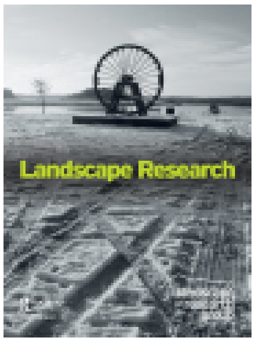

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Systematic Assessment of Maps as Source Information in Landscape-change Research

NIINA VUORELA, PETTERI ALHO & RISTO KALLIOLA

ABSTRACT *A methodology is proposed for systematic map assessment to contribute to landscape-change research. Two major topic areas are dealt with, namely: content, quality and usefulness of landscape information on different maps; and methods used in the spatial conversion of maps into digital systems (e.g. geographical information systems). The major focus is on information about physical landscape characteristics (e.g. land cover) and land uses. The approach was tested using a sequence of nine large- and medium-scale basic maps of the island of Ruissalo in SW Finland from between 1690 and 1998. Fundamental differences were found in the thematic consistency of landscape information, mainly related to the scale, purpose and generalization of landscape information on different maps. Spatial matching was tested for a set of three old maps using four image rectification functions. The results showed that spatial matching of old maps is difficult, and success in rectification is influenced by many factors. Evaluation and selective transformation of landscape information from maps and the use of supportive information from other sources can assist in landscape-change analysis based on map sequences.*

KEY WORDS: maps, landscape information, landscape change, geographical information system

Introduction

The ecological significance of landscape change has been outlined in many studies of landscape patterns, processes and species assemblages (see, for example, Christensen, 1989; Forman, 1995; Fry, 1998). In contrast to present and recent past landscapes where such features can be observed using remotely sensed data and field surveys, historical landscapes must be interpreted from secondary data sources. With extensive spatial and temporal coverage in many regions, maps provide a unique information source for this purpose. Maps and map-like illustrations have been used as a means of communication for over 4000 years (Campbell, 1993; Dorling & Fairbairn, 1997). Mapping techniques and

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products have gradually developed, especially from the 16th century onwards, as knowledge about the Earth's form and shape has increased.

In landscape studies, maps have been used for a variety of purposes, such as analysing changes in land use and in the built environment (see, for example, Roeck Hansen, 1996; Sporrong, 1990), or reconstructing landscape and vegetation transitions over time (Berglund & Olsson, 1991; Foster, 1992; Simpson *et al.*, 1994). Large map collections are available in many countries, representing a great potential for describing and understanding the development of landscapes through time (Kienast, 1993; Tollin, 1991; Vuorela *et al.*, in press). Today, landscape analyses are increasingly performed using digital tools, such as image processing and geographical information systems (GISs). In many cases, sequences of maps have been interpreted and used to represent spatio-temporal information about landscape (see, for example, Skånes & Bunce, 1997; Weir 1997). As landscape-change analyses often extend over a long period of time, very different source maps have been used. These vary from modern digital basic maps to historical land-use maps. Map sequences have been converted into thematic representations in a GIS, and differences between time slices have been observed and defined (see, for example, Cousins, 2001; Johnston, 1998; White & Mladenoff, 1994).

The three basic map attributes of scale, projection and symbolization (Monmonier, 1996) are important issues to consider when maps are used in landscape-change analysis, and when sequences of maps are transformed to digital systems (Keates, 1996). Scale, which refers to the size relationship between the real world and its cartographic representation, affects both the level and focus of the survey and the visual representation of the objects on a map. In digital map analysis, scale is often simplified to refer to the visual control of the geographic data on an interface or, in raster GIS analyses, to pixel size and spatial resolution. The role and effects of scale on the quality of landscape information are, however, difficult to define, as the scale notion on a map does not directly express the scale at which observations of the real world were made.

Projections are used to transform the three-dimensional real-world surface onto a flat, two-dimensional plane. In digital systems, storage, analysis and visualization of geographic data is based on the use of shared projections and reference systems. Thus, when converting a series of old maps into digital maps their reference systems need to be spatially adjusted (Dunn *et al.*, 1991). Although the principle is clear, projection and map datum issues can present difficult practical challenges to map transformation. Many old maps, for example, have either very little or no information at all on the reference system (i.e. datum, projection) used, or may contain various geometric distortions (Dickinson, 1979).

Maps contain heterogeneous landscape information, which is represented on a map as graphic signs and texts. Success in map interpretation is greatly dependent on the skills and knowledge of the map user (MacEachren, 1995), including an understanding of the influences of the purpose, scale and time of the mapping, and of the generalization techniques used in map production (Campbell, 1993; Harley, 1996; MacEachren, 1995; McGranaghan, 1993). Graphic signs have been geometrically categorized into points, lines and areas, and further to different size, shape, colour, hue, texture and orientation forms (Monmonier, 1996; Robinson, 1982). The same geometrical classification is also used in digital vector data structures (Campbell, 1993; Robinson *et al.*, 1995).

Since maps are created through a series of information transformations (data collection, classification and simplification), it may be difficult to assess landscape representations on a map in relation to the actual characteristics of the landscape (Robinson *et al.*, 1995). Further, transformation of old maps requires considerations of the interpretation, conversion, storage and representation of landscape information in a GIS (Richardson, 1996).

There are three particular challenges for the application of GISs to sequences of maps when undertaking landscape-change analysis. First, converting different maps into digital, geo-referenced landscape information involves dealing with both geometric and semantic inconsistencies and uncertainties on maps. Second, maps are static representations of landscapes, which are dynamic and continuously changing systems. Third, map comparison and change analysis is difficult to perform between maps (Kienast, 1993), as distinguishing actual change from errors in interpreting and converting maps presents a practical challenge to landscape-change analysis (Johnston, 1998, p. 120).

These challenges constitute the emphasis of this article, where we propose a methodology for systematic map assessment to contribute to landscape-change research. We identify two major topic areas: (1) the content, quality and usefulness of landscape information on different maps; and (2) the methods used in map interpretation and conversion for their further use in a GIS. In this study, we emphasize physical landscape characteristics (e.g. land cover, topography) and land uses, which we consider as the typical and most often-used landscape information. Systematic assessment includes the documentation of maps according to the number, cartographic representation and thematic consistency of different landscape feature classes. By methods used in map conversion, we refer to ways in which maps can be transformed from their original form into thematic representations in a GIS. The research strategy is tested using a sequence of nine large- and medium-scale basic maps of the island of Ruissalo in SW Finland dating from 1690 to the present.

The Study Site

The island of Ruissalo (9 km^2), our test area in the present study, is situated in the coastal archipelago of SW Finland, close to the city of Turku (Figure 1). The landscape of the island reflects the diversity of both natural and human-induced environmental factors. The motivation to use Ruissalo Island in this study lies in its intriguing land-use history and the good availability of cartographic information reflecting landscape changes.

The land-use and land-ownership history of Ruissalo can be divided into several phases (Vuorela, 2000). The island was an estate of Turku castle during the 16th century, a wage-farm of the governors until the 19th century, and finally a summer housing, recreation and conservation area of the city of Turku (Soiri-Snellman, 1985). Human activities on Ruissalo, together with variable physical landscape characteristics, have resulted in a heterogeneous and diverse landscape of different woodlands, parks, gardens, arable land, meadows and recreation areas (Vuorela, 2000). Woodlands, forming approximately one-third of the land area, vary from deciduous-dominant oak (*Quercus robur*) to Scots pine dominant (*Pinus sylvestris*). The built environment is characterized by old villas, roads and paths and different recreation sites, including a golf course,

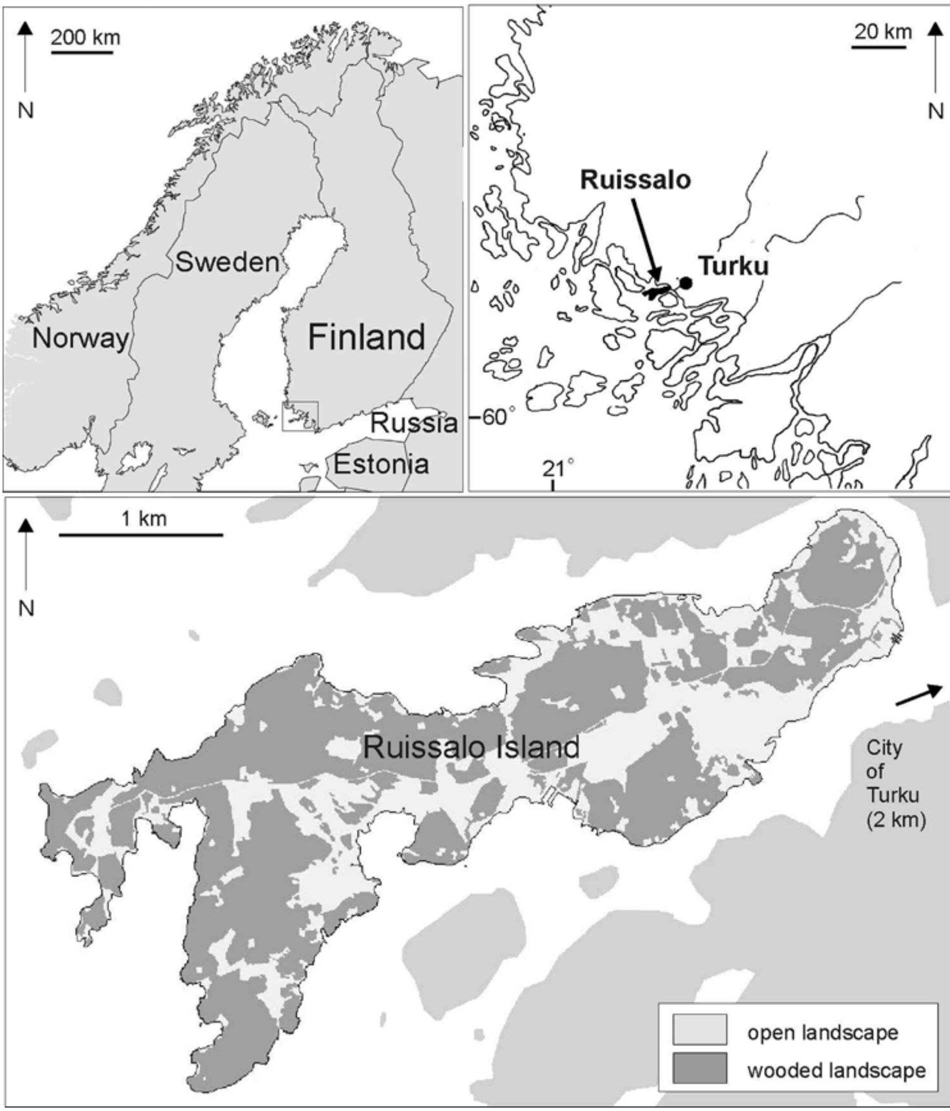


Figure 1. The study site of Ruissalo Island, located in the archipelago of southwest Finland.

camping site and botanical gardens. In addition, extensive areas of common reed (*Phragmites australis*) characterize the littoral zone on shallow sites.

Material

Nine different maps from a period spanning three centuries were selected for this study, mainly large- to medium-scale topographic and basic maps from different mapping periods and traditions (Table 1, Figure 2). In the following, each map is described according to its basic characteristics and information structure.

Table 1. Basic characteristics of different maps used in this study

Map	Mapping extent	Sheet division	Mapping purpose	Publication year	Cartographer(s)	Map scale	Product type[a]	Map structure[b]	Archive[c]
Geometrisch affrijtningh öfwer Runsala Ladugårdh	regional	according to parish	land use	1690	O. Mört	*ca.* 1:4000	1 a	1 + 3	NLSF (h)
Karta öfver Runsala med derunder lydande holmar	local	—	land-use planning	1846	B. Ekqvist	*ca.* 1: 4000	1 a	2 + 3	TT NLSF (t)
Russian topographic map (Venäläinen topografikartta)	regional	no. 1313	military	1880[d]	—	1: 42 000	2 a	1 (2) + 3	GD (t) MA (h)
Senate map (Senaatinkartta)	regional	no. XVI line A	military	1881[d]	—	1: 21 000	2 a	1	MA (h)
Transportkarta öfver Runsala ö	local	—	land-use planning	1892	M. W. Gull	1: 8000	2 a	1	TT GD (t)
The municipality map (Kuntakartta)	regional	municipal	basic map	1920	—	1: 20 000	2 a	1	NLSF (h) TT
Topographic map (Topografinen kartta)	national	no. 1043 09, Turku	basic map	1947	T.Vuori	1 :20 000	2 b	1	NLSF (h) GD (t)
Basic map (Peruskartta)	national	no. 1043 09, Turku	basic map	1981	M.Katila, K.Heiskanen	1: 20 000	2 b	1	NLSF (h) GD (t)
Basic map (Maastokartta)	national	no. 1043 09, Turku	basic map	1998	—	1: 20 000	3 b	1	NLSF (h) GD (t)

[a] 1 = hand-drawn; 2 = printed; 3 = digital; a = based on table measurements; b = based on aerial photography.
[b] 1 = short descriptions within map; 2 = explanatory descriptions on a separate sheet; 3 = quantitative measures.
[c] NLSF = The National Land Survey of Finland; MA = military archive; TT = Turku town; TOPO = topographic office; GD = Geography Department; h = Helsinki; t = Turku.
[d] Originate from the same mapping in 1880–1881.

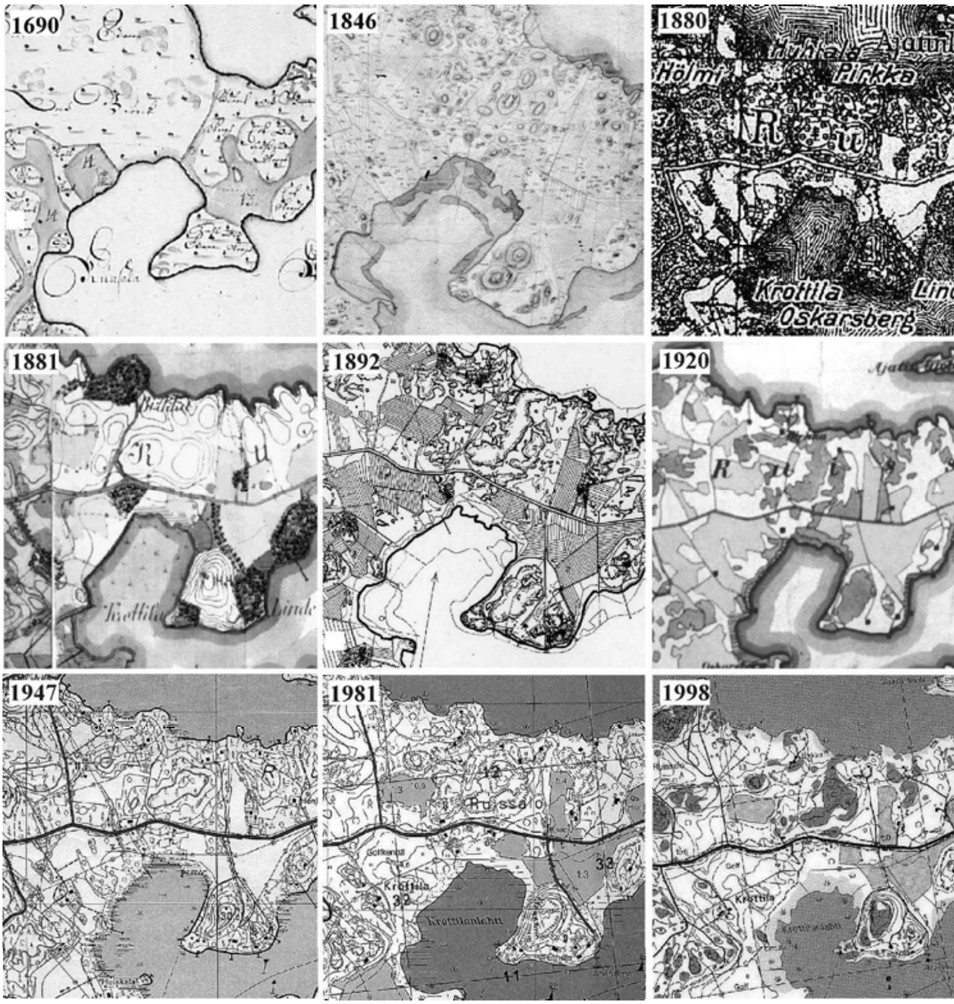


Figure 2. Example illustrations of the maps used in the study. See Table 1 for details of the maps.

Map 1: Geometrisch affrijtningh öfwer Runsala Ladugårdh medh des qvalitet et qvantitet (1690)

This source is a geometric mapping of the jurisdictional districts of Finland during the time of Swedish governance in the country. Regional surveyors, in this case Olof Mört, were ordered to map both arable land and meadows within their districts, primarily to the scale of 1:4000 (Suomen maanmittari-yhdistys, 1929). This mapping represents a continuation of the work which had already started in 1633 upon the Swedish King's decision to send surveyors to Finland to map the extent and quality of arable land and meadows (Johnsson, 1965; Lönborg, 1901). Woodlands and other outer areas were also described, names of the meadows and streams marked, and buildings numbered and registered (see, for example, Gustafsson, 1933). At the time of the mapping, there was one manor on the island, which was a wage farm settled by the governors of the region (Perälä, 1954). The map is supplemented with short texts in the margin and within the symbols on the map (e.g. woodland areas).

Map 2: Karta öfver Runsala med derunder lydande holmar (1846)

This coverage is a Ruissalo-specific mapping to a scale of 1:4000, which was initiated after the Russian senate gave the ruling rights of Ruissalo to the town of Turku in 1845 (Dahlström, 1942). Finland was a Grand Duchy under the Russian Empire from 1809 to 1917. Commission surveyor Berndt Ekqvist of the Turku-Pori province was assigned to map the island for the implementation of future land-use plans (Soiri-Snellman 1985). Thus, mapped features emphasize land uses and potential future land uses. Special attention was given to the mapping of oak woodlands. All map objects were numbered according to each parcel, and explained and quantitatively described in a separate survey book.

Maps 3 and 4: the Russian topographic map (1880) and the Senate Map (1881)

These are military maps, based on the surveys of the Russian Topographic Service in Finland between 1870 and 1917 (Gustafsson, 1932, 1933, pp. 86–88). Mapping was conducted by a plane-table method to a scale of 1:21 000. Eventually, two different map products came out of this mapping. In Russia, topographic maps were produced either at the original scale or at 1:42 000 scale. These Russian topographic maps constitute important documents of the time, since large parts of Finland were topographically described relatively early on (Niemelä, 1984, 1998; Paulaharju, 1947). Copies of the original plane-table maps were donated to Finland and coloured later on. These are known as the Senate Maps. In addition to landforms, both maps include typical features of the basic maps: arable land, meadows, roads and buildings.

Map 5: Transportkarta öfver Runsala ö med underlydande holmar samt Bockholmen (1892)

Cartographer M.W. Gull mapped Ruissalo Island at the end of the 19th century. His work finally resulted in two hand-drawn map products, the transport map (1:8000) from 1892 and parcel maps (1:1000), constituting 46 pieces, from 1895. Due to the overwhelming amount of detailed landscape information on the parcel maps, only the transport map was selected for this study. Both maps are based on the same mapping, and most of the mapped features of the large-scale maps can be found on the transport map. The transport map includes short symbol descriptions, while the parcel maps have large explanatory texts and measurements in a survey book.

Map 6: the municipality map of Turku (1920)

This is a later-coloured parish map, which was mapped according to the administrative district of Turku. Originally, parish maps were produced as a black and white sheet-map series between 1825 and 1950, covering *ca.* 27% of Finland (Niemelä, 1998, p. 27). The parish maps of the Turku area do not have symbol fillings, which significantly decreases their usability compared to the coloured municipality map.

Map 7: topographic maps (1947)

These maps were produced to a scale of 1:20 000, starting from the time of the independence of Finland (1917), and their production continued until 1947 (Niemelä, 1998, p. 40). The earliest topographic maps were produced by the National Land Survey, after which production was continued by the Military Topographic Service (Topografikunta). From 1930 onwards, mapping was based on aerial photography instead of the long-used plane-table measurements. The 1947 map is based on the 1939 and 1945 aerial photographs and is a partly coloured map with black, red and brown lines and blue fillings.

Map 8: the basic map of Finland (1981) (peruskartta)

This map includes general information about the landscape, and was designed for a large audience of users, both professional and the general public (e.g. for recreational or orienteering uses) (Niemelä, 1998, p. 54). The mapping is based on aerial photography at a scale of 1:10 000, but maps are printed at a scale of 1:20 000. The design of the basic map was created during the 1940s by combining two earlier national map products, the parish map and the topographic map (Niemelä, 1984). The cartographic design of the basic map is based on the use of six colours.

Map 9: the basic map of Finland (1998)

The visual appearance and the map production methods of the basic maps were renewed at the National Land Survey during the 1980s and 1990s (Niemelä, 1998). Currently, the production of the basic maps is from a digital database (maastotietokanta), which includes thematic information in vector format. Original mappings are made at the scale of 1:5000 to 1:10 000. The digital database is updated every 5–10 years, except for roads, which are updated every year (Niemelä, 1998, p. 134). The cartographic visualization of the basic map has changed through this transformation. Currently, the printed basic map (maastokartta) is visually very different from the traditional basic map and is based on the use of several colours.

Methods

Research Approach

The study was based on a systematic assessment of the sequence of maps from 1690 to 1998 and consisted of the evaluation of landscape information and the testing of digital transformation of maps (Figure 3). Our evaluation aimed to assess the amount and nature of landscape information in maps and cartographic representation, and the thematic consistency of 15 different landscape feature classes (e.g. arable land, meadow, woodland). Digital transformation of paper maps involved testing and comparing different rectification methods with respect to a set of three old maps. After this, a selection of landscape information classes was evaluated along the temporal sequence (1690–1998) to explore the usability of various landscape feature classes in change analysis. In order to emphasize the significance of temporal evaluation, an example of woodland change detection is presented in this paper.

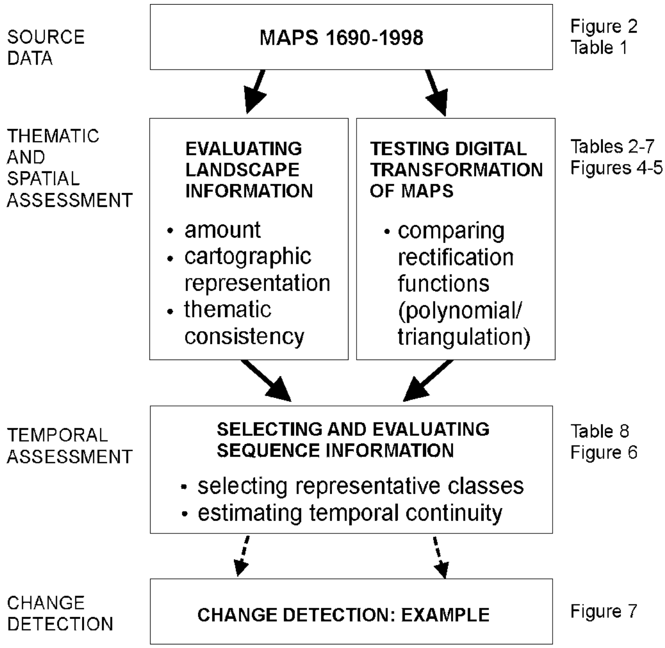


Figure 3. The research strategy used in the study.

Evaluation of landscape information was implemented as consecutive work phases where results were compiled into tables and collated. They all included some degree of subjectivity (in interpretation), but this factor was kept under control by systematic and repeatable assessment. As a result, landscape information along the time sequence was based on documented step-by-step assessment. This allowed the possibility of estimating the relevance and usability of landscape information in land-cover-change analysis.

Evaluating Landscape Information

First, all maps were evaluated according to the amount of landscape information, which was categorized into seven major landscape information themes: landforms, geology, hydrology, vegetation, land use, built-up environment and planning. These themes were considered to be typical landscape information categories provided by most basic maps. The amount of landscape information was defined as the number of map-feature classes in each landscape category. Examples of land-use feature classes include arable land, meadows and pastures. Some of the feature classes can represent more than one landscape information category: for example, on some maps 'meadow' was considered to give information on both land use and vegetation.

Second, 15 landscape feature classes were chosen for further evaluation. These were: topography, soils, dikes, shoreline, woodland, bog areas, reed areas, arable land, meadows, gardens, parks, buildings, roads, fences and land-use plans. After determining whether the feature class primarily indicated a physical or a functional characteristic of the landscape (e.g. land cover, land use), the cartographic representation of each feature class was then evaluated by observing its geometry (point, line, area) and boundary vagueness (crisp, fuzzy). Subsequently, the thematic consistency of each feature class was assessed as consistent or partly consistent (fragmented) information content. Thematic consistency referred to the comprehensiveness of information content in a feature class. As an example, many classes can appear as clear and comprehensive (e.g. based on the cartographic representation, name of the class), but actually lack exact or clear explanation of the class definition.

Testing Digital Transformation of Maps

Digital transformation was implemented using image processing software and tested with a selection of three scanned maps (1690, 1846, 1892). All these maps had no datum and projection information available, nor any evidence of the reference system or mapping procedure used. Therefore, we used image rectification based on the use of ground control points (GCPs) and rectification functions. The work was conducted using the facilities of the Laboratory of Computer Cartography at the Department of Geography, University of Turku.

All three maps required pre-processing prior to being rectified. First, maps were photographed onto 35-mm colour-slide film, developed and scanned with a film scanner (Nikon Coolscan II). A repro film of the 1690 map was available and was provided by the Turku Provincial Museum. This was scanned using a table scanner (Agfa Studio Scann II). Possible distortions caused by the camera lens and desktop scanner were not evaluated, nor was the shrinkage of original maps estimated (see, for example, Hunt & Smith, 1985). Digital map images were imported into image processing software (ERMapper 5.5) for geo-referencing. The Finnish Co-ordinate System (Gauss-Krüger projection) was used as the reference system in rectification.

The testing of digital transformation was based on geo-referencing, using GCP registration and a set of four different rectification functions, both polynomial and triangulation (e.g. Mather, 1987). In practice, a geo-referenced image, in this case an aerial photomosaic (1996), was used as an image pair, from which GCPs were selected. Generally, the best GCP points are easily recognizable and spatially accurate landscape features, such as path crossings or houses. In this study, we were obliged to use different types of GCPs due to the lack of similarity in the built environment between the raw (old map) and the registered (photomosaic) data sets. One set of GCPs for each map was selected in order to compare the rectification results performed with different methods. Triangulation was further tested for the 1690 map with fewer GCPs.

After geo-coding (i.e. selecting GCPs), map images were rectified using three polynomial (linear, quadratic, cubic) functions and a triangulation function (Delauney) with the nearest-neighbour re-sampling method (see, for example, Lillesand & Kiefer, 1994; Mather, 1987). Further, a triangulation rectification was tested for the 1690 map using *ca*. 65% of the original points. The first-order, linear transformation can only rectify scaling, rotation, shearing and reflection (Hardy, 1978), and not the image's non-linearity. Higher-order functions, also known as 'warping' methods, are used when non-linear geometrical distortions are expected. The triangulation function creates a mesh of triangles from the selected GCPs and the area of each triangle is rectified separately using a first-order polynomial function (Earth Resource Mapping Pty Ltd, 1998, p. 478). In this study, differences and success (i.e. spatial fit) in rectification were estimated with the aid of root-mean-square (RMS) errors (polynomial functions) and check points (all functions, triangulation). Check points were used so that

Table 2. The overall number of landscape feature classes representing selected landscape information themes[a]

Landscape information categories	Number of landscape feature classes 1690	1846	1880	1881	1892	1920	1947	1981	1998	Total/theme
Landforms	1	1	1	1	1	×	2	2	2	11
Geology	1	2	1	2	1	1	2	2	2	14
Hydrology	2	2	2	2	2	1	3	3	3	20
Vegetation	3	7	6	5	7	4	6	6	6	50
Land use	7	6	5	4	8	3	6	5	6	50
Built-up environment	4	5	6	6	8	4	6	7	6	52
Planning	1	3	×	×	1	1	×	×	×	6
Total/map	19	26	21	20	28	14	25	25	25	

[a] Themes without representative classes are marked with '×'.

the difference between their geo-coded (i.e. expected) location and determined (rectified) location was calculated (see, for example, Weir, 1997).

Selecting and Evaluating Sequence Information

Based on the systematic evaluation and rectification tests, a selection of landscape feature classes was identified for the map sequence evaluation (i.e. temporal assessment) (Figure 3). Representative classes from different maps were recognized using three categories: direct transformation possible, selective transformation (split/merge) possible, and rejection suggested. The major focus was on the land-cover and land-use information, and the quality of landscape feature classes and maps.

The selected landscape feature classes were evaluated along the time sequence by first comparing classes between maps, and then combining supplementary information from written documents and aerial photographs to estimate the temporal continuity of feature classes on different maps. The main purpose of this process was to distinguish which classes from which maps are suitable for GIS-based change analysis. This assessment phase produced the final set of representative feature classes for monitoring changes in the landscape. A practical demonstration of the overall assessment process was carried out for the single class of 'woodlands'.

Results

The Amount of Landscape Information

There was not much variation in the overall amount of landscape information between maps, except for the year 1920, where only 14 landscape feature classes were found (Table 2). The two Ruissalo-specific mappings (1846, 1892) had the highest number of map-feature classes. Most of the map classes related to the anthropogenic environment (i.e. land use, buildings) and land cover (i.e. vegetation).

Table 3. Estimation of whether the feature class primarily indicated a physical or functional landscape characteristic[a]

Landscape feature class	Map								
	1690	1846	1880	1881	1892	1920	1947	1981	1998
Topography	●	●	●	●	●	×	●	●	●
Soil	■	■	×	×	●	●	●	●	●
Dikes	×	■	■	■	■	×	●	●	●
Shoreline	●	●	●	●	●	●	●	●	●
Woodland	■	■	■	■	■	■	●	●	●
Bog area	×	●	×	×	■	×	×	×	×
Reed area	×	●	●	●	●	×	●	●	●
Arable land	■	■	■	■	■	■	■	■	■
Meadow	■	■	■	■	■	■	●	●	●
Garden	■	■	■	■	■	■	■	■	×
Park	×	×	■	■	■	■	×	■	■
Building	■	■	■	■	●	■	■	■	■
Path, road	■	■	■	■	■	■	■	■	■
Fence	■	■	■	×	×	■	■	×	×
Land-use plan	■	■	×	×	■	■	×	×	×

[a] ● = physical (e.g. species, type, form); ■ = functional (e.g. land use); × = no information available.

Nearly all maps presented some information on the landforms (i.e. topography) of the island. Information on geology and hydrology was limited and related to specific soil formations (e.g. sandy beaches, clay areas), features in the bedrock (e.g. outcrops) and dikes, springs, shores and the sea. Direct information on vegetation was sparse, but information about vegetation was included in woodlands, bogs, gardens, grasslands and arable land classes. Land-use information was diverse and visualized through several landscape feature classes, such as meadows, arable land, parks, gardens and fences (grazing areas). All maps provided information on buildings, paths and roads, and some maps on other constructions, such as piers, bridges and fences. Information on planning was sparse and consisted mainly of future land use and construction plans.

Most of the feature classes on the maps made prior to the use of remote sensing characterized different human activities in the landscape, such as agricultural land uses (Table 3). Buildings and roads were primarily classified based on their use (e.g. mansion, croft, barn) and soils, dikes and woodlands were recognized merely through their use value (e.g. grazing, possible sites for cultivation). For example, in the 1892 (1895) survey book 'woodland' was defined as land area which could not be placed in any of the previous categories (which included, for example, arable land and meadows). After aerial photography became the basis for mapping, most of the feature classes were mapped according to their visual appearance or texture. For example, the term 'meadow' no longer referred just to land use, but also to the texture and structure of the land cover. Topography and shoreline characteristics (e.g. reed areas) were exceptions to this trend. They have been important physical characteristics of the study site and are thus represented on most of the maps.

Table 4. Estimate of the cartographic representation (geometry, boundary) of each Landscape feature class[a]

Landscape feature class	Map								
	1690	1846	1880	1881	1892	1920	1947	1981	1998
Topography	◩	◩	*	*	◩	×	*	*	*
Soil	T	T	×	×	T	T	◩	◩	◩
Dikes	×	*	–	*	*	×	*	*	*
Shoreline	*	–	–	*	*	*	–	–	–
Woodland	■	◩	■	◩	■	■	■	■	■
Bog area	×	◩	×	×	◩	×	×	×	×
Reed area	×	■	◩	◩	■	×	◩	◩	◩
Arable land	■	■	■	■	■	■	■	■	■
Meadow	■	■	■	■	■	■	■	■	■
Garden	◩	■	◩	◩	■	◩	■	◩	×
Park	×	×	◩	◩	■	◩	×	◩	■
Building	◑	●	●	◑	●	●	●	●	●
Path, road	–	–	*	*	*	*	*	*	*
Fence	*	*	–	×	*	×	×	×	×
Land-use plan	T	◩	×	×	T	–	×	×	×

[a] ■◩ area: distinctive/fuzzy; ●◑ point: distinctive/fuzzy; * – line: distinctive/fuzzy; T = text information; × = no information available.

Cartographic Representation

Symbol geometry was conventional on most of the maps and feature classes (Table 4). For example, classes which indicated extensive coverage on the island (e.g. land uses, vegetation) were represented as area symbols using different colours and fillings. Linear landscape elements, such as dykes, shoreline, roads and fences, were constantly represented with line symbols, also using different colouring and symbol design. Buildings were shown with point-like signs. The feature class 'topography' showed most variation on maps. On the oldest maps, topography was indicated as area symbols, while on the latest maps the use of contour lines was the norm. The most recent maps were also supplemented with symbols indicating steep gradient in the relief. A great deal of information was delivered by texts. This was the case particularly with soils, woodlands, gardens, parks and planning, especially on the oldest maps (1690, 1846). Texts also supplemented land-use information (e.g. cultivated crops, animals grazing). In general, descriptive texts were short, except on the 1846 map, where the sub-classes of meadows were explained and the most common tree species listed in a separate survey catalogue.

Boundary characteristics (crisp, fuzzy) of the land-use and land-cover feature classes were generally crisp. Arable land, meadows, woodlands and roads were sharply delineated. Topography, soils, bog areas and land-use plans were mainly indicated with fuzzy boundary characteristics on old maps. For example, on the 1690 map, topographic information was marked with round, grey, cloud-like symbols. There seemed to be a tendency towards fuzzy delineation on the latest maps in terms of the reed areas, soils, shoreline information and, in some cases, with parks (Table 4). In the case of the 1690 map, buildings were shown as iconic signs and their exact location was difficult to determine.

Table 5. Estimate of the thematic consistency of each feature class[a]

Landscape feature class	Map								
	1690	1846	1880	1881	1892	1920	1947	1981	1998
Topography	◑	◑	●	●	◑	×	●	●	●
Soils	◑	◑	×	×	◑	◑	◑	◑	◑
Dikes	×	◑	◑	◑	◑	×	●	●	●
Shoreline	◑	◑	◑	◑	◑	◑	◑	◑	◑
Woodland	◑	◑	◑	◑	●	◑	●	●	●
Bog area	×	◑	×	×	◑	×	×	×	×
Reed area	×	◑	◑	◑	◑	×	◑	◑	◑
Arable land	●	●	●	●	●	●	●	●	●
Meadow	◑	◑	◑	◑	●	◑	●	●	●
Garden	◑	●	◑	◑	●	◑	◑	◑	×
Park	×	×	◑	◑	●	◑	×	◑	◑
Building	●	●	◑	◑	●	◑	●	●	●
Path, road	◑	◑	●	●	●	◑	●	●	●
Fence	◑	●	◑	×	●	×	×	×	×
Land-use plan	◑	◑	×	×	◑	◑	×	×	×

[a] ● = consistent; ◑ = fragmented, partly consistent; × = no information available.

Thematic Consistency of the Feature Classes

Nearly all feature classes showed variability in their thematic consistency (Table 5). Inconsistency within the same map product was found in many feature classes and was particularly typical of the old maps. Only the 1892 map was an exception, as we evaluated its information content to be consistent in 11 classes and even partly consistent in the remaining ones.

Land-use and built-environment classes (e.g. arable land, roads) were rather consistently represented on all maps. The classes 'woodland' and 'meadows' were, however, inconsistent on the oldest maps, but more consistent on later maps. In other words, as the definition of woodlands and meadows on older maps was based on land uses, it was difficult to determine the actual class definition and delineation. As an example, it is known that meadows were both wooded and open until the end of the 19th century. On some maps, it was difficult to say whether these sites were included in 'woodland' or meadow'. For example, on the 1846 map, descriptive texts revealed that meadows, represented with one symbol on the map, were actually of two different types. Topographic information was very uncertain on the old maps (except those of 1880 and 1881), where there was very little indication of what the symbols actually indicated (e.g. highest sites? relatively high sites?).

The three most recent maps displayed inconsistency, especially in the details of soils, reed areas and shoreline. This related mainly to the nature of these classes. Change from the sea to shoreline and then to reed areas is gradual, and sharp boundaries rarely exist. This can also be the reason for the inconsistency of the woodland class. In the case of soils, information was biased and only visually detectable features were marked on the map (clays, boulder fields, sand shores). This is evident on the latest maps, which are designed for a variety of uses; more detailed soil information can be obtained separately from different types of soil maps such as 'Map of the Quaternary Deposits' (Maaperākartta, 1996).

Table 6. Mean and total RMS errors for polynomial rectification functions. Units are in metres

	Linear		Quadratic		Cubic	
Maps	Mean	Total	Mean	Total	Mean	Total
1690	28.10	1546.10	26.51	1458.00	26.20	1438.70
1846	6.90	781.40	6.70	762.80	6.51	737.80
1892	4.80	518.20	3.80	413.00	3.90	417.70

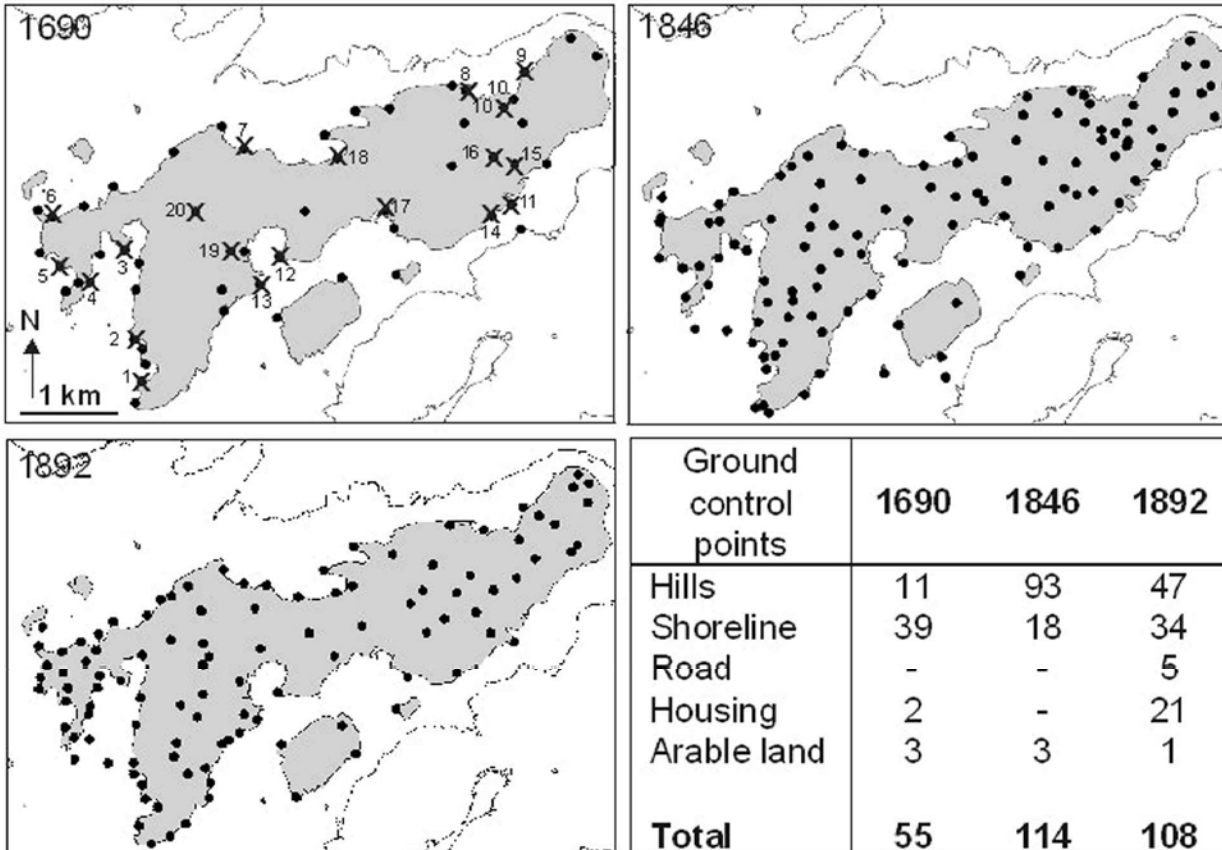
Digital Transformation of Maps

A selection of 55 GCPs was made from the 1690 map (Figure 4). The majority of these were features of the natural environment, such as shorelines and hilltops. These were quite evenly distributed over the island but, due to the scarcity of built features on the 1690 map relative to the 1996 photomosaic, large gaps were left between defined GCPs. Also, it was very likely that there were location errors in determining GCP locations due to cartographic representations. In the case of the 1846 map, 114 GCPs were found, mainly due to detailed mapping of the topographic variation of the island (a total of 93 points were hilltops). When searching for GCPs, a stereoscopic interpretation of the aerial photographs was used to locate small hilltops on both the map and the aerial photomosaic. For the 1892 map, it was possible to use some of the houses (21 points) as rectification points but, even so, nearly 50 out of 108 GCPs were hills.

The overall residuals (mean RMS) of different polynomial functions show only little variation within one map but, in general, are much higher in the case of the 1690 map than the two other maps (Table 6). The mean RMS error for the 1690 map was over 20 metres in all polynomial functions, while it was less than 5 metres in the case of the 1892 map. Location differences of the check points between polynomial and triangulation functions indicate that, in general, both the third-order polynomial and the triangulation give a better spatial match than the first- and second-order functions (Figure 5). There is little difference between the cubic and the triangulation rectification, especially for the two 19th-century maps. In the case of the 1690 map, triangulation check-point errors are smaller than in any polynomial function; however, further inspection of the triangulation using 35 GCPs (*ca*. 60 %) showed that errors are very high (Table 7). These exceeded the residual averages of the polynomial functions (Table 6) and were as high as 200 metres at the outermost sites (e.g. shoreline). This suggests that triangulation is very sensitive to the number and quality (coverage, spatial accuracy) of GCPs.

Selecting and Evaluating Sequence Information

Based on the evaluation, it appears that the 1880, 1881 and 1920 maps are of little use for landscape-change analysis compared to the level and consistency of feature classes on other maps (Table 8). A great number of classes can be rejected from these three maps. It is possible, however, to use these maps as supportive data sets in defining the temporal continuity of landscape information (Figure 6).



Ground control points	1690	1846	1892
Hills	11	93	47
Shoreline	39	18	34
Road	-	-	5
Housing	2	-	21
Arable land	3	3	1
Total	**55**	**114**	**108**

Figure 4. Distribution and types of ground control points used in the rectification tests of the 1690, 1846 and 1892 maps. Numbered points marked with 'X' refer to the second rectification test carried out with the 1690 map (see Table 7).

Table 7. Displacement of the 20 check points in the second triangulation rectification of the 1690 map (with 65% of the points). See the distribution of the points in Figure 4. Units are in metres

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
112.9	59.4	34.4	92.3	42.9	70.3	209.2	48.7	127.5	30.7	16.6	29.9	60.6	122.1	49.9	63.6	112.1	61.9	163.7	69.9

Check point	Maps	Displacement of the check point (m)			
		1st	2nd	3rd	Tri
1	1690	56.3	44.7	75.7	51.8
	1846	13.9	6.6	3.9	1.7
	1892	4.3	3.4	2.6	1.9
2	1690	64.5	86.6	14.1	11.9
	1846	10.2	7.8	5.8	5.6
	1892	18.3	16.6	16.1	15.7
3	1690	86.3	53.8	12.1	6.8
	1846	7.2	4.0	2.6	2.5
	1892	3.4	2.5	2.2	1.9
4	1690	72.6	71.0	46.4	5.7
	1846	7.9	4.3	3.4	2.4
	1892	6.7	5.9	4.9	0.9
5	1690	53.2	32.1	11.2	10.2
	1846	19.2	16.6	12.6	11.4
	1892	11.5	7.3	3.7	4.2
6	1690	12.8	54.5	44.4	10.7
	1846	19.2	15.1	13.9	13.5
	1892	1.8	1.6	1.6	0.8

Figure 5. Six check points were used in estimating the spatial fit between different maps (1690, 1846, 1892) and rectification methods (polynomial, triangulation). Values account for the difference between expected and actual location of the check points (displacement).

For example, an estimation of the time of change (i.e. event) between the 1846 and 1892 maps can be traced using the 1880 and 1881 maps.

In terms of the feature classes, only a few landscape feature classes can be traced reliably through all of the maps, and most require supportive information in their transformation (e.g. woodlands). These supportive data sets can vary from aerial photographs to written records and landscape photographs. The

Table 8. Selection of the representative landscape feature classes for map sequence evaluation[a]

Landscape feature class	Map								
	1690	1846	1880	1881	1892	1920	1947	1981	1998
Topography	⊗	⊗	⊗	⊗	⊗	×	⊗	⊗	●
Soil	⊗	⊗	×	×	⊗	⊗	⊗	⊗	⊗
Dikes	×	◑	◑	◑	◑	×	●	●	●
Shoreline	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	◑
Woodland	◑	◑	◑	⊗	◑	⊗	●	●	●
Bog area	×	◑	×	×	◑	×	×	×	×
Reed area	×	⊗	⊗	⊗	⊗	×	⊗	⊗	⊗
Arable land	●	●	⊗	◑	●	◑	●	●	●
Meadow	◑	◑	⊗	◑	◑	◑	◑	◑	◑
Garden	⊗	●	◑	◑	●	⊗	◑	◑	×
Park	×	×	◑	◑	●	⊗	×	◑	◑
Building	◑	●	⊗	⊗	●	⊗	●	●	●
Path, road	●	◑	●	⊗	●	⊗	●	●	●
Fence	◑	◑	⊗	×	◑	×	×	×	×
Land-use plan	⊗	⊗	×	×	⊗	⊗	×	×	×

[a] Grey boxes indicate direct and selective transformations. ● = direct transformation (point/line/area); ◑ = selective transformation (split/merge); ⊗ = rejection suggested; × = no information available.

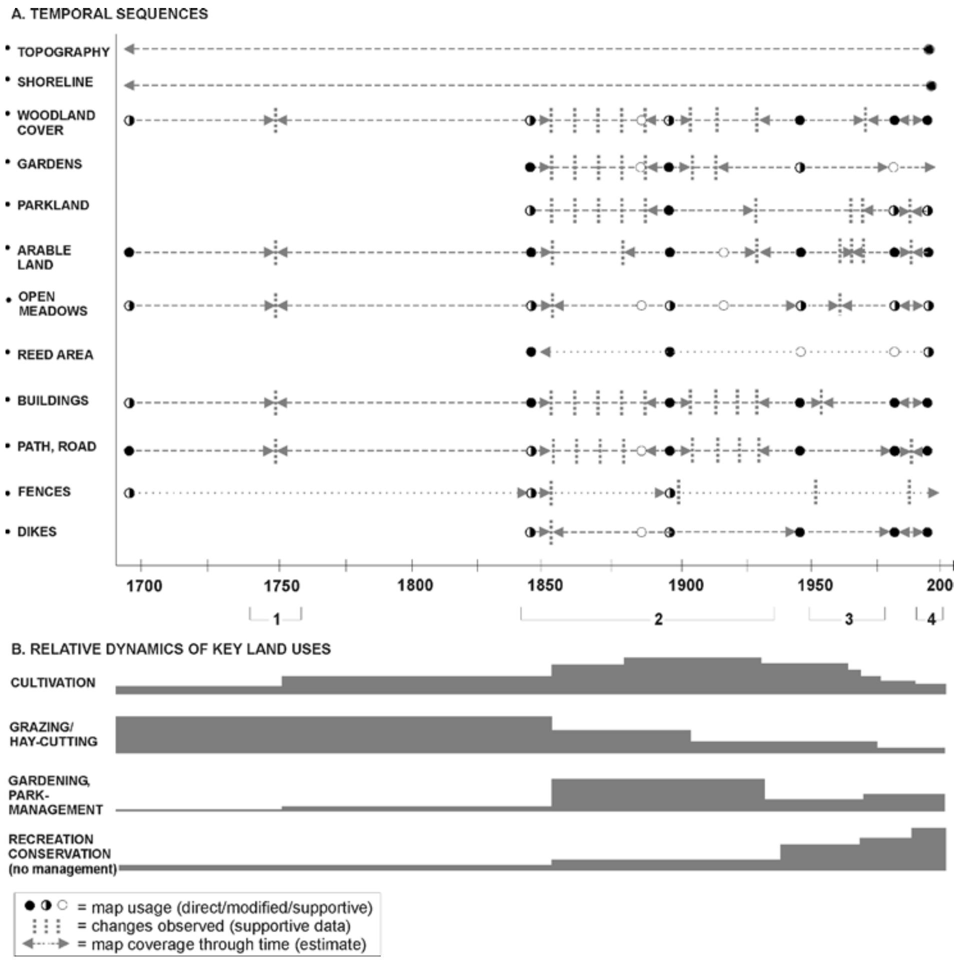


Figure 6. (A) Estimate of the temporal continuity of selected landscape feature classes from different maps. Numbers refer to Appendix Table A1, where examples of supportive data are listed. (B) Relative dynamics of key land uses during the observed period.

final decisions, such as the identification of key land-use types and periods, can thus be justified by a combined set of information from various sources.

The use of the following set of feature classes is suggested for land-cover-change analysis between 1690 and 1998: arable land, meadows, woodlands and built environment, consisting of buildings and roads. These represent characteristics of land cover most reliably along the temporal sequence. Woodland and meadow classes require spatial adjustment due to inconsistencies in their thematic content. Topography, on the other hand, can be used as background information in change detection, and it is reliable from only the latest map (1998). The use of gardens and parks is more complicated, as these are mainly land-use-indicative classes and they can exist either within or outside wooded landscape. Thus, their information content can overlap with that of the woodlands. The use of these two classes depends on the level of landscape information observed.

Figure 7 illustrates an example of the reconstruction of the woodland cover between 1690 and 1998. It was based on the use of these maps and a combination of other information sources (see Appendix 1). Major changes in woodland cover between 1690 and 1846 were initiated around the 1750s (see, for example, Vuorela, 2000). Immediately after the 1846 mapping, land uses in woodlands changed, and parks and gardens were introduced. This kept most of the woodland cover the same as before, except for small areas where houses were built and where wooded meadows were cleared for arable land (Vuorela & Toivonen, in press). Towards the present-day, woodland cover has increased (from the 1970s onwards) due to tree plantings and abandonment of agricultural land. As an example, the 1846 woodland cover was re-established by combining parts of the meadow class (the sub-class 'wooded meadows') into a selection of polygons from the original woodland class. Further, bogs were combined with the woodlands class. In the case of the 1892 map, a combination of several classes was required to establish woodland coverage (e.g. parks, gardens).

Discussion

Landscape Information Content on Different Maps

Landscape information classes were very similar on different maps, but variability was evident, especially in the thematic consistency of some classes (e.g. soils, woodlands, meadows), and the quality of some maps (1880, 1881, 1920). This suggests that there are certain landscape characteristics which these types of maps generally describe: landforms with associated resources (forests, water, potential land for agriculture) and land use with human-made constructions (houses, roads).

Further, the initial purpose and scale of the mapping affects the level of generalization of feature classes and seems to affect different feature classes differently. For example, the woodland and meadow classes are much more sensitive to scale and generalization effects than is the arable land class. This leads to inconsistent spatial and thematic representation of feature classes between maps, and creates problems in the relative (i.e. between-maps) adjustment of the map classes (see, for example, Weir, 1997). Systematic assessment also indicated that some landscape feature classes were copied from one map to another (see also Dickinson, 1979; Rubin, 1990). For example, topographic information on the 1892 map seems to be the same as on the 1846 map, but cartographically simplified.

Developments in both surveying techniques (from plane-table measurements to remote sensing) and map production (from hand-drawn to computer-assisted) are reflected in the thematic content of landscape information on old maps. On plane-table maps, meadows were primarily mapped as land-use patches, and on remote-sensing maps, meadows were mainly a land-cover class. The latter referred as much to grazed meadows as to the variety of grass-covered open landscapes in different stages of succession. Thus, it can be concluded that maps based on aerial photography mimic the physical patterning in the landscape, but they contain less information on site-specific land properties than the older generation of maps. However, site-specific land-use information on old maps may be expressed through texts. The expression of topography in our

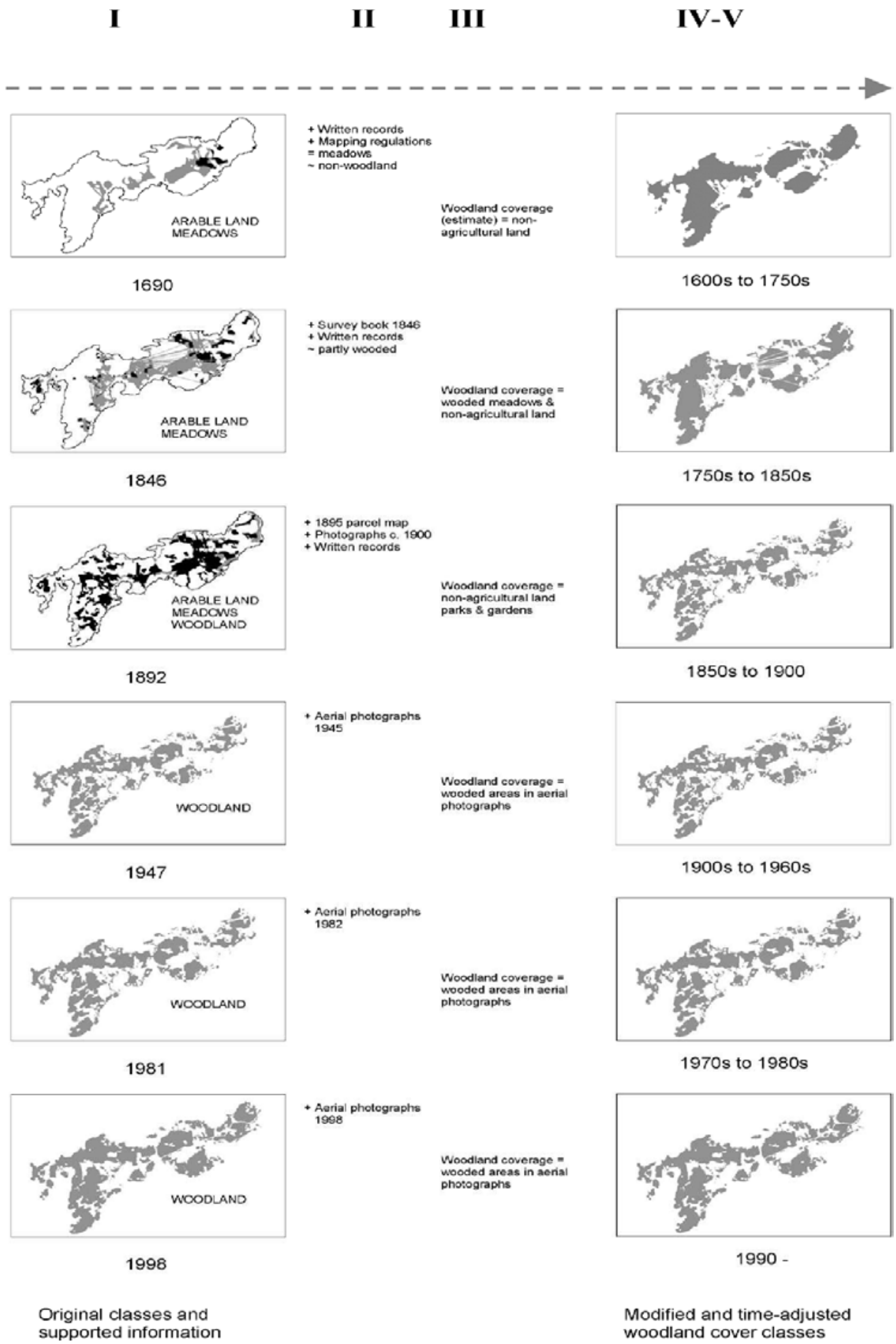


Figure 7. Reconstruction of the woodland coverage from a sequence of maps. For each map, a chain of information transfer from source map to woodland coverage map is presented. The transformation consisted of: (I) evaluating landscape information; (II) using supportive data for woodland cover interpretation; (III) adjusting and planning transformation; (IV) digitizing woodland cover; and (V) estimating the temporal continuity of maps.

sequence of maps showed distinctive development in cartographic representation due to surveying techniques (see also Bygden, 1919; Wennström, 1990). On the earliest maps, representation of topography was by iconic map signs. Contours were introduced into Finnish maps relatively early (Niemelä, 1984) and were used on the 19th-century Russian topographic maps.

To summarize, three major types of map-feature classes can be identified. First, there are feature classes prone to single-level and consistent representations (e.g. arable land). These classes tend to have a fairly good spatial and thematic consistency in their representation, and the scale and the purpose of the mapping have influenced them less. Second, there are diverse landscape feature classes which maps tend to describe very differently. Often, their spatial representation gives the appearance of consistency (e.g. crisp boundaries) but, in practice, it might be difficult to tell the definition and content of these classes (Keates, 1996, p. 257). These are sensitive to mapping purpose, and to scale and cartographic generalization techniques. The third landscape feature class type is inconsistent in both thematic and spatial context and often lacks temporal continuity. In other words, these classes are often map specific, and it is difficult to tell which areas/sites they concern, and how they have been defined. Often, these inconsistencies are related to the problematic nature of the classes (e.g. gradually changing boundaries between land-cover classes) or their irrelevance in the mapping effort. Typical examples in this study were shoreline, bogs, reed areas, gardens, soils, and even topography on some maps.

Digital Transformation of Old Maps and Different Landscape Feature Classes

Based on the results of this study, it seems appropriate to distinguish three phases in the process of converting information from old maps into landscape representations in a GIS. First, both absolute and relative landscape information content and reliability on different maps should be carefully evaluated. Second, selective transformation of landscape information needs to be carried out by careful consideration of the consistency of each landscape information class through the sequence of maps in use. This information should also be optimized and calibrated in relation to other data sources, such as remotely sensed images and supplementary information. Third, the information content of each set of data, including those extracted from old printed maps, should be carefully adjusted to the shared map reference system in the digital realm.

In this study, image rectification by re-sampling was a necessity in the attempt to adjust old maps to a reference co-ordinate system, as there was no reference information on the old maps. Since the geometry of these maps was unknown, we tested the suitability of four rectification methods for the spatial adjustment of these maps. Linear polynomial rectification brought the worst results, as it assumes a consistency in the accuracy of the survey that is seldom the case on very old maps. Using either higher-order polynomials or triangulation, better fits can be achieved between old maps and the digital reference data. Of these, triangulation appears particularly promising for those cases where varying levels of spatial inaccuracy exist within the same map sheet.

There are, however, many issues which complicate this process. These include finding a suitable set of GCPs, identifying geometric inconsistencies on the map from the errors induced by the control-point selection, and assessing residuals and spatial fit of the rectification (see also Mather, 1995). In the case of very old maps (e.g. the 1690 map) there is not much choice in the GCP selection. It may be difficult to find suitable GCPs (e.g. to minimize the RMS and maintain spatial coverage), and the use of features of the physical environment as GCPs has a much higher likelihood of inducing measurement errors. This was also the case in this study, where some control points had higher errors than others (also evident in check points; see Figure 5 and Table 7). Leaving these out, however, would have left some parts of the interest area without enough GCPs.

In the case of polynomial methods, each point affects the overall residual, and thus even one point being in a wrong location can worsen the spatial fit of the rectification. Thus, polynomial methods would require careful selection and testing of GCP sets to find the one with the lowest residuals and good coverage of points. In the case of triangulation, the number and coverage of the GCPs is critical, as it affects the size of the local transformation (the triangle) and can therefore result in severe spatial inconsistencies. As shown in the test on the 1690 map, reducing the number of points used in triangulation induced high and unpredictable spatial inconsistencies.

Rectification tests imply that spatial inconsistencies on old maps are difficult to remove (see also Weir, 1997), and are thus sensitive to shifts in the landscape information database. The nature of landscape information on old maps is often both spatially and thematically vague, and cannot be that explicitly located and classified (e.g. some descriptive texts). Systematic assessment of landscape information on a sequence of maps studied can, however, help enormously when estimating both the absolute and relative information content and quality on different maps, and indirectly contribute to decisions about their digital cartographic representation (see also Faiz & Boursier, 1996; Kalliola, 2000).

The question of how GISs should be constructed in the case of time-related landscape analysis has, to a large extent, remained unanswered. Despite the fact that time problems have been addressed by many scientists (see, for example, Chrisman, 1998; Langran, 1993; Wachowicz, 1999) and dynamic approaches have been suggested (see, for example, Frank, 1998), the contemporary GISs are criticized as being too space oriented. Time is treated simply as a framework within which differences between several time slices are compared, and not a phenomenon as such (see, for example, Wachowich, 1999, p. 10). Based on the results from this study and our previous studies (see, for example, Vuorela, 2000; Vuorela & Toivonen, in press), it is difficult to do land-cover-change observations using multiple data sets and GISs in any other way. It is, however, essential to use supplementary data and additional information to assess the quality of the time slices used. Moreover, it is essential to extract each piece of landscape data carefully from its best possible source. A sequence of maps always contains considerable redundant material, which helps to assess the quality of information between different maps. Moreover, the excess of available data sources provides the researcher an opportunity to select the best source for any individual information. As an example, the majority of features concerning the physical environment can be extracted most reliably from the most modern sources, while old maps remain unique sources for information concerning past land uses.

Maps are important but challenging data sources for landscape researchers due to the diverse nature of the information contained on them. Maps can be used in a broad spectrum of landscape research, from ecological to political, social and cultural (Burnett & Kalliola, 2000; Sporrong, 1990). However, each research question will demand information extraction from a specific perspective. Interpretation and possible use of maps in a GIS thus requires systematic assessment of the content and quality of landscape information, adjusted to the problem to be solved. This is essential in scaling the relationship between representations on a map to the map's future uses in a GIS. Although much of the recent development in landscape ecology has been dedicated to improved landscape observation and analysis tools (i.e. remote sensing, GISs), historic maps still maintain their uniqueness as the most immediate documents of past landscape patterns. Thus, it is worthwhile to emphasize the need to integrate information extracted from old maps into modern data processing environments and at the same time stress the importance of systematic and well-documented work methods in any such effort.

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Appendix

Table A1. Supportive information used in interpreting changes within different map classes (see Figure 6). For details of land-use information see Vuorela (2000)

Time	Map feature class	Data type	Observed changes
ca. 1750s	Woodland cover Arable land Open meadows Buildings Paths, roads	• literature	• several crofts built around the island • spread of arable land, meadows and paths • clearing of some woodland into arable land and meadows
1850–1930s	Woodland cover Gardens Parkland Arable land Open meadows Buildings Paths, roads Fences	• literature • photographs • newspapers • unpublished archive record	• island divided into 46 parcels • parcels rented with several rent contracts (20–50-year periods) • approx. 100 villas built around the island • increase in cultivation, decrease in meadows • clearing woodland for construction • establishing parks and gardens • building roads and paths • removing cattle from the woodlands *ca.* 1900
1950s–1960s	Woodland cover Parkland Arable land Open meadows Buildings Fences	• aerial photos 1945, 1962 • literature • photographs • unpublished archive record	• recreation planning, new buildings and summer houses • parkland from woodlands to open sites • decrease in arable land and cattle, increase in unmanaged grasslands (abandoned arable)
1970s–2000	Woodland cover Parkland Arable land Paths, roads Fences	• aerial photos 1945, 1962 • literature • unpublished archive record	• woodland plantations and sowing • conservation of woodlands • decrease in arable land • new parks established on meadows and arable land • bicycle roads, nature trails