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Retrospective land cover/land use change trajectories as drivers behind the local distribution and abundance patterns of oaks in south-western Finland

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ABSTRACT

Valuable cultural landscapes are challenging to sustain. They are usually rare and reflect unique histories of nature–human interactions. We have studied the influence of environmental factors on the present distribution, age and abundance of oaks in a unique forest site in south-western Finland. The Landscape Change Trajectory Analysis (LCTA) approach was tested to improve management strategies at a local level. We used geospatial analysis in GIS on existing data from a recent forest inventory, a multi-temporal land cover/land use analysis, and a digital elevation model. The results show that mature Penduncalate oaks (*Quercus robur*) are restricted to the eastern parts of Ruissalo island and their present abundance patterns can be linked with change trajectories as opposed to physical conditions. While the prevailing strategy of strict protection seems to lead to an increasing amount of dead wood, the lack of management hampers the regeneration of oaks. We suggest four principles for future management of these sites that could be applied throughout the hemiboreal region of Europe with similar historical development: (1) management regimes should be spatially explicit in terms of land cover history instead of treating valuable oak biotopes as one homogenous unit; (2) management units should be determined by biotope dynamics and development rather than present status and distribution; (3) management should allow strict protection of sites with long duration of protection and high abundance of decaying oak wood to support biodiversity; (4) alternative management regimes should be introduced in sites with high potential for re-establishment of light-abundant favourable conditions.

1. Introduction

1.1. Introduction to Landscape Change Trajectory Analysis (LCTA)

The establishment and maintenance of conservation areas and protected sites form an important mechanism in sustaining ecologically valuable biotopes and landscapes. Increasingly, such sites possess values simultaneously related to nature, ecology and cultural heritage, all promoted by present societies. By identifying rare habitats, endangered species, fragmented biotopes and diverse cultural landscapes, an important linkage may be established between existing features in the landscape today and the processes enabling such qualities to be originally formed (Skånes, 1997; Haines-Young et al., 2003).

Landscapes, seen as ecological systems, are challenging targets to manage and sustain due to their constant dynamics and evolution. This inevitably draws attention to the factors driving and directing changes in the landscape. Landscape configurations and patterns change with more or less intentional land use planning processes and the actions involved (Antrop, 1998; Boothby, 2000; Marcucci, 2000). Changes, largely related to the complex interactions of abiotic and biotic factors including humans, transform landscape patterns through time. In research, it is widely acknowledged that linking these underlying and present functional and spatial properties is of primary importance when dealing with the status, resilience and dynamics of present ecosystems and associated species (Bengtsson et al., 2003; Löfvenhaft et al., 2004; Haines-Young, 2005). There is also a great need to implement this knowledge in practical management of dynamic and multifunctional landscapes.

Landscape change detection is an important and popular field of research due to increasing environmental concern. This field is also promoted by the wide availability and potential of techniques for remote sensing and corresponding imagery across multiple scales in time and space. Techniques of image processing and geographical analysis enable effective detection of landscape changes and support the designing of, for example, monitoring systems or landscape

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characterizations based on the use of sequential spatial data sets (Brandt et al., 2002; Haines-Young et al., 2003; Clark et al., 2004). There are numerous papers dealing with land cover and land use change detection based on satellite imagery (e.g. Nagendra et al., 2004) and aerial photographs along with historical sources, such as old aerial photographs, maps and cadastral records (Kienast, 1993; Skånes, 1997; Cousins, 2001; Mendoza and Etter, 2002; Vuorela et al., 2002; Käyhkö and Skånes, 2006). Several methods are available for geographical analysis of landscape data, many based on combinations of cartographic and statistical techniques within the spatio-temporal framework of Geographical Information Systems, GIS (Skånes and Bunce, 1997; Marceau et al., 2001; Bender et al., 2005; Reger et al., 2007).

Landscape changes are problematic to present and evaluate ecologically since the impression of change is only arbitrary, reflecting the available and utilised spatial data sources and methods. Furthermore, detected changes are reflections of the choice of spatial and temporal scales of the data and analysis (Antrop, 1998; Bürgi et al., 2004; Ernoult et al., 2006; Käyhkö and Skånes, 2006). Any serious discussion on the driving forces or underlying factors of landscape change should thus relate to these issues. Additionally, one landscape configuration is not inevitably better than another, since it depends for whom and in what context we are evaluating the patterns (Potschin and Haines-Young, 2006). Despite the challenging nature of landscape patterns and change detection studies, spatio-temporal analyses extending over decades, even across centuries can be a highly rewarding means of evaluating landscape systems, their present status and potential development.

Landscape Change Trajectory Analysis (LCTA) is one approach for seeking relationships between the present-day landscape patterns, their attached values and the past; with underlying governing dynamics with particular research questions (Käyhkö and Skånes, 2006). Change detection is based on the combined use of spatial data sets forming a space–time sequence for analyses in GIS. The methodological challenges of LCTA lie in the successful use of the various data sets in combination. As the approach is primarily retrospective, the focus is on the present-day landscape and related values. This sets high demands on the quality and interpretation of the utilised landscape data.

In this study, LCTA approach is applied in the assessment of the status and development of a key biotope, an oak forest, to meet the demands of linking scientific knowledge with practical management needs. The study period covers ca. 300 yrs and is based on the combined use of geographical information originating from a recent forest inventory, historical and thematic maps, aerial photographs, archive material and field work. The following main research questions were set:

- What is the spatial relationship between the present structural, topographical and land cover/land use change patterns of oak forests?
- What do these relationships and evidence together suggest about the present patterns, development and potential management of oak biotopes in the study site?
- What are the advantages and methodological challenges of the LCTA approach in the assessment of key biotopes?

1.2. *Study site Ruissalo Island in SW Finland*

South-western Finland represents climatically the most favourable region in Finland, phytogeographically known as the boreonemoral or hemiboreal (Sjörs, 1963; Ahti et al., 1968). Its northern limit in Finland is indicated by the distribution of Pendunculate oak (*Quercus robur* L.) below referred to as oak, which is why the coastal areas of SW and S Finland are also known as 'the oak zone'. Oak represents a thermophilic element in the distribution of vascular plants of Northern Europe, being primarily limited by the amount and extent of summer heat (Dahl, 1998). Although the region is within the oak zone, only one percent of forests are today dominated by broad-leaved deciduous trees, such as oak (Hämet-Ahti, 1988; Alanen et al., 1995). Deciduous grove forests are biologically the richest and the most varied forest habitats in Finland. Many associated plant and animal species are rare and specialised, which is why these forests have been highly acknowledged in the national and European biodiversity protection programmes and networks (Ympäristöministeriö, 1988; European Commission, 2003).

The island of Ruissalo, immediately off the coast of Turku, is a typical as well as an exceptional oak forest site in the region (Fig. 1). The overall appearance of the landforms is typical, including geological shear zones and glacial erosion. The region was exposed to isostatic land uplift and subsequent wind and wave erosion after the last deglaciation (Fogelberg, 1986). Rugged hills are dominated by Scots pine (*Pinus sylvestris* L.) and flat, low-lying sites with thick

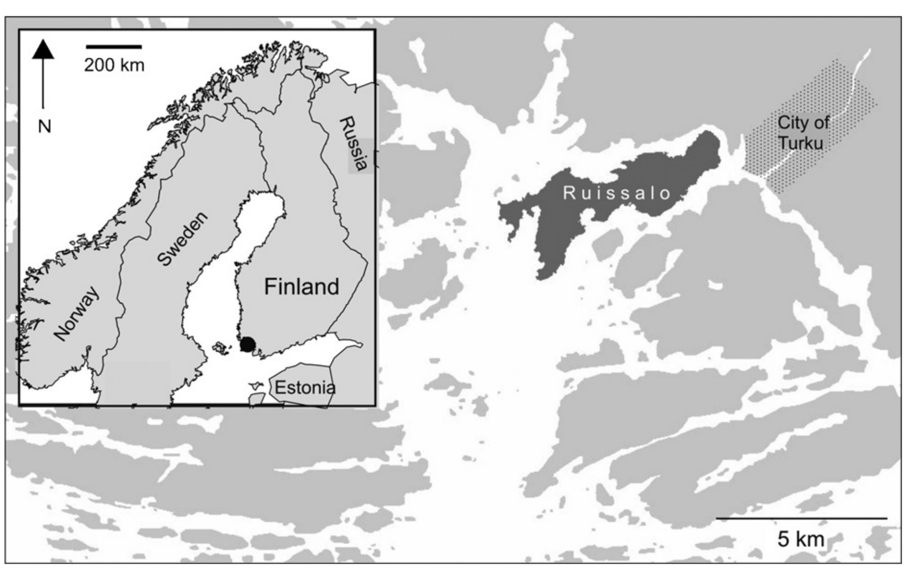

Fig. 1. Ruissalo Island (ca. 900 ha) near Turku, south-western Finland.

clay deposits are occupied with cultivation, meadows, parks and related land use activities. Approximately one third of the forests are dominated by oak and other broad-leaved deciduous trees. The cultural landscape reflects unique land ownership and land use history, such as a royal hunting park in the 16th century, a wage-farm of the regional governors until the 19th century, and a summer housing area of the merchants of Turku until the early 20th century (Vuorela, 2000, 2001).

The majority of the Ruissalo oak forests are protected due to their significant ecological value related to the broad-leaved deciduous trees and associated fauna and macro fungi (Lounais-Suomen ympäristökeskus, 2007). Ruissalo hosts rare species, such as the hermit beetle (*Osmoderma eremita*) and several other red listed species of high protection value. The core areas of the broad-leaved deciduous forests are protected with overlapping conservation and protection programmes, such as Strict Nature Reserves (since 1983, 85 ha), Herb-rich Woodland Protection Programme in Finland (since 1989, 151 ha) Natura 2000 (site code FI0200057, 852 ha) and most recently with the expansion of the Strict Nature Reserves (2007, 248 ha). Some oak forest areas were set aside for protection already in the 1930s (Vuorela, 2000). Ruissalo is also the region's most important recreational area and protected site due to its cultural environment. Ruissalo was assigned as a nationally valuable landscape by the Finnish Government in 1995. The overall management of Ruissalo forests and landscape is a challenging effort due to these multiple values.

2. Materials and methods

2.1. Spatio-temporal data sets, variables and the created database

The analyses were based on the combined use of existing spatio-temporal data, derived from four main sources (Fig. 2). Forest stand data were extracted from the Forest Inventory Database of the Real Estate Department of the City of Turku created in 2002–2004. The original delineation of the forest patches in the inventory was

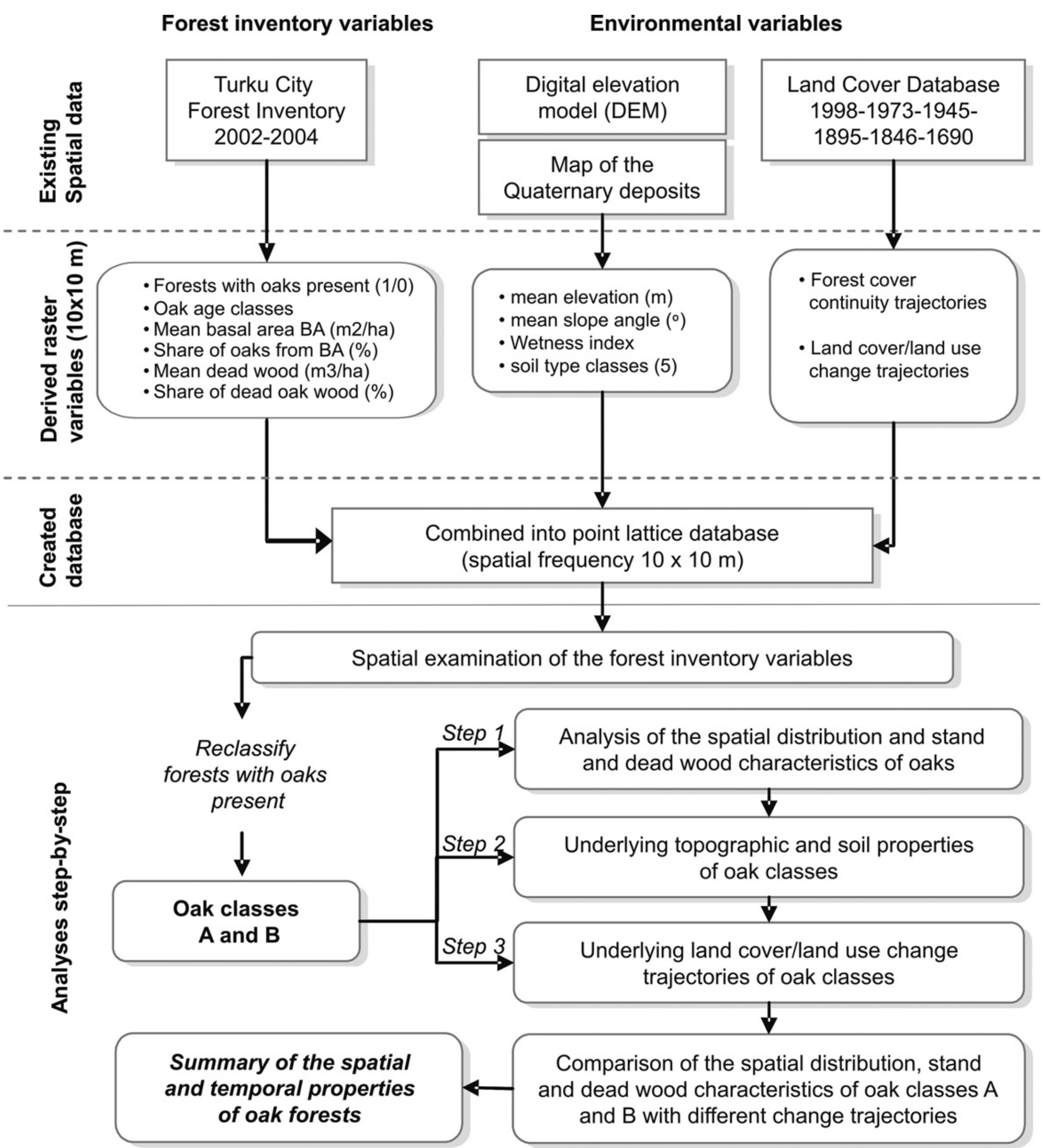

Fig. 2. Flow diagram of data sources, derived raster variables, database creation and analyses steps used in the case study.

based on the use of orthogonally rectified CIR aerial middle-scale (1:15 000–1:25 000) photographs from July 2002 and stand information, such as species composition, age distribution, and dead wood, which was collected in the field for the individual forest patches (Mäkitalo, 2006). These field measurements correspond to the mean of 4–8 relascope measurements per forest patch. This design restrains use of statistical analyses, which address within-patch variation of the variables. Patch data were converted from MapInfo (.tab) files to ArcGIS 9.1 (.shp) and the stand information was extracted as a text file from the original X-City database, and restructured in MS Excel. Once the linkage between patches and related stand and dead wood attributes were established in ArcGIS, the patches now contained ecologically relevant information about the presence, dominance, age structure and dead wood characteristics of oaks (Table 1).

Data on the environmental variables were compiled from a digital elevation model, DEM (Oksanen and Sarjakoski, 2005), map of the Quaternary deposits (1:20 000 produced by the Geological Survey of Finland), and the land cover/land use database of Ruissalo (Vuorela, 2001). A selection of DEM variables was used in this study, namely mean elevation (m), mean slope angle (°) and mean wetness index (Moore et al., 1991; Ostendorf and Reynolds, 1993). Quaternary deposit classes, referred to below as 'soil type', used in the analysis were clay, gyttja clay, till, bedrock and other deposits (sand, silt, and gravel). The classification depth was 1 m so 'bedrock' is largely characterised by a thin layer of till. Land cover variables were derived from the Ruissalo land cover change database, which was originally hierarchically classified and stored in vector (.shp) format as separate time slices (1998, 1973, 1945, 1895, 1846 and 1690). These data were derived from visual interpretations of aerial photographs and historical land use maps (Vuorela, 2001; Vuorela et al., 2002; Vuorela and Toivonen, 2003). For this case study, both land cover and forest land use information were used to reconstruct retrospective forest cover continuity and forest land use/land cover change trajectories to be compared with the present forest inventory variables.

Forest inventory and environmental variables were converted and resampled into 10 m × 10 m raster data sets with an identical spatial extent. The cell size was chosen to match the resolution and detail of the used data sets, especially the land cover data, which is able to show the elongated and narrow patterns of the forest–meadow transitions zones without creating an undesirably large data set. These edge areas of the forests are important for the landscape management. All variables were then combined as attributes into a point lattice file matching the centre points of the raster cells. The database consisted altogether of approximately 90,000 points, of which circa 27,000 (30%) represented the coverage of the forest with oaks present (Fig. 2).

Table 1
Forest inventory variables used in the analysis

Variables derived from the inventory	Specification
Forests with oaks present (1/0)	Forest containing oaks according to the inventory
Young aged oaks	Oaks <50 yrs (age estimate)
Intermediate aged oaks	Oaks 50–150 yrs (age estimate)
Mature aged oaks	Oaks >150 yrs (age estimate)
Mean basal area BA (m^2/ha)	Mean value for the entire patch
Share of oaks from BA	Oak share of total species in the patch
Oak-dominant forest	Oak BA > 50%
Non oak-dominant forest	Oak BA < 50%
Oak share not recorded	Oak BA not measured since trees have been too small in diameter
Mean dead wood (m^3/ha)	Mean value for the entire patch
Share of dead oak wood (%)	Mean value for the entire patch
Oak class A*	Oaks >150 yrs present, can also include younger oaks
Oak class B*	All oaks are <150 yrs

* Reclassified variables used in the analysis after detailed examination of the forest variables.

2.2. Analysis steps

Prior to the actual analyses, the forest inventory data were examined spatially using information of age and dominance of oaks in the forests. On the basis of the preliminary examination, forest patches were reclassified into oak classes A and B (Table 1). Oak class A was established from patches containing mature oaks (>150 yrs). Oak class B was established from the patches where only younger oaks (<150 yrs) were found. Together, the spatial coverage of classes A and B show the maximum extent of forest patches where oaks are present. With this classification, the spatial patterns and related forest stand and environmental attributes of oaks could be analysed without separating the patches into too detailed and too few patches per class. Then, the three analyses steps were carried out (Fig. 2).

The first step of the actual analysis investigated the spatial distribution, stand properties and dead wood characteristics within classes A and B. Classes A and B were further divided according to oak dominance from basal area measurements.

In the second step, underlying topographic and soil type properties within the selected land and forest patches were studied to examine if these indicate any similarities or differences between non-forest and forested areas in general and between oak classes and oak dominance in particular.

In the third step, underlying land cover and land use change trajectories and forest management regimes were identified based on the overlay analysis of the multiple temporal (T^1–T^n) land cover/land use attributes from the compiled point database. The analysis was targeted spatially for the three forest patch variables: patches with oaks present, oak classes A and B. At first, the dynamics of forest cover, based on the presence/absence of forests retrospectively from 1998 to 1690, were analysed and then compared with the present-day forests containing oaks. This enabled evaluation of the continuity and age of forest cover within the present forest patches with oaks. Then underlying land use/land cover change trajectories from 1690 to 1998 for all forest patches with oaks were established. Trajectories were aggregated on the basis of expert knowledge and the similarity and frequency of trajectories into 5 main and further to 15 detailed land use/land cover trajectory types. The work was done under the assumption that grassland management and related grassland-forest dynamics are the most essential management regimes relating to spatial differences of oak populations. These are mainly grazing and mowing and presence of park management or other open land cover phases, and duration of forest protection (Slotte, 2001; Vuorela, 2001; Eliasson, 2002).

Once the change trajectories were established, forest with oak in general and specifically oak classes A and B with different trajectory types were compared spatially with the inventory variables of oak age, oak dominance and dead wood characteristics (all species vs. oak) to reveal any links between the present forest structures and particular types of underlying human-induced dynamics.

3. Results

3.1. The present distribution and characteristics of the forests with oak

Oak is present in 54% (270 ha) of the inventoried forest area (Table 2). The total number of forest patches with oaks is 284, with patch sizes varying from 0.1 to 10.4 ha (average 1 ha). Oak classes

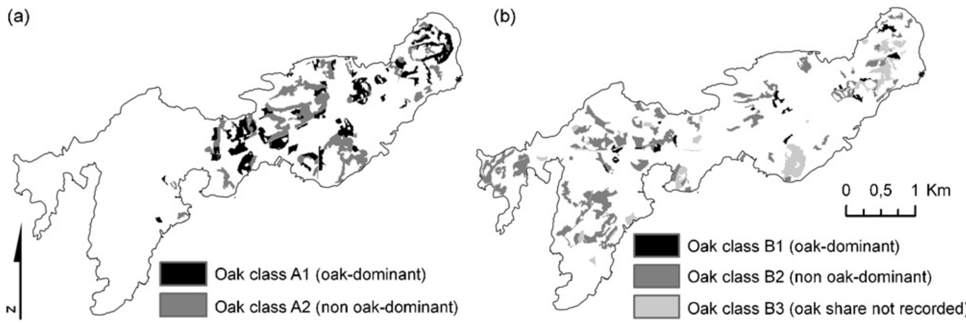

Fig. 3. The distribution patterns of oak classes A and B with subdivisions into oak-dominant (A1 and B1), non oak-dominant (A2 and B2) and oak share not recorded (3B). Basal area was not recorded for individuals due to too small stem dimensions.

A and B each occupy approximately 50% of the forests with oaks present. There are two most common age structures within these classes. Out of class A, 98 patches are a combination of intermediate (50–150 yrs) and mature aged oak stands (>150 yrs) and of oak class B, 116 patches are stands between 50 and 150 yrs. The dominance of oak is typical to oak class A due to mature stands, while only 4% of oak forests are young stands dominated by oaks (B1). The mean basal area (BA) estimates are similar for both classes, but the average volumes of the dead wood are higher for stands with mature oaks. Similarly, the share of dead oak wood is nearly 70% in oak class A, while less than 20% for oak class B.

Forests with mature oaks (oak class A) are distinctively concentrated to the eastern part of the island while oak class B, with only intermediate and/or young aged oak stands, are evenly distributed across the island (Fig. 3). On the basis of the dominance of oak (>50% of BA), patches are spatially fragmented, but most of the oak-dominant patches are found in the east. Altogether, oak class A is rich in both living and dead oaks and concentrated to the east side of the island and oak class B is mainly mixed stands of oak and other tree species with more even spatial distribution across the island (Fig. 3).

3.2. Underlying topographical and soil properties

The prevailing edaphic conditions, indicated by the selected topographic variables, follow the general pattern of the physical conditions created by glacial erosion, isostatic land uplift and consequent wave and wind erosion. The majority of Ruissalo Island is covered with shallow till deposits/bedrock outcrops (52%) and clays (30%). While clays occupy the lowermost parts of the land, tills characterised the slopes and hills of the island.

For the different forest classes studied, mean elevation, mean slope, mean wetness and soil classes show little variation in general (Figs. 4 and 5). However, forest areas do differ from the open land areas. Only within mean elevation could some differences between forest classes be seen (Fig. 4). Throughout the island, oak is topographically concentrated on the low-lying slopes and is missing from the uppermost parts of the slopes. Forest areas grow mainly on the shallow till deposits and bedrock outcrops (70%), while non-forested areas are found equally on many soils types, especially clay (Fig. 5). This is an anticipated result, since all areas favourable to arable cultivation have been utilised and are not forested.

3.3. Forest cover dynamics retrospectively between 1998 and 1690

Ruissalo forest cover has been relatively stable through time. Nearly 70% of the entire island's forest cover is retrospectively continuous from 1998 to 1690. A similar pattern is evident for oak classes A (67.2%) and B (76.3%). The rest of the present forest cover with oaks has emerged gradually during the course of the centuries.

The spatial pattern of forest cover continuity shows the gradual emerging of the forest areas on the edge areas of the present forest patches. This phenomenon is related to the past grassland-forest dynamics, with semi-open grasslands gradually closing into forests on the edge areas. Some recent forest areas have been arable fields and meadows, which have gradually turned into forested land due to ceased management.

3.4. Land use change trajectories from 1690 to 1998

Oak classes A and B can be grouped into five main and 15 detailed trajectory types on the basis of land use/land cover dynamics (Fig. 6). The most common trajectories for the forest patches with oaks are type 1 (33%) and 2 (28%), which relate to the

Table 2
Patch, stand and dead wood characteristics of oaks classes A and B based in the forest inventory data

Inventory variables	Forests with oaks present						
	A	A1	A2	B	B1	B2	B3
No. of patches	133	63	70	151	21	101	29
Minimum patch size (ha)	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Maximum patch size (ha)	5.1	5.1	5.1	10.4	1.4	4.1	10.4
Average patch size (ha)	1.0	1.0	1.0	0.9	0.5	0.9	1.2
Total cover (ha)	132	64	68	141	11	95	36
% Of forests with oaks	48.3	23.2	25.1	51.7	4.0	34.6	13.1
% Of all inventoried forests	26.1	12.5	13.5	27.9	0.0	18.7	7.1
Mean BA (m^2/ha)	18.8	17.9	19.7	18.7	19.7	19.6	16.0
Mean% of oaks	49.0	69.6	30.0	15.8	77.1	14.7	0.0
Mean dead wood (m^3/ha)	9.5	8.7	10.2	3.8	3.8	3.8	3.7
Mean% of dead oak wood	68.8	75.9	62.3	17.4	47.7	19.5	2.6

Subclasses 1 are oak-dominant, 2 are non oak-dominant and 3 refer to patches where oak share has not been recorded in the BA measurements.

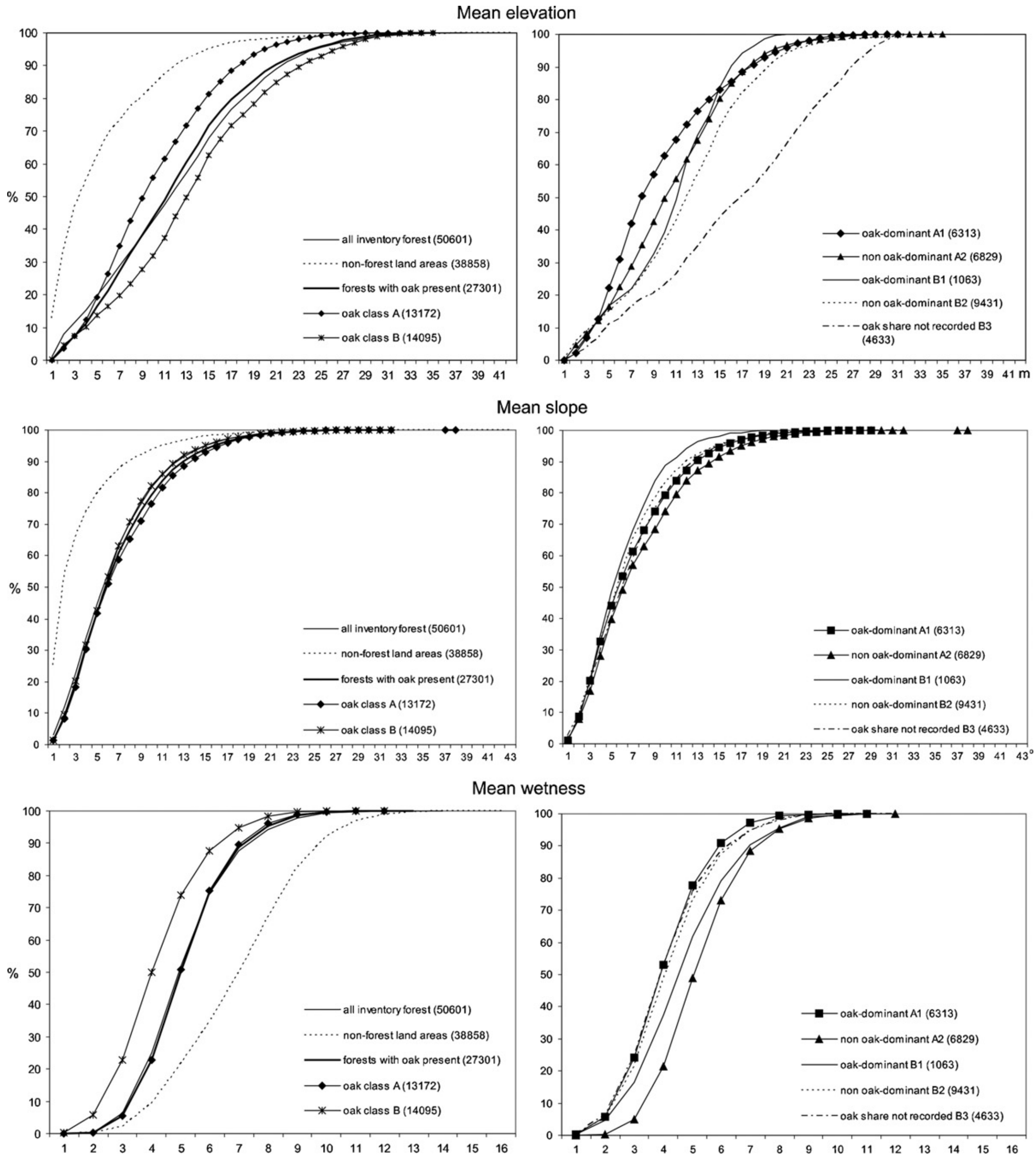

Fig. 4. Cumulative frequency (%) graphs of mean elevation (m), mean slope (°), and mean wetness values (index value) in relation to the selected land and forest variables, including the oak classes in Fig. 3. Number in brackets indicates the number of points for the respective forest/land class. Right hand figures show detailed oak classes.

histories of forest pasture and hay mowing followed by regular forest management and in many cases by forest protection. The rest of the trajectory types (3–5) are less common within the forests with oaks, where type 3 (11%) represents park management phases, type 4 (17%) semi-open grassland phases, and type 5 (12%) represents phases of other open land covers.

A comparison of the average cover percentages of different trajectories for all forest with oaks and oak classes A and B separately reveals that type 2 (39%), 3 (14%) and 4 (20%) are more common for oak class A, while type 1 characterises over 50% of oak class B (Fig. 7A). Further, for oak class A, trajectories 2D (26%) and 4A (16%) stand out as most common ones, while for oak class B, types 1C (24%) and 1B (17%) are most abundant. The highest contrasting trajectory cover percentages for oak classes A and B are types 1B and 2D (Fig. 7A). Altogether, subtypes of 1 are more common for oak class B, while others are more common for oak class A.

The mean basal area estimates vary between 16 and 20 m^2/ha across the five main trajectory types for the major oak forest categories, being lowest for trajectory type 4 (Fig. 7B). Oak classes A and B do not show any significant difference in BA estimates at the general level, but are highest for the trajectory 2E (BA > 22 m^2/ha) and lowest for 4B (mean 13 m^2/ha) throughout. The most divergent BA measurements for the two oak age classes are 2A (Fig. 7B).

The mean share of oaks varies between 21 and 44% for all the forests with oaks (Fig. 7C). Type 3 and 4 have the highest average share of oaks and type 1 the lowest. Throughout, oak class A shows higher oak dominance, the only exception being trajectory 2E. On average, the most oak-rich trajectories are 3B (53%), 4A (45%) and

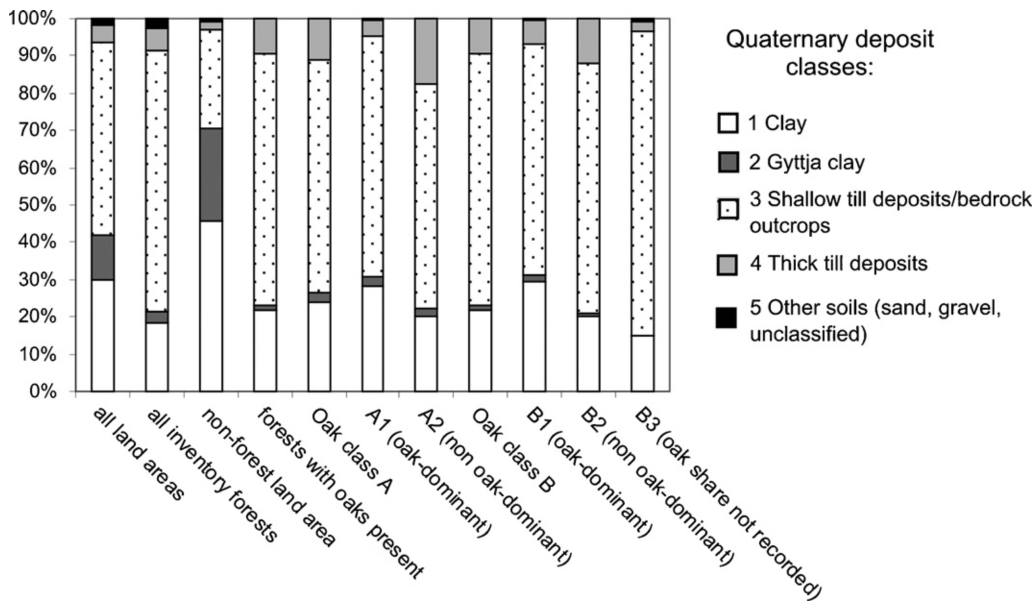

Fig. 5. The share of Quaternary deposit classes within the selected land and forest variables. Variables are the same as in Fig. 4.

2E (41%). For oak class A, types 3B, 2C and 1B all have a nearly 60% average share of oaks, while 2E shows an average oak share of only 36%. The highest deviances from the averages are visible in the trajectories 1B, 1C and 2C.

The highest average dead wood estimates characterise trajectory type 2, and respectively types 2D and 2E, with the lowest for type 3 and 3C (Fig. 7D). Dead wood is more abundant for oak class A than B, reaching 16 m^3/ha (type 2E). In general, the average estimates for both oak classes and their trajectories together vary between 4.2 and 9.6 m^3/ha. The lowest values for the oak class B are found in types 3C (1 m^3/ha) and 4B (2 m^3/ha).

The mean share of dead oak wood is very high in some of the oak class A trajectories, such as types 2 and 4 (>70%) (Fig. 7E). Generally, the share of dead oak wood varies from 20 (type 1) to 60% (type 2). At the detailed level, trajectory types 2E shows overall dead oak wood percentages close to 80%. For oak class A, trajectories 1A, 1B, 2E, 3A and 4A reach as high as 78–89%. For oak class B, only 2E shows high percentages of dead oak wood (82%).

4. Discussion and concluding remarks

4.1. Land cover/land use change trajectories as drivers behind the local distribution and abundance patterns of oaks

The influence of land cover dynamics and different land use regimes over the centuries is clearly reflected in the present distribution and abundance patterns of oaks. The restricting factors of oaks are the site ruggedness (bedrock and thin soils on top of the hills) and cultivation practices over the centuries (low-lying sites). It is, however, important to note that a majority of the fields were cultivated as soon as new land was uplifted from the sea (Vuorela, 2001). Thus, oak forest clearance is not the primary reason for oak missing from the clay-dominant sites.

The analysis of the underlying land use/land cover trajectories suggests that the distinctive eastern emphasis of the mature oaks is rather a result of different ownership patterns with animal husbandry and associated land uses of grazing, mowing, and cultivation over the centuries. This involved direct (i.e. selective cutting) and indirect (e.g. grazing creating light-abundant forest conditions) supporting mechanisms for the broad-leaved deciduous trees, which formed an important component in the semi-open grassland systems (see also Slotte, 2001). There exists no historical evidence which would fully reveal if the western parts of the island have previously been occupied with mature oaks, but this study clearly indicates that the maximum extent of mature oaks matches the wooded pasture and hay meadow influence of Ruissalo Manor at least from the late Middle Ages (16th century) until the 1850s. Thus human impact is most likely a supportive, rather than destructive process from the distribution perspective. This is important to recognise when attempting to manage and sustain oak forest qualities in this kind of landscape.

The animal husbandry of Ruissalo Manor created a dynamic transition zone on the edge areas of the forests and grasslands. These diverse, gradually shifting ecotone conditions supported the growth of large, wide-crowned oak individuals, which were able to enjoy the warm and light-abundant site conditions (see also Vuorela and Toivonen, 2003). Such edge dynamics are missing from the western forest areas, where outland forest pastures were turned into regular forest management areas and suitable sites were converted straight into crop cultivation during the late 19th century (Vuorela, 2000, 2001).

In general, the dominance of oak is more common in the forest patches with large oak individuals present since these greatly influence the basal area estimates. The dominance of younger oak stands is not common and most of these oaks form mixed forests with other tree species. As a result, the oak class B patches are rarely oak forests in terms of dominance. The few oak-dominant patches with younger oaks can be found in the east as a result of selective removal of older oak stands or due to decaying of the mature oaks.

The abundance patterns within oak class A patches reflect primarily the spatio-temporal influences of the past forest management regimes rather than any physical conditions. The most oak abundant patches represent trajectories from wooded meadows and grazing to park or semi-open grassland management and further to protection without management. The latter allowed regeneration of oaks and resulted in the abundant oak forests, which have been protected on the island for the past decades. Therefore, it can be argued that oak abundance is a result of two major consecutive land use activities; namely, the oak-favouring

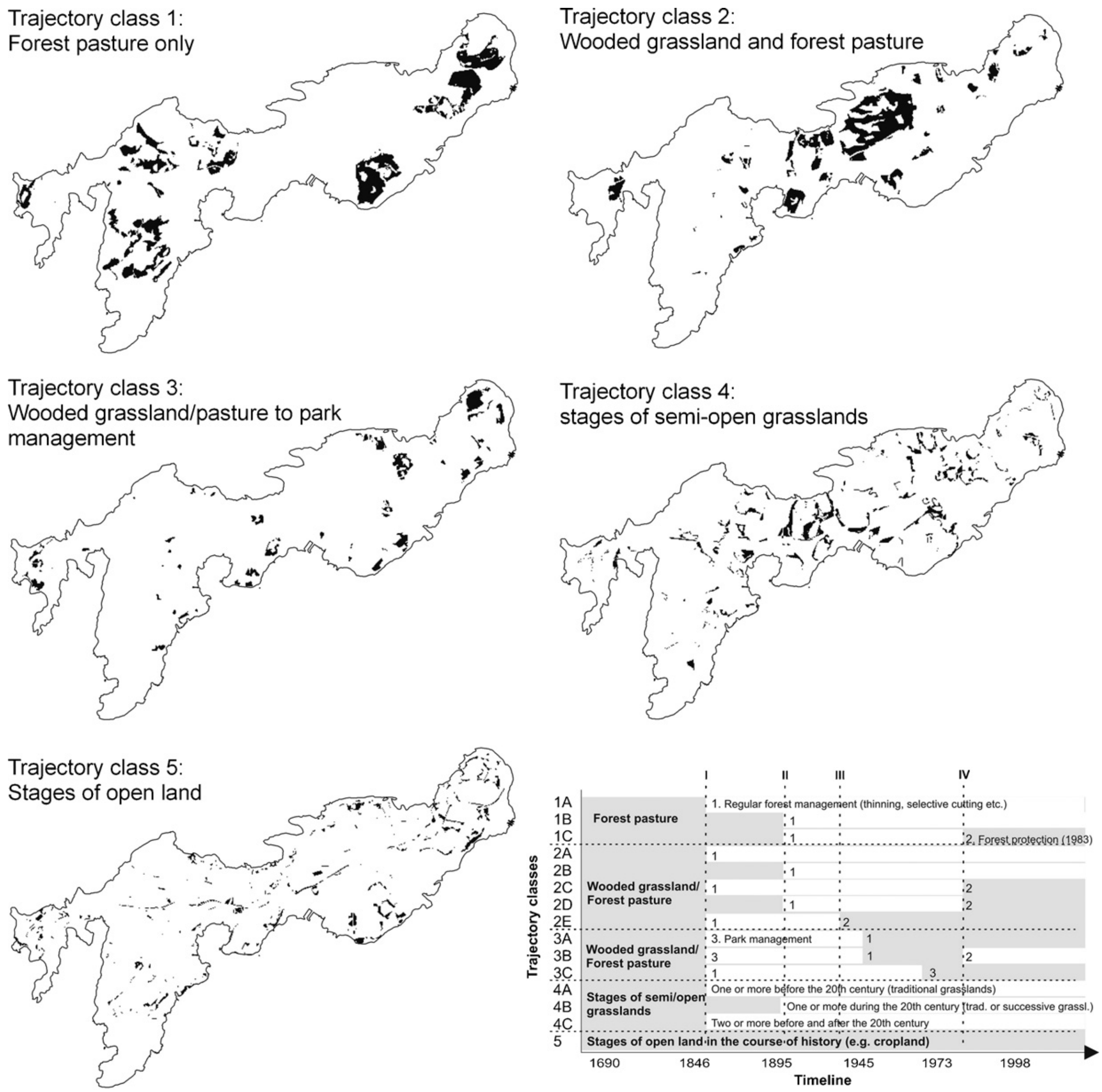

Fig. 6. Maps of the five main land cover/land use change trajectory types within the present forests with oaks. Trajectories are based on the identification of major land cover and land use changes 1690–1998. Roman numerals refer to a selection of events according to: (I) diversification of the land uses due to establishment of the summer residences after the1850s, simultaneous decrease of animal husbandry, (II) end of forest grazing in the 1890s, (III) establishment of the first forest protection areas in the 1930s, and (IV) establishment of Ruissalo Nature reserves in 1983 (see further in Vuorela, 2000, 2001).

management regimes during the past centuries combined with time-lag responses of the forests to ceased management.

4.2. Implications for the management and conservation of valuable oak biotopes

The results indicate that the analysis of the past land cover/land use change trajectories is vital to the sustainable maintenance of oak forest biotopes. Currently, forest patches with the longest duration of strict protection show a lower degree of oak dominance, while patches where at least some selective cutting has occurred during the past decades, are still more oak dominant. The prevailing strategy of strict protection seems to lead to an invasion of other deciduous species, hampering the regeneration of oak seedlings. Today, the highest volumes of dead oak wood can be found within the protected areas set aside from active management already in the early 20th century and the amount of dead oak wood is likely to increase within the mature oak stands as the old trees gradually decay.

The results also suggest the feasibility of challenging existing oak forest protection strategies and seeking alternative ways of managing the cultural environment, in this case with oaks. Therefore, the following four principles for future management of these oak forests are suggested. (1) Management regimes should be spatially explicit especially in terms of land cover history instead of treating valuable oak biotopes as one homogenous unit; (2) these spatial management units should be determined on the basis of biotope dynamics and development rather than only on its present status and distribution; (3) management should allow strict protection of those oak forest sites which show the longest duration of protection and abundance of decaying oak wood to support diversity attached to these type of habitats; (4) new management

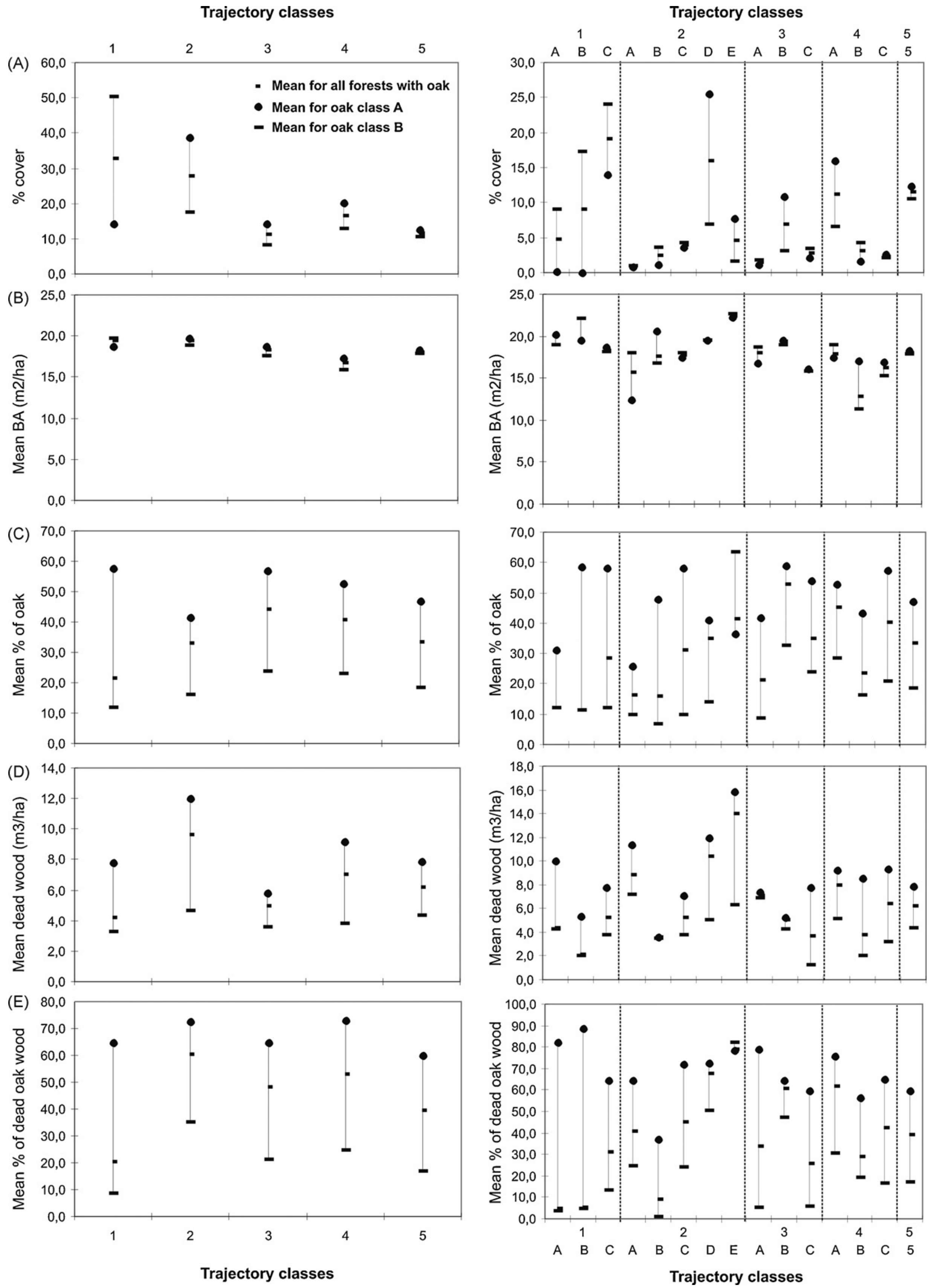

Fig. 7. Summary graphs showing the mean values of the selected forest stand and dead wood variables (A–E) within the major oak forest classes and their respective change trajectory types: all forests with oaks (-), oak class A (●) and oak class B (—). The trajectory information is presented at two levels, with five trajectory types on the left graphs and 15 on the right side graphs. These graphs enable a comparison of the variable mean values between oak classes A and B and in relation to all forests with oaks. Note that the vertical scale of the graphs is different in the left and right graphs for the variables (A), (D) and (E) due to scaling of the results.

regimes should be introduced in those sites which have the highest potential for re-establishment of open, light-abundant oak forest conditions.

4.3. Advantages and methodological challenges of the LCTA approach in the assessment of key biotopes

The forest inventory database was an interesting as well as a challenging data source to link spatially with historical data sets. It facilitated testing if meaningful relationships between the present stand variables and underlying environmental and cultural variables could be established. There are, however, several inconsistencies and uncertainties arising from the creation and merging of spatial data derived from multiple sources through time. Since the forest stand inventory data does not hold any within-patch variation of variables, cell-based statistical analyses were not used when exploring the relationship between stand variables and environmental variables. Linking spatially 10 m × 10 m resolution continuous variables (elevation, slope, and wetness index) to these would not improve the results as the response variable (land/forest category and mean variables) would not represent corresponding spatial variation. However, we have illustrated the variation of these environmental variables within different land/forest classes by calculating cumulative elevation/slope/wetness value curves and comparing these.

Typical sources of error result from the varying scales and mapping purposes between the data, as described earlier by several authors (Skånes, 1997; Petit and Lambin, 2002; Vuorela et al., 2002; Couclelis, 2003; Vuorela and Toivonen, 2003; Ahlqvist, 2004). All spatio-temporal models are broad generalisations of the true dynamic properties of landscapes. When dealing with retrospective analysis extending over centuries, the choice of data sets is not optimal, but reflects a rational selection of spatial data available to match the set research questions. The visual delineation of land cover/land use polygons from aerial photographs and historical land use maps allows control of the thematic and spatial quality in categorical land cover/land use data for relative change detection purposes (see also Vuorela, 2001; Vuorela et al., 2002). The aggregation of change trajectory types on the basis of expert knowledge was useful in generating meaningful change sequences from the perspective of oaks and was preferred in relation to using any automatic or semi-automatic clustering techniques based solely on quantitative variables of trajectories.

When compiling geographical databases from heterogeneous data sets, there are practical challenges related to the under- or over-representativeness of the data. Several generalisations had to be made in order to control these problems. For example, some forest areas were excluded from the analysis due to spatial inconsistency between forest inventory and environmental data sets. Many of the non-inventoried sites, such as private gardens, would typically have contained oaks but were excluded. Oaks had to be generalised into two categories for spatial examination (A and B), since too few patches would have represented the mean values of the derived inventory variables (Table 1) thus obstructing spatio-temporal interpretations. A horizontal sample size of 10 m × 10 m was used for the analysis to retain the oak patch as the primary spatial management unit. By making the spatial grain more detailed, only the number of the pixels would have increased without an increasing level of cartographic and thematic detail. By generalising the cell size further, spatial information of the change trajectories would have been partly lost, since some of the patches and trajectories are elongated and narrow horizontally.

Landscape Change Trajectory Analyses are methodologically challenging efforts due to the heterogeneity and uncertainty of data sets, but rewarding strategies to capture spatially explicit change trajectories characterising present key biotopes. There exists an unfortunate gap between different landscape analyses approaches hampering the combined use of historical and contemporary data sets. The demands for spatial, temporal and thematic accuracy of the intended analyses are sometimes too rigorous. It has to be accepted when using historical sources that spatially explicit knowledge does not refer to absolute spatial quantities, but rather to relative qualitative characteristics of the key biotopes.

As such, any effort to evaluate key biotopes should include a temporal dimension and use of historical data even though it is a time-consuming effort. This analysis encourages combined uses of contemporary and historical data to argue for better and differentiated management of valuable biotopes. When implementing such analyses at a local level, it is possible to draw attention to the most explanatory historical factors. This is crucial, also when landscape trajectory analyses are applied at broader scales and spatial data is less abundant. It can be argued that the principles stated above could be applied throughout the hemiboreal region of Europe (comprising parts of Sweden, Finland, Norway, the Baltic countries) with similar historical development.

Land cover/land use change trajectory analyses are often implemented in controlled case study sites, where diverse data sets and time-consuming data processing phases have enabled spatio-temporal analysis. Rarely is such temporal depth available for broader scale studies. However, from the perspective of oak ecosystems, where the same individual trees have experienced multiple land use regimes over the centuries, this study has demonstrated how such temporal depth and empirical local knowledge is crucial to the outcome of the analysis.

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