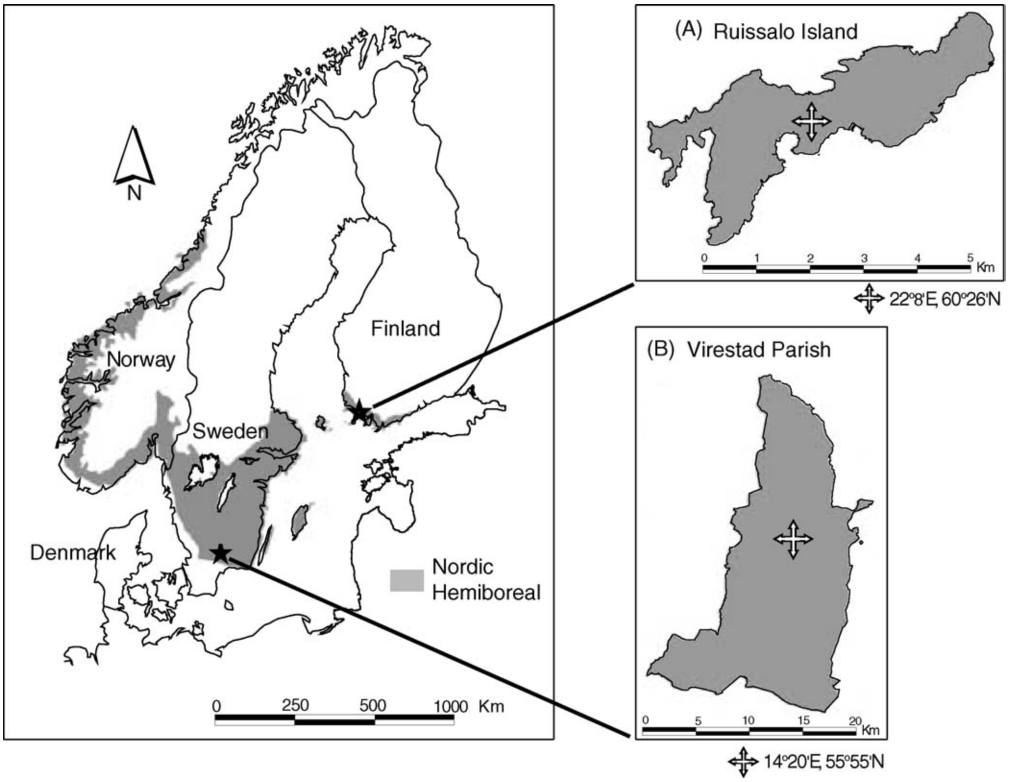


Fig. 1. The two case study areas are both phytogeographically part of the hemiboreal vegetation zone between the temperate and boreal zones in Northern Europe (Sjörs, 1963; Ahti et al., 1968). Ruissalo Island (A) is located in the SW archipelago of Finland and Virestad Parish (B) is situated in south Sweden.

by providing habitat or indirectly as corridors to species movement and migrations (Fritz and Merriam, 1993; Riffell and Gutzwiller, 1996). As part of the implementation of the Convention on Biodiversity, many European countries have identified and mapped key habitats in an effort to study and maintain biotope and species level richness (Ministry of Environment, 1998). One of the essential aims in this task is to identify habitat characteristics, either by compositional structures or functional processes, which are critical to the maintenance of, and losses or increases in the long-term biodiversity (Walker, 1992; Cousins and Eriksson, 2002).

Knowledge of land cover and land use change is valuable as most European biotopes, as well as those in other parts of the world, are characterised and governed by human influences. Further, many threatened species are linked to biotopes highly modified by human utilisation through time (Hansson, 2000). Both oak woodlands and grasslands are widely acknowledged as important in supporting high levels of habitat and species diversity as well as landscape amenity and recreation values. Varying anthropogenic disturbances since the Middle Ages or even earlier, have influenced grassland and oak woodlands with their different successional stages (Berglund, 1991; Slotte and Göransson, 1996). These disturbances include mowing, leaf harvesting, grazing, trampling, burning, sowing, cutting, and recently both recreation and even overprotection. Although grasslands and oak woodlands are often treated as two separate biotopes, they may be seen as different positions along the natural succession gradient from open grassland to closed forest. Hence, they have more in common than their respective biodiversity and amenity values. In major parts of southern and central Sweden, deciduous and mixed forests often represent spontaneous vegetation successions on land with a long history of grassland management (Ekstam and Forshed, 1992; Emanuelsson, 1996; Slotte, 2002). This is also the case for Finland, where, for example, a large number of the threatened species are found in meadow habitats and deciduous woodlands, which have undergone various human induced changes throughout history (Rassi et al., 1992; Pykälä and Lappalainen, 1998).

Grasslands, as defined in the Swedish case study, are the highest hierarchical level of all land cover types which are currently influenced by, or still show evidence of, grazing or mowing (Skånes, 1996b). They are characterised by light-demanding herbaceous vegetation. However, because of the transitional stages between rural and forest landscapes, grasslands may also include biotopes that are botanically classified as heath, mire or forest vegetation. This wide definition of grasslands therefore includes oak woodlands to a great extent. This modification, at the expense of the modern definition of forest, is necessary to make in change trajectory studies since the definition, management regime, and representation of grasslands, as well as other biotopes, will vary over time and between sources. Grasslands are more than a land cover group; they also represent the dynamic transition zone between the arable landscape and the forest landscape, dating back to the old village society where grasslands were mainly located between the arable fields and the outland forests. This transition zone has diminished considerably and the present-day landscape consists more often of arable fields in direct contact with managed coniferous forests.

3. Retrospective view on landscapes

The concepts of time and space have been widely discussed by Hägerstrand (1974, 1985) who developed the field of time-geography, where the core element is a conceptual framework of a web of life-lines, or trajectories, woven by individuals, objects and actions in the time-space (Bladh, 1995). The fundamental ideas of time-geography are also present in landscape change analysis, which tries to identify when, how and why landscapes evolve through time.

Since human activities are one of the main mechanisms that change and modify landscapes, a great number of Nordic landscape change studies deal with land use or land cover changes and dynamics through time (Keisteri, 1990; Skånes, 1990; Foster, 1992; Ihse, 1995; Fjellstad and Dramstad, 1999; Cousins, 2001a; Vuorela, 2001; Löfvenhaft et al., 2002). Jones (1991) argues that all landscapes are cultural landscapes, in a physical sense, and that ecological processes must be viewed in a historically specific context. Although the vegetation cover and drainage patterns of a landscape are transformed by human actions, basic features of topography and geology normally remain recognisable and can still be traced within a cultural landscape. However, a major problem is that many actions lead to events that were unforeseen, resulting in even greater complexity of relationships within the landscape (Hägerstrand, 1994).

By using time as a vertical process, an inherent chronology is attached to landscape patterns (Skånes, 1997; Antrop, 2000). These chronological relationships between landscape patterns and their chorology provide information about the spatio-temporal dynamics of landscape elements. Retrospective analysis is useful, as it links the present-day landscape with past landscape dynamics and enables trajectories to reveal continuity, turnover, directions or degree of changes in relation to present-day situation. Hence, a retrospective dimension is essential when dealing with qualitative aspects of the present-day and future landscapes, their biodiversity and cultural heritage.

A retrospective method permits regressing back in time from a relatively well-known present (Norton, 1989), by observing the present-day situation through field recordings and remote sensing to past times where sources are scarce and difficult to verify without making assumptions based on present-day conditions and plausible paths of change.

3.1. Data and information of past and present landscapes

One of the main challenges of landscape change analysis lies in the heterogeneity and fragmented distribution of landscapes information, both in space and time. This heterogeneity limits the spatial and temporal tracking of landscape patterns in detail. Can these problems be assessed and overcome? It can be argued that a major issue in landscape change analysis lies in the balanced use of the available data sets and this heavily influences the ways in which landscape trajectory analysis can be carried out. Restrictions and limitations in merging and combining spatio-temporal information of landscapes are inherently part of the process of analysing landscape changes (Skånes, 1997; Vuorela, 2001; Petit and Lambin, 2002).

In practice, landscape change analyses are carried out at various temporal and spatial scales. Information of landscapes is often obtained from a variety of data sets, from satellite images, aerial photographs to cadastral maps and historical records. These data sets provide a powerful tool to estimate the spatial extent of landscape features at one particular moment in time. However, field studies are needed to estimate the quality of the target features (Brandt et al., 2002; Haines-Young et al., 2003). The challenge of change analysis lies in the combined uses of landscape information originating from variable sources (Skånes, 1997; Vuorela, 2001). Hence, what constitutes relevant landscape information depends on the research purpose and varies accordingly.

Today, most landscape change analyses are performed using tools and techniques in geoinformatics. These include the use of remote sensing, image processing techniques, geographical information systems (GIS) and digital cartography. Landscape changes have been quantified as well as visualised using the tools available. Usually, the representative data sets have been stored in GIS as time-slices, which have been used in landscape change detection (Kienast, 1993; Simpson et al., 1994). To achieve compatibility between different levels and thematic structure of detail in data sources, the landscape classification should be designed with a hierarchical dimension (Antrop, 2000). The principles of hierarchical classification are based on holism, enabling recognition and description of a whole or an entity by a limited number of its abstracted properties, or diagnostic characteristics (Küchler and Zonneveld, 1988; Zonneveld, 1994). A hierarchical approach will allow comparison between different classification systems through co-registration and aggregation of unique classes into higher levels that are more compatible.

3.2. *Change trajectory analysis*

While most outcomes of change analyses are presented as landscape pattern maps or land cover change statistics, increasing focus has been towards more dynamic representations of landscape changes. These involve, for example, identification of landscape trajectories, which focus rather on processes of change than states of landscapes patterns at different moments in time. Landscape trajectories, which often describe the overall spatio-temporal transformations in land cover/biotopes, have been developed as a means to identify the core character of landscapes and therefore, have been found useful in practical management and conservation of valuable landscapes. The use of trajectories, alternatively labelled land-use-history profiles (Skånes, 1996a) or land-cover transitions (Cousins, 2001b), allow a more qualitative representation of spatial data where areas with the same land cover class today can be thematically separated due to different land use and land cover history. This approach provides us with a tool to understand ongoing changes in the landscape and their drivers (Skånes, 1996a; Vuorela, 2001).

The focus of landscape change trajectory analysis is on change as a dynamic process. This is different from an approach where landscape patterns, i.e. states of a landscape, are observed and measured at any one moment in time (Haines-Young, 2000). It is possible to use the terms landscape pattern and structure both in a temporal and functional context referring to landscape changes and dynamics through time (Antrop, 1998). In order to determine landscape change, a decision on the level of landscape classification is needed and technically, a minimum of two time slices is required. Thus, the temporal structure of the landscape consists of changes in the relations between different elements. The intrinsic characteristics of spatio-temporality of a pattern can be summarised into five categories (Peuquet, 1994); the temporal cohesiveness including transitions of individual objects (e.g. key biotopes) over time; the temporal similarity of objects (i.e. rate and magnitude of change); the temporal continuity or pattern; the hierarchical organisation, consisting of different processes operating at different temporal scales; and the incompleteness, referring to the limited knowledge that we always have of the changes.

To conclude, change trajectories cannot be determined without spatial intersection of data. From the perspective of using layer-based GIS, at least three time steps are needed in order to build a change trajectory. This is a contrast to landscape change analysis, which can be implemented using only two time layers as described above. As landscape patches, structures and patterns are relative concepts, landscape change is inevitably a relative concept as well. Dynamics and stability are reflections of spatio-temporal landscape observations at a particular scale and over a particular time period (Farina, 1998; Petit and Lambin, 2002).

4. Landscape change trajectory analysis: a stepwise synthesis from two case studies

The following section synthesises the conceptual settings and the main phases of landscape change analysis implemented in the two case studies and suggests a stepwise procedure for landscape change trajectory analysis (Fig. 2).

4.1. Step I: Specification of spatio-temporal data and their representation of target objects

Although a challenging task, combining spatio-temporal data originating from various sources is a necessity for spatio-temporal landscape analyses extending to cover centuries. When retrospective change analysis approach was adopted in these two case studies, the first step involved spatial, thematic and temporal evaluation of the data properties. These were carried out with focus on the representation of key biotopes and landscape patterns in a temporal sequence of data.

In the following, we present major coherent findings of this work phase from the respective case studies

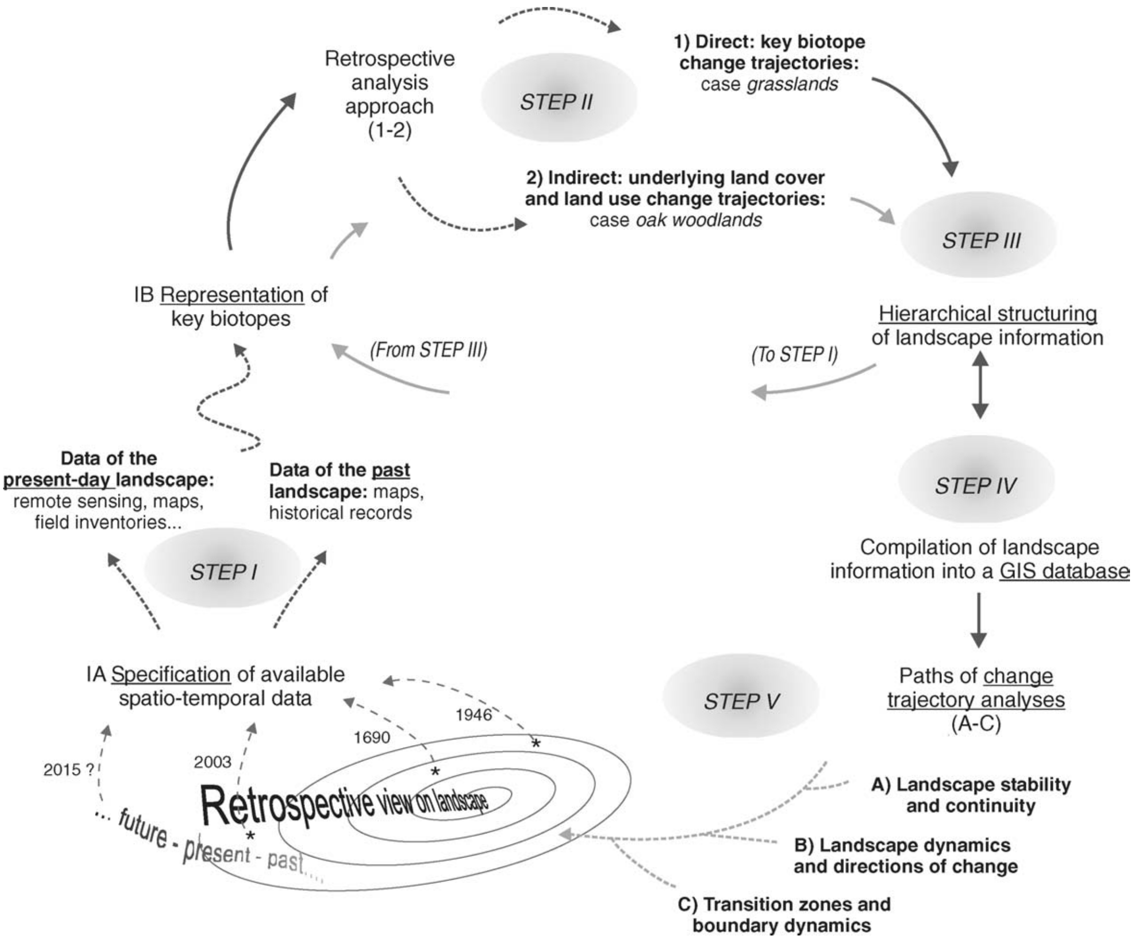


Fig. 2. A conceptual model for direct/indirect retrospective landscape change trajectory analysis including methodological solution during sequential work steps (I–V). See details for each step from the text.

(Skånes, 1996c, 1997; Vuorela, 2001) that are crucial to consider when setting up a change trajectory study. The spatial data potentially applicable in landscape change trajectory analyses are manifold and diverse, resulting in a heterogeneous set of spatio-temporal landscape information. In order to prove successful, an integrated method must involve the combination of transdisciplinary and multi-temporal spatial data such as aerial photographs and old cadastral maps, which were the main sources in the two case studies. The problems arising from the translation and integration of data into a digital environment from heterogeneous sources with different spatial, temporal, spectral and/or thematic resolutions also need to be acknowledged. The procedure of data evaluation must be systematic. In these case studies it involved mainly the analysis of remotely sensed data and map data properties. Visual interpretation of remote sensing data also allows a holistic perception of the landscape, resting on expert decisions, but at the same time makes it more difficult to evaluate.

Regarding detailed landscape sources, the role of aerial photography remains important, not only in integrating satellite imagery and field inventories, but particularly in retrospective landscape studies, where its temporal coverage is unsurpassed. Due to the retrospective approach that requires data with a long time sequence, satellite imagery will not replace aerial photographs as a primary source of landscape data in change trajectory analysis. The use of various remote sensing data should therefore be complementary, rather than exclusive. Old cadastral maps provide information of long-term continuity and turnover in land use. It should be recognised that map feature classes vary remarkably in their thematic, spatial and temporal representation. Map feature consistency clearly reflects the purpose and scale of the mapping, as well as the skills of the surveyor and cartographer. The uncertain nature of landscape information with respect to unclear and/or dynamic definitions of some key feature classes, such as woodlands and grasslands, is also reflected in map feature inconsistency.

Information on key biotopes, oak woodlands and grasslands, seems to be inconsistent in the data sets due to variation in definitions and representation. Information of oak woodlands is also highly sporadic and their pattern cannot be identified with sufficient accuracy from a temporal data sequence. A modified and adjusted classification of key biotopes is therefore needed for the temporal sequence. Land cover and land use information within woodlands and grasslands can be identified from the spatial data sources and their written supplements thereby providing indirect information regarding their distribution and quality. The spatial qualities of the maps also provide information in estimating the ecological conditions for biodiversity in the past indicating, for example, the direction and magnitude of change. In Finland and Sweden these data extend back to the 17th century when mapping began.

4.2. Step II: Direct or indirect change trajectory analysis?

After specifying the relationships between data sets and landscape information two different approaches for the implementation of landscape change trajectory analysis were apparent. Firstly, a direct approach, in which spatio-temporal dynamics of the key biotope are observed, and secondly an indirect approach, in which the present-day configuration of the key biotopes are assessed in respect of underlying and surrounding land cover and land use dynamics.

A direct approach was used for the grassland case study (Virestad). Grasslands are detectable in aerial photographs as well as explicitly classified, although with varying nomenclature and definitions, in the old maps. This direct approach was possible since the grassland concept was adjusted in a hierarchical structure to bridge these inconsistencies in terminology (see further Step III below).

An indirect approach was applied for the oak woodland case study (Ruissalo) due to lack of reliable information about the development of the spatial extents of this key biotope through time. The major focus was therefore set on the underlying land cover and land use dynamics. This information was combined from several data sources extending from the 17th century to the present-day. Firstly the analysis of overall land cover dynamics was implemented and secondly, land use changes and transitions within woodlands were analysed. The knowledge of the change trajectories and interactions of past landscape/land use patterns was then linked spatially to the present-day oak woodlands. The present-day oak woodlands were described and their conservation and management status were re-evaluated using the information of underlying landscape dynamics.

Both direct and indirect change trajectory analyses are challenging, since the choice of an appropriate entity type for landscape representation is not easy. In principle, a combined direct and indirect approach may be optimal since a given key biotope might well be well represented in one source/time slice, while only indirectly accessible in other.

4.3. Step III: Hierarchical structuring of landscape information

When spatio-temporal data are to be integrated and merged through intersection in systems such as GIS, hierarchical classification can be used as a means to deal with spatial and thematic inconsistencies evident in any spatio-temporal sequence of data. It is of primary importance that possibilities and restrictions related to the data sets are understood and reflected in the decisions regarding thematic representation and structure, i.e. hierarchical classification, of the landscape information. In practice, this involves choice of entity types, database structure, and the choice of transformation process for each data set. To facilitate comparison, the common nominators between different classification systems and source materials used need to be identified and established.

Due to the emphasis on oak woodlands and grasslands, the hierarchical classification system may seem inconsistent since it is not equally detailed in all land cover groups. However, this is to be seen as an expression of the holistic approach applied, where these key objects were chosen for their qualities as diagnostic characteristics, which go far beyond the traditional definition of a land cover type (Skånes, 1997; Vuorela, 2001).

In accordance with their inherent heterogeneity, the classification and representation of grasslands varies between sources, making detailed comparisons difficult (Table 1). This means that to monitor changes within grasslands over time, involving more than one type or generation of sources, a modified classification system has to be used (Skånes, 1996b). In the present study, the classification systems were designed to illustrate the major variations detectable in aerial photographs and old cadastral maps.

The range of variation within the heterogeneous grassland vegetation, to give one example, is set by key criteria, facilitating numerous combinations of several characteristics (Table 2). Some of the criteria are applicable for aerial photographs, while others are more readily traceable in cadastral maps. All of these criteria were considered during the manual interpretation process, although not individually. Some of them were instead used indirectly as indications of specific land use/land cover qualities in a comprehensive interpretation, e.g. soil or moisture regime. This infers that, although the individual data layers might provide detailed landscape information, strong generalisations

Table 1
The applicability of key criteria and consequent representation of biotopes used in the classification of grasslands in aerial photographs and cadastral maps, respectively

Key criteria building the knowledge of grasslands	Characteristics arbitrary or gradients	Representation in	
		a. photo	c. map
Structure and texture in canopy	Open–wooded–forest succession	+	(+)
Moisture regime	Dry–mesic–moist–wet	+	+
Soil type	Bedrock, till, sand, clay, organic, etc.	(+)	(+)
Soil surface conditions	Degree of boulder content	+	(−)
Soil nutrient properties	Acid–intermediate–calcareous	–	+
Position within the old village system	Infield–outland	–	+
Land use regime	Mowing–grazing	(−)	+
Management intensity	High–low–abandoned	(+)	(+)
Cultivation degree	Semi-natural–cultivated	(+)	(+)

The range of variation within the heterogeneous grassland vegetation is set by these key criteria, resulting in numerous classes of possible combinations (modified after Skånes, 1996a). In the column to the right, a. photo: aerial photograph, and c. map: cadastral map. +: principal criterion with an applicable set of characteristics and clear representation; (+): important criterion with indirect or varying applicability of some characteristics; (−): peripheral criterion with limited applicability and unclear/deficient representation; −: criterion with no applicability, cannot be directly traced in the source.

Table 2
Joint classification system used in the change trajectory analysis, grassland case study

Historical maps 1741–1811 (T_1)	Tot T_1 53	Joint ($T_1 - T_3$)	Tot $T_{2\text{–}3}$ 18	Air photos 1946, 1993 ($T_{2\text{–}3}$)
Infield mosaic including hay meadows, pasture and farmsteads	10	1 infield mosaic/arable land	5	Including lay fields and cultivated/ improved grasslands
Hay meadows and pasture without tree symbols, both infield and outfield, dry–mesic–wet	21	2 open semi-natural grasslands	6	Unimproved (restrictive classification in 1993 photos), dry–mesic–wet
Enclosed hay meadows and pasture with tree symbols, and outfield areas not specified as forest	9	3 wooded grasslands	2	Including wooded grasslands regardless of improvement and heterogeneous deciduous forests, dry–mesic–wet
Water surfaces and running water	2	4 water	1	Water surfaces and running water
Non agricultural areas; dense forest, unmanaged mires, etc.	11	5 forest/remaining land	4	Non agricultural; dense forest, clear-cuttings, unmanaged mires, built-up areas.

Two classification systems optimised for aerial photographs and historical maps, respectively, were joined in a generalised system containing only five clearly compatible major land cover classes (1–5) for the respective time layers ($T_1 - T_3$). A system of 53 classes was designed for the cadastral maps (1741–1811) and for the aerial photographs a relatively rough system designed to fit the old black and white photographs was used containing 18 classes (modified after Skånes, 1996a).

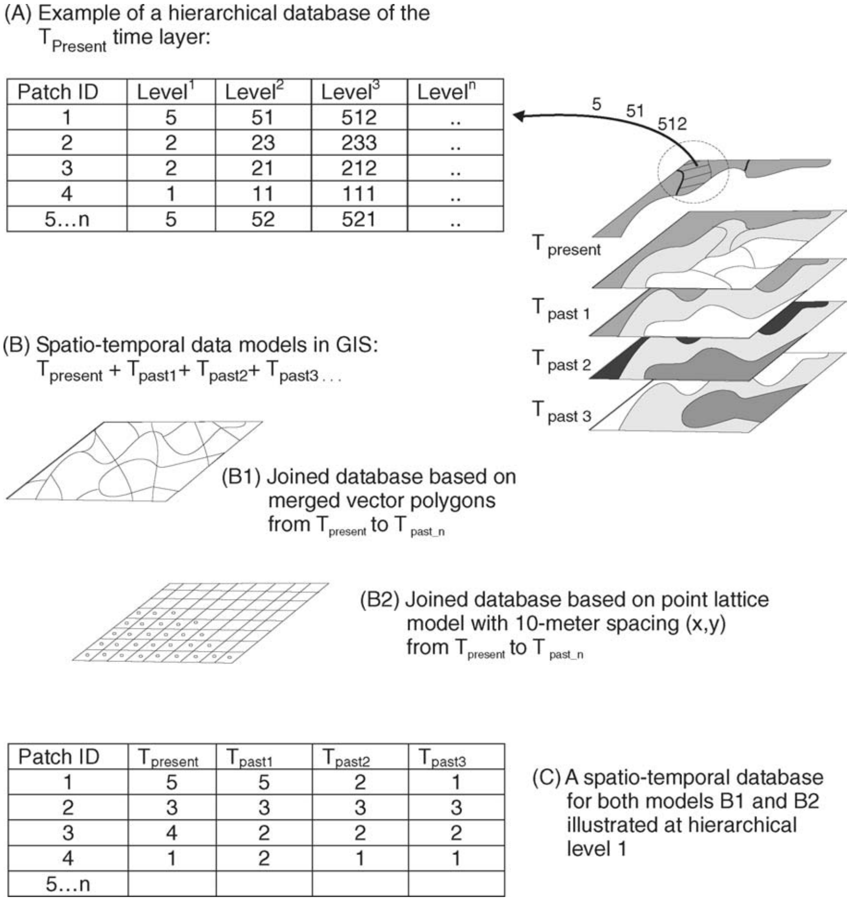
had to be made in order to produce comparable time series from multiple data (Table 2). There were problems in harmonising the information content originating from different sources (Dunn et al., 1991; Marcucci, 2000; Petit and Lambin, 2002), and therefore the classification used in the change detection was carried out according to the coarsest data set. This calls for case-specific and context sensitive solutions to be developed and implemented.

4.4. Step IV: Compilation of landscape information into a GIS database

The process of building a geographic information database from spatio-temporal data usually consists of several phases in which data sets are first evaluated, as was shown in previous steps, and then transformed with the aid of a conceptual model into a digital spatial data model in a GIS (Peuquet, 1994; Chrisman, 1998). Change trajectory analyses implemented in GIS can be based on several types of data models and database solutions, such as relational, hierarchical and object-oriented (Langran, 1992; Walsh, 1994). For landscape change analysis, hierarchical models are useful as they enable representation of landscape information at multiple scales in one spatio-temporal database. This approach was necessary in both case studies, which used modifiable area units (grasslands) and indirect, multiple scale analysis of land cover and land use changes (oak woodlands).

The change trajectory analysis method in both case studies concerned time as the framework in which changes in geographic entities were observed. In other words, spatially explicit entities on sequential maps were intersected and compared to determine the location and nature of changes. Such a model, consisting of sequential snapshots (Langran, 1992; Johnston, 1998; Stead, 1998), has frequently been used as a basis for landscape change analysis. It can be applied both with raster and vector models. A polygon-based model was used in the grassland case (Skånes, 1996c) and a point-lattice, equivalent with raster cell model, was implemented in the oak woodland case (Vuorela, 2001). A schematic illustration of a hierarchical snapshot database is shown in Fig. 3.

Due to spatial and thematic inconsistencies, the GIS compilation of landscape information requires optimisation for each data set. With heterogeneous data sets, such as maps and remotely sensed data, digital transformation is a tedious and selective process. All data sets need to be fed into the GIS and rectified and co-registered accordingly. The process is neither straightforward nor automatic as is illustrated in the following example, which lists the main work phases of digital transformation of old cadastral maps. The original maps were photographed at the archives and the pho-



Patch ID	$Level^1$	$Level^2$	$Level^3$	$Level^n$
1	5	51	512	..
2	2	23	233	..
3	2	21	212	..
4	1	11	111	..
5…n	5	52	521	..

Patch ID	$T_{present}$	T_{past1}	T_{past2}	T_{past3}
1	5	5	2	1
2	3	3	3	3
3	4	2	2	2
4	1	2	1	1
5…n				

Fig. 3. A schematic illustration of the hierarchical landscape information, which was stored as digital vector data in a GIS using layer-based model (A). For landscape change trajectory analyses, the separate sequential time layers were converted into a joined database at a desired spatial scale (B). In the case of grasslands (B1), the joined spatial database was a compilation of all polygons from each time step. For oak woodlands (B2), a point-lattice grid with 10 m spacing was used to pick the equivalent land cover/land use values from the same locations on all the time steps. The joined database included patch/point specific land cover/land use histories (C).

tographs scanned into digital images. This requires adjusting of image resolution and contrast. The images were imported into digital image processing software for geometric correction and resampling into equivalent coordinate system. This includes testing the most appropriate methods (e.g. higher-order polynomial or triangulation techniques) as well as estimating operational errors in the process before and after the resampling procedures (see details in Vuorela et al., 2002).

Landscape information was digitised into vector polygons straight from the digital raster image. This is based on the manual interpretation of maps together with supportive literature and implemented according to the hierarchical classification scheme. The digitised classes were spatially adjusted to remove possible digitising errors as well as interpretation inconsistencies. In many cases, the final class adjustment is done after all sequential layers have been digitised since some inconsistencies can only be revealed in relation to the adjacent time steps. This concerns, for example, mistakes in the original map products, copying effects between adjacent maps or rectification errors. Attribute information was added to each time slice, including manual extraction of additional information from accompanying map documents not present in the actual map.

Different spatial data sets were merged into one sequential database for change trajectory analysis. In the case of a polygon model, this concerns creation of one spatial dataset with intersecting polygons from all time slices. Each polygon possesses its own retrospective history (Fig. 3). In case of a point-lattice model, a point lattice matrix with 10 m spacing was used to pick equivalent attribute information from all time steps into a joined database. The spatio-temporal database allowed trajectory analysis between time steps to be carried out. The prerequisite for such database was, however, a time-consuming design and adjustment of landscape classes for each representative time step (Table 2).

4.5. Step V: Paths of landscape change trajectory analysis

Hierarchical spatio-temporal databases enable different types of change trajectory analysis to be carried out. In the following sections we present examples of different techniques that have been used in these two case studies. The continuity and directions of change are two important factors that influence ecological qualities of a land cover. Hence, the investigation of direction of change demands a qualitative dimension to land cover types. Assuming that former land use has a decisive influence on the present-day plant composition, this retrospective approach provides an important means to describe and evaluate potential biodiversity in the present-day landscape.

We have categorised trajectory types and direction of ongoing and future successions according to their major contributions for landscape sustainability assessment into: landscape stability and continuity; landscape dynamics and directions of change; and key biotope boundary dynamics. For further details, we refer to the original publications of Skånes (1996c, 1997), Vuorela (2001), Vuorela et al. (2002), and Vuorela and Toivonen (2003).

4.5.1. Landscape stability and continuity

In the case studies, continuity was investigated under the main assumption that grassland/oak woodland habitats, which show spatio-temporal continuity, have a high potential biodiversity. This assumption is dependent on stability of critical habitat characteristics in situ and continuity as to vegetation composition and regeneration over time. Continuity can be considered a measure of landscape class/patch stability in space and time. In retrospective change analysis, continuity is measured backwards in time and it can be determined within different time frames. Since the applied spatio-temporal databases in both case studies concerned time as the framework in which changes in geographic entities were observed, the continuity reflects the temporal sequence of the used time steps. Two different measurement techniques of continuity were applied in the example studies.

Firstly, continuity can be measured as an overall stability between the latest (present-day) and the oldest data records. This technique enables observations of the total variation within all time steps. The visualisation of continuity analysis implemented at the land cover level in Ruissalo Island using a Change Index developed for the purpose is shown in Fig. 4. The Change Index gives zero values for all points in the model when the land cover class has remained the same throughout the time period. By comparing the Change Index values with the current land cover classes, one can determine the degree of continuity for all land cover classes (see details in Vuorela and Toivonen, 2003). Further, by overlaying the Change Index values with the present-day oak woodlands, an indirect estimate of their continuity in time is obtained. This shows, for example, that 60% of the present-day oak woodlands occupy sites with a history as wooded environment, while 40% have different underlying land cover history profiles. These are likely to be secondary oak woodlands that are either successional stages or planted/sowed on formerly cultivated land or grassland (Vuorela, 2001).

Secondly, continuity can also be measured step-by-step between time slices in the database tracing the individual paths of land cover components and their successional stages. This enables determination of the temporal length of continuity and transitional properties (Fig. 5). Basically, continuity exists when the lines in Fig. 5 run horizontally through all time slices. However, it can be argued that continuity is not always an absolutely static condition but does in fact contain dynamic elements within specified frames, depending on what has happened and which consequences are expected. In the grassland case study, this means allowing the same grassland patch to develop tree cover at one point in time that is again removed through intensified land use returning to its open state without considering the continuity broken. Although

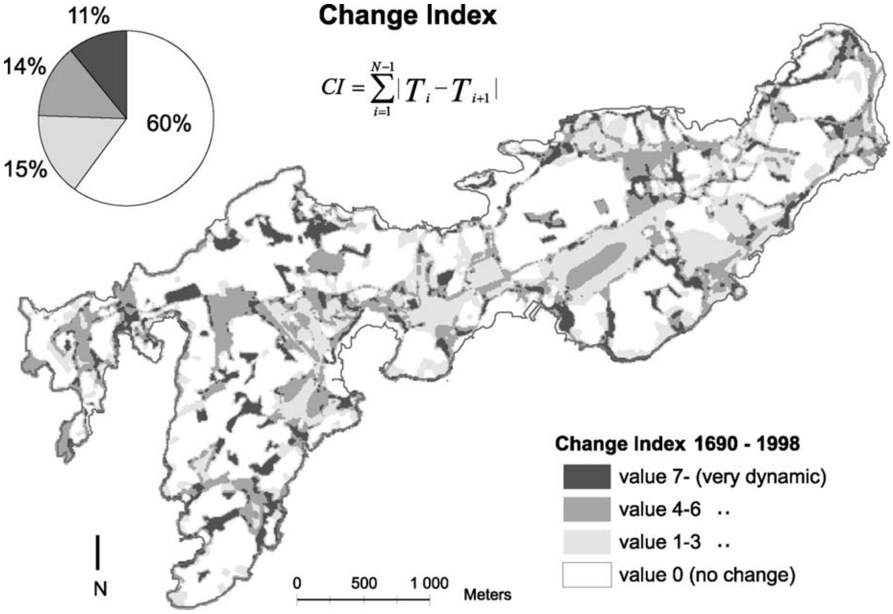


Fig. 4. Change Index is based on the comparison of land cover categories between each adjacent time instants. Land cover classes have been given expert opinion values, which act as weighted values and indicate the degree of human influence in each land cover class. The final index value is a sum of all fluctuations and therefore indicates the degree of land cover change (value > 0) or continuity (value = 0) during the whole time period (1690–1998). See details in Vuorela (2001) and Vuorela and Toivonen (2003). The graph shows the percentage of Change Index values within the present-day oak woodlands.

changes have occurred, they have done so along a spontaneous successional path that should be considered reversible. Given continuous grazing over a long time period, such a patch will have approximately the same ecological conditions and potential biodiversity status as grassland without trees or with a sparse tree cover during the entire investigation period. Although abandonment and spontaneous encroachment causes great pressure on vegetation types that depend on certain types of human activity, still the effects are less drastic for grassland plant species than the impact of continuous grazing combined with fertilisation.

4.5.2. Landscape dynamics and directions of change

In general, determination of landscape dynamics has an inverse relation to the process of determining continuity. The same land cover types in the present-day landscape can have different land use/land cover histories (Fig. 5) and consequently represent varying ecological conditions today. Analysis of change trajectories therefore provides a qualitative aspect on the present-day landscape classes and patches that is useful when assessing qualitative aspects of biodiversity and sustainability issues on a landscape scale.

Change trajectory analysis using GIS enables spatially explicit trajectories. This is an advantage in the sense that the present-day landscape patches are associated with a specific land use/land cover history. On the other hand, these types of analyses generate an overwhelming number of potential trajectories, which might be difficult to interpret. Through the reclassification and aggregation of similar paths, such an approach will allow the comparison between different sources with varying representation of target objects. This makes analysis a combination of automatic GIS detection techniques and interpretation based on expert opinion. The latter is crucial as GIS can generate artificial changes if there are spatial and thematic inconsistencies in the data sets that cannot be understood and treated correctly without the holistic dimension of human expert decisions. Two examples are given on change trajectory analysis in the following.

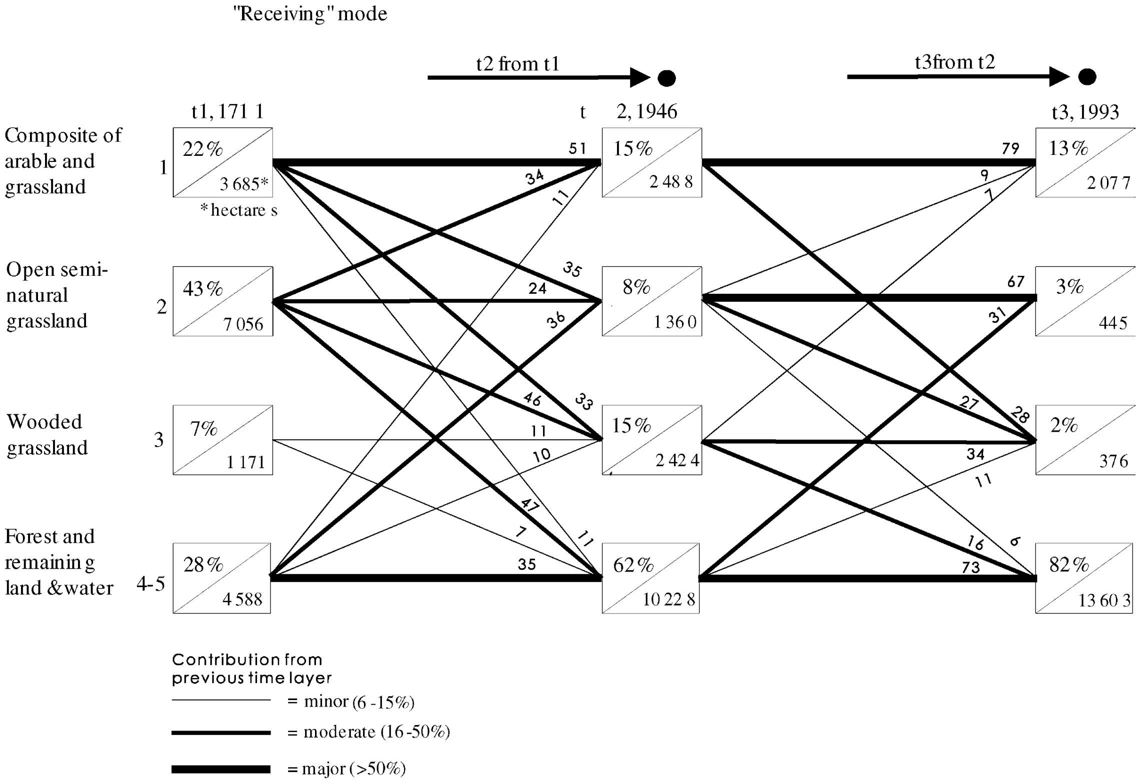


Fig. 5. The total number of possible change paths between every individual time step ($T_1 - T_n$). The receiving mode indicates the retrospective view on changes and stability in land cover. This enables a step-by-step measurement of continuity between time slices in the database. It also forms the basis for tracing the individual paths of land cover components and their successional stages and thereby extracting their individual change trajectory profiles (see Fig. 6.The lines are to be followed from right to left from the receiving time layers T_2 and T_3. The line width accentuates the major trends within the grassland case study with increasing width from minor and moderate to major change (from Skånes, 1996a).

The first example is taken from the grassland case study where the actual and plausible change trajectories for four major groups (agricultural, open semi-natural grassland, wooded grassland, and remaining land and water) were aggregated. Although there are theoretically additional possible combinations than used in the present example, only those which were: ecologically plausible; and fairly common (contributions below 5% were excluded) in Virestad, were extracted (Fig. 6A). Here, ecologically plausible means that the development is likely to occur within the frames of temporal scale and local ecological prerequisites, such as land use impact and paths of natural succession on the acid soils of Virestad. As described above, continuity may include aspects of dynamics. However, some dynamics and successional paths are not acceptable and will render the patch a different land cover history that is not to be considered as stable or continuous. An example of this would be a grassland patch that is tilled for agricultural production and after some time used as grassland again. The effects of such trajectories might be irreversible in some regions with poor soils in the hemiboreal area. This discussion highlights the usefulness of change trajectories, not only to monitor changes, but also to define and understand the complexity of continuity.

The aim of the aggregation of individual change trajectories into groups was to enable an evaluation of

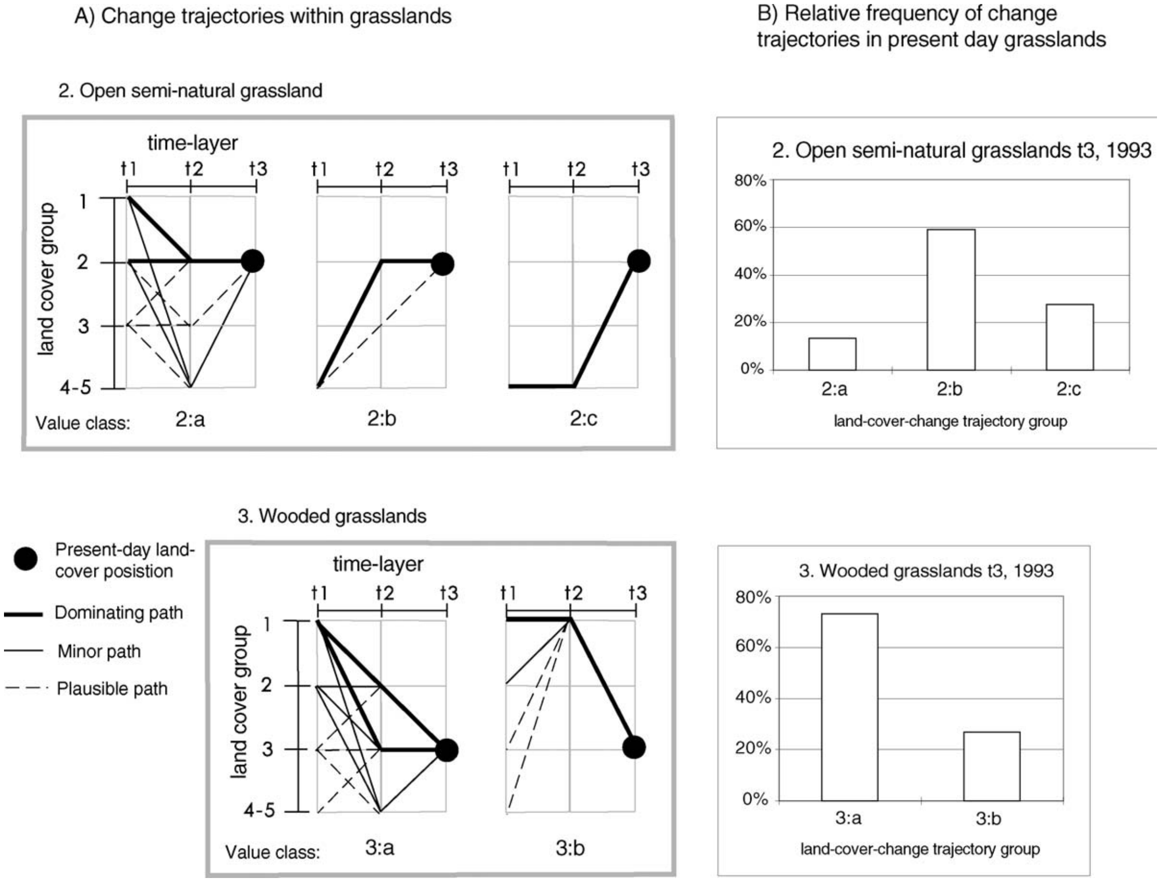


Fig. 6. (A) Individual land-use-history profiles over time $T_1 - T_3$ regarding open semi-natural grasslands and wooded grasslands extracted from Fig. 5.The individual land-use-history profiles within each of the present-day land cover classes; 1–4/5 illustrate major differences in land use history in patches that have the same land cover today, indicating different properties such as potential biodiversity due to different land use and land cover history. (B) Illustrates the heterogeneity in land cover history in each land cover group today, indicating qualitative variation and potential biodiversity (modified after Skånes, 1996a).

land-cover history and the expected potential biodiversity status in individual grassland patches. Groups 2a and 3a have the highest expected biodiversity status due to their high degree of continuity. These are all old grasslands that have been present during the whole period of investigation (1711–1993). Grasslands in group 2b have a continuity of less than 180, years but more than 50 years, while those in group 2c originate in the class of remaining land and water in the last 50-year period (Fig. 6A). Accordingly, wooded grasslands have two major paths. Path 3b has considerably lower potential biodiversity status than 3a since these grassland patches have all been cultivated in 1946 and since then turned into wooded grasslands. Open semi-natural grasslands occupied only 3% of the total Virestad area in 1993 (Fig. 5). Out of these, less than 20% are continuous for the whole investigation period (Fig. 6B). When considering the documented loss of >90 of all semi-natural grasslands in Virestad over the investigated period, this is an alarming situation for the expected biodiversity status of the area. Fortunately, patches derived from formerly open semi-natural grasslands dominate the present-day wooded grasslands.

In the second example, derived from the oak woodland case study, land use change trajectories were determined within the spatial extents of the present-day oak woodlands (using only the those oak woodlands, which showed Change Index 0 in the land cover continuity analysis). The number of each possible land use combinations was calculated and the most common and representative types were identified. To pick up the essential changes over the study period 1690–1998, the classification task was trisected and points were grouped first within the time periods '1690–1846', '1850–1895' and '1945–1973–1998'. These time frames represent three distinctive land use periods (Vuorela, 2000). A total of six different land use trajectory types/groups between 1690 and 1998 were identified and used to reclassify the present-day oak woodlands (Vuorela, 2001; Vuorela and Toivonen, 2003).

The land use change trajectories identified within oak woodlands seem to reflect both large shifts in land use traditions during the study period but also local differences in land use activities in the woodlands. These suggest the following links to the present-day features of the oak woodlands: multiple woodland texture classes suggesting suppressed management and adaptation to physical sites conditions after intensive land uses; large and diverse oak canopies and fragmented distribution of the oak dominant woodlands indicating locally variable land use transitions; and presence of specific plant and animal species indicating specific land use activities in the past (e.g. grazing, parks).

As understood from the discussion above, in some studies, such as the grassland case, the border between landscape stability on the one hand, and dynamics and directions of change on the other hand is not crisp. This implies that the two paths A and B (Fig. 6) may be jointly used in some studies to optimise landscape change trajectory analyses.

4.5.3. Key biotope boundary dynamics

The third example of change trajectory analyses is not focused on change dynamics per se, but rather on changes that have taken place in the surroundings of the key biotopes. Oak woodlands and grasslands constitute an important transition zone between the agricultural landscape and the forest landscape in the hemiboreal vegetation zone. This transition zone can be treated as a dynamic boundary between two biotopes. Boundary dynamics are considered as an important functional characteristic of landscape patches influencing species movement, persistence and colonisation (Forman and Moore, 1992; Kent et al., 1997).

Land cover and land use changes were analysed around the present-day oak woodlands with the main aim of illustrating changes occurring at the edge of the old oak woodlands. The transitional zone was defined as a 50 m buffer zone around old oak woodlands. This buffer analysis was restricted to oak texture classes, which indicated mature woodlands (Vuorela and Toivonen, 2003). Results from the buffer zone analyses were quantified as a percentage of different land cover and land use classes at each time step (Fig. 7A).

The findings in the oak woodland case study suggest that the edge dynamics in the oak woodlands during the past centuries have been significant. These results support the transition model of the grasslands as presented in Fig. 7B. Until the 1850s, the woodlands and meadows, the two prevailing land cover types in Ruissalo, coexisted in gradual transition zones (Diekmann, 1994). These transition zones were usually characterised by wooded meadows, which were mowed and grazed (Nilsson, 1997; Slotte, 2002). As cultivated fields replaced most of the open meadows at the end of the 19th century, an abrupt transition boundary was formed between the woodland areas and arable land. Similarly, some of the oak trees along the gradual transition zone were felled. Cultivated fields surrounded oak woodlands for about a century (1850s–1960s). During the last 30–40 years, the abandonment of arable land has allowed regeneration of woodlands at open sites, but these secondary woodlands are composed of spruce, birch (*Betula pendula*), aspen (*Populus tremula*) and goat willow (*Salix caprea*) rather than broad-leaved trees. Boundary dynamics have caused distinctive deformation in the shapes of the present-day oak trees. The individuals that used to grow at woodland margins can be identified based on the elongated, asymmetrical shape of their crowns. Many of the once distinctively visible oak woodland patches are shaded now by stands of secondary woodlands (Vuorela, 2001).

5. How can change trajectory analyses facilitate assessment of potential biodiversity and sustainable management of key biotopes?

Landscape analysis focusing on the idea that landscapes are continuously changing and dynamic systems causes reconsideration of the philosophy of how to preserve and manage key species and biotopes in semi-natural grasslands and woodland environments (Noss, 1990; Kupfer, 1995). Traditionally, the identifi-

(A)

	Different buffer classes for mature oak woodlands	1690 (%)	1846 (%)	1895 (%)	1945 (%)	1973 (%)	1998 (%)
Land cover	Cultivated arable land	2	11	27	26	16	8
	Grazed meadows	11	14	3	4	1	0
	Other meadows	1	3	3	1	7	7
	Other grasslands	0	0	0	1	4	10
	Built environment	0	0	6	9	11	9
Woodland land use	**Conservation**	0	0	0	2	2	26
	Light management	1	2	19	48	51	32
	Parkland	0	0	5	5	2	2
	Wooded pasture	52	54	27	0	0	0
	Wooded pasture/meadow	19	7	3	0	0	0
	No data	15	9	6	6	6	6

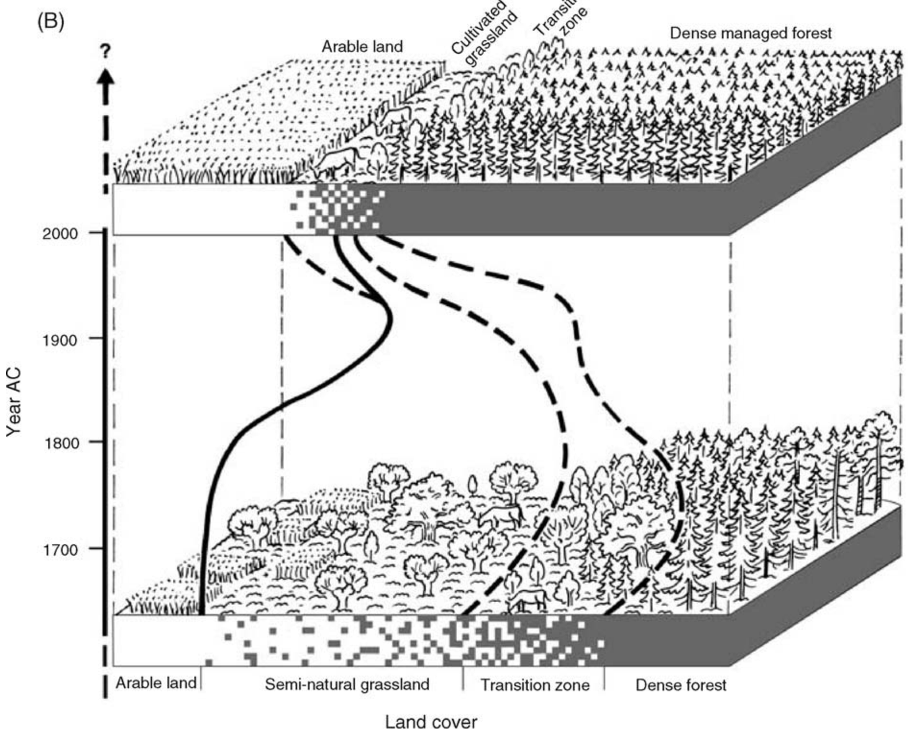


Fig. 7. Oak woodland-grassland transition zone has changed dramatically during the past 300–400 years mainly due to land use and consequently land cover changes (A and B). While majority of the boundaries of oak woodlands were wooded pastures and meadows from the 17th to late 19th century, arable land, built environment and secondary woodlands are surrounding these oak stands today (A). Grey boxes illustrate buffer coverage over 10% (compiled after Skånes, 1996a; Vuorela, 2001).

cation and delineation of these sites has been based on the measurements of in situ habitat characteristics and qualities, such as biodiversity or scenic value (Selman, 2000). Since there is evidence that key biotopes can support a high number of threatened species, or act as major pathways for species migration across the landscape (Fritz and Merriam, 1993; Bennett, 1999), it has been strongly suggested that any analysis of potential key biotopes and their management and protection needs should include assessment of the effects of underlying landscape dynamics (Forman and Collinge, 1997). It is vital to understand the factors that either maintain or change the sites, and the relationships between the sites and the surrounding landscape. The past can reveal alternative possibilities, options and suggestions for the management of key biotopes (Emanuelsson and Bergendorff, 1986; Marcucci, 2000).

The implemented change trajectory analyses in this study were aimed at measuring spatial and temporal dynamics of key biotopes. The methods applied illustrate the diversity of ways to analyse landscape changes. How can this knowledge be used further in assessing the sustainability of key biotopes and associated biodiversity values? Our focus was on three important habitat characteristics: stability and continuity; dynamics and directions of change; and key biotope boundary dynamics. The results show that implemented change analysis techniques provide information about these qualities of the chosen key habitats. The major contributions for key biotope sustainability assessment are summarised below.

Firstly, a significant number of the key biotopes show habitat continuity, including minor changes within the range of continuity, throughout the study period. This was the case both in the direct and indirect analysis of landscape continuity. Applied GIS techniques enable these findings to be linked explicitly in the present-day landscape as the key biotope patches gain an additional quality character from their past dynamics. As an assessment tool this is valuable since conservation and management actions can be spatially targeted in the landscape.

Secondly, analysis of landscape dynamics and directions of change both within and around the key biotopes offer valuable tools for distinguishing different development histories and change processes for key biotope patches. It is important to realise that the changes within vegetation quality are often greater than changes in the extents of the habitats (Bunce et al., 1999; Haines-Young et al., 2003). This perception could well be an artefact originating from not acknowledging land cover history and the need to use well designed classification systems, and can be assessed through the use of change trajectory analysis, which not only considers the present-day distribution and configuration of habitats, but also paths of land cover transitions that will indicate qualitative changes and properties within the habitats. Furthermore, it would also be valuable to appreciate the fact that landscape dynamics are scale-dependent as was shown in the example cases. For example, the Change Index indicated oak woodland continuity but land use change trajectory analysis within oak woodlands showed variable land use change trajectories for different woodland patches. Therefore, prior to implementation of any management or conservation plans, landscape processes should be understood at multiple scales (Noss, 1990; Herrmann and Osinski, 1999; Boothby, 2000; Gulinck et al., 2001). This challenges evaluation of landscape functions and highlights the importance of overall change processes at multiple scales to those of single time and scale spatial patterns of the landscape.

Landscape conservation and management decisions are made within the current political and social context. For the future management of multi-valued landscapes, it is essential to consider both ecological and cultural values. Although our focus is mainly on biodiversity implications of landscape change trajectory analysis, the method is valid also in a wider perspective. The trajectories are derived from land use history information, acknowledging the importance of nature-society interactions in landscape ecology, as pointed out by Potschin and Haines-Young (2006). From an ecological point of view, a decision to manage the landscape in favour of a particular species or biotope can have the opposite influence on the success of other species. Similarly, if the opinion of a particular stakeholder group is allowed to dominate, we are likely to disappoint another group (Jones, 1993; Haines-Young, 2000). Knowledge of landscape change trajectories creates a tool which can be used to communicate the dynamic nature of landscapes to different stakeholder groups. One suitable technique is image manipulation, which provides a visual means to represent how landscapes would look like under different management regimes (e.g. Jones and Emmelin, 1995; Silvennoinen et al., 2001; Tahvanainen et al., 2001). Human opinions, perceptions and preferences for a particular landscape feature vary considerably, and often according to what the landscapes are used for, e.g. agricultural production, recreation, scenic beauty, and who evaluates the landscape (Meinig, 1979; Haines-Young, 2000; Silvennoinen et al., 2001; Tahvanainen et al., 2001). Humans do not behave in a consistent manner in their evaluation, but rather reflect the surrounding atmosphere and attitudes, which are likely to change through time (Nassauer, 1995; Palmer, 2001).

6. Concluding remarks

The usefulness of landscape change trajectory analysis for the assessment of potential biodiversity is evident since it provides knowledge of the functional properties of the landscape, key biotopes and associated species. We think these techniques can contribute to the assessment of biodiversity maintenance, which has been recognised as one of the habitat functions of natural capital of landscapes. It shifts the focus from in situ species composition to functional space-time properties of habitats and therefore acts as an indirect, qualitative means of biodiversity assessment including the cultural dimensions of diversity. The qualities of landscape change trajectory analysis are highly dependent on the success of data transformation and merging into GIS, which requires data-specific and context sensitive solutions. This is especially true when data sets extend over long time periods and are heterogeneous, such as maps, remotely sensed data and field investigations. It is of primary importance that spatio-temporal databases are spatially and thematically adjusted and co-registered after digital transformation. This requires the user to modify the data sets carefully into compatible formats, considering both inherent and operational data errors and the spatial, temporal and thematic scales used in the analysis. Supplementary data sources are vital in adjusting and optimising the information on landscapes and in evaluating the results from the change trajectory analyses.

Thus, it is worthwhile emphasising that the results from landscape change trajectory analysis are approximations and generalisation of a complex reality. While GIS provides a relatively efficient tool for change analysis, the challenge lies in detecting the character (e.g. linear, stepwise, gradual, abrupt) of changes between the snapshots and determining whether the differences were indeed changes, or errors originating in the interpretation and processing of the data. Since gaps in landscape change trajectory analysis are likely to remain due to lack of continuous information of landscape dynamics, assessment of habitat functions should be based on the use of several, parallel techniques.

We feel there remains major research to be done in the field of sustainability assessment of habitat function and we anticipate new findings through joint ventures also in the future.

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