DISSERTATIONES GEOGRAPHICAE UNIVERSITATIS TARTUENSIS

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THE APPLICABILITY OF GIS DATA IN DETECTING AND REPRESENTING CHANGES IN LANDSCAPE: THREE CASE STUDIES IN ESTONIA

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CONTENTS

LIST OF PUBLICATIONS

This thesis is based on the following papers, which are included at the end of the thesis:

I. Peterson, U., **Aunap, R.** (1998) Changes in Agricultural Land Use in Estonia in the Nineties Detected with Multitemporal Landsat Imagery. *Landscape and Urban Planning*, No. 41, pp. 193–201

II. Kont, A., Jaagus, J., **Aunap, R.** (2003) Climate change scenarios and the effect of sea level rise for Estonia. *Global and Planetary Change*, 36, pp. 1–15

III. **Aunap, R.**, Uuemaa, E., Roosaare, J., Mander, Ü. (2006) Spatial correlograms and landscape metrics as indicators of land use changes. In: Martin-Durque, J. F., Brebbia, C. A., Emmanouloudis, D. E., Mander, Ü. (Eds.) Geo-Environment and Landscape Evolution II. Evolution, Monitoring, Simulation, Management and Remediation of the Geological Environment and Landscape. WIT Transactions on Ecology and the Environment, Vol. 89, pp. 305–315

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I. Fully responsible for the GIS modelling and data analysis

II. Partly responsible for data analysis and manuscript preparation, fully responsible for the cartographic support of the analysis

III. Fully responsible for manuscript preparation and data analysis

1. INTRODUCTION

The landscape approach is widely recognised today as a powerful method of multidisciplinary environmental research (Lioubimtseva and Defourny 1999, Bastian 2001, Antrop 2006a). The investigation of land use changes is the main area in landscape research (Forman and Gordon 1986, Zonneveld 1995), being one of the key issues in global environmental change (Alcamo *et al.* 1998).

In spite of its small territory, Estonia has quite a mosaic of landscapes, which are characterized by relatively high biodiversity (Arold 1993, Sepp 1999). This can be explained by the country's location in a transitional belt in terms of geology, climatology and culture (BIODIVERSITY 1999). Thus Estonian landscapes exist in a volatile balance controlled by many formative forces and open to different types of changes. This makes landscapes here attractive to any kind of investigation, especially those linked with change analysis. Estonian geographers have a long tradition of investigating landscape regions and the dynamic relationships of small landscape units (Roosaare 1994). The different directions of landscape studies that exist in Estonia have been influenced by German, Russian, Scandinavian and Anglo-American schools of landscape study (Peil *et al.* 2004).

Applied geography, in the form of maps and spatial information, has been applied in the service of discovery, planning, cooperation, and conflict for at least the past 3000 years (Bolstad 2006). The computer-based **geographic information system** (GIS) is a new tool in this venerable chain. GIS has been inducted enthusiastically by environmental research, including landscape change detection, and found ever broader implementation. Sometimes the enthusiasm involved with GIS has caused attention to shift from essential analysis to inevitable technical finesses, since GIS has specific prerequisites and individualities dealing with spatial information.

Although there are many principles that may be used to model a geographic phenomenon together with different GIS analysis strategies, it is quite common that the need for holistic understanding of the world is forgotten starting from the conceptualization of the reality model and followed by the selection of methods appropriate for particular data operations. Therefore it is not rare that landscape studies produce artefacts throughout GIS usage (Burrough *et al.* 2000). Also, in studying the landscape changes it is important how adequately the landscape is represented in the GIS model. Since the world is perceived as a set of material entities possessing highly correlated structures, a **representation** of geographic phenomena becomes a fundamental issue in developing a GIS application (Feng *et al.* 1999). Landscape is often comprehended through the land cover/ land use. There is no single ideal classification of land use and land cover, and it is unlikely that one could ever be developed (Anderson *et al.* 1976). Different perspectives in the classification process exist, and the process itself tends to be subjective, even when an objective numerical approach is used. There is, in fact, no logical reason to expect that one detailed inventory should be adequate for more than a short time, since land use and land cover patterns change. Each classification is made to suit the needs of the user, and few users will be satisfied with an inventory that does not meet most of their needs (*ibid.*).

Use of GIS in landscape studies is thus pretty much about how well the spatial data conceptually fit the rules defined in digital data models. In cartography, the question of the proper form of the cartographic representation of different spatial phenomena has been discussed for centuries, and the general conclusion is that it (the presentation model) is primarily determined by the interests of the map (MacEachren 1995). It is obvious that for geoinformation science we may assume the same basic principle starting from the aim that the goals of a study need to be determined before choosing the spatial data and methods of study.

The problem may also be approached from a pragmatic angle – as modelling provides approximate results anyway, we have the freedom to ask on what to concentrate our research efforts. Is it more reasonable to add data, enhance data quality or change study methods?

Cartography has a similar situation related to map readibility. It is possible to add more and more data (information) to a map, but the efficiency of the map ceases to increase at some point. The predominant understanding in cartography is that the data does not necessarily need to be correct in each and every detail but the **meaning** of the representation must be adequate (Wood 1992). In other words, a balance must be found between a sufficiently accurate result and the complexity of the analysis.

Thus in this study we have not endlessly tried to find the most precise or universal solution, but instead followed the essential approach in cartography, i.e. finding the most adequate solution for every case, as every study is fundamentally unique.

The **main objective** of this study is to highlight the general principles of the usability of spatial data to determine landscape changes. Although changes are addressed throughout the whole thesis, more important for the general topic are the solutions found for the detection of changes. Here attention is paid to how to detect the changes using GIS, and which technical and logical constructions are needed to do this. Discussion is based on three different applications of GIS, demonstrating the options for choosing the spatial data in relation to change detection techniques and the general conceptual approach. More particularly, the following questions are addressed in the study:

a) to determine the common application principles used in GIS to study and analyse landscape changes,
b) to ascertain to what extent different structures of spatial data are useful in analysing landscape changes, and to what extent decisions are influenced by the choice of modelling ideology,

c) to study specific possibilities for the detection of landscape changes as seen in certain geoinformatic solutions addressing Estonian landscapes,
d) to ascertain how principles useful in cartography can be applied in GIS analysis.

The Paper I (Peterson and Aunap 1998) addresses the question of linear decision about the suitability of the pixel to belong to a certain class (remote sensing application) and detection of the changes in the class. The Paper II (Kont *et al.* 2003) approaches the methods to detect locational changes of a linear system as seen on a coastline due to sea level rise. The approach includes neighbourhood operations and non-spatial modelling techniques as an important cofactor. The Paper III (Aunap *et al.* 2006) deals with the detection of landscape changes using synthesis statistics (autocorrelation).

2. THEORETICAL FRAMEWORK

2.1. Landscape

In common language, and even as the scientific term, the word ‘landscape’ is particularly complicated and diversely used (Richling 1983, Slak and Lee 2003, Antrop 2005, Alumäe 2006). The composition and dimensions of landscape are vague.

In geosciences like physical geography, geomorphology, geology etc., the landscape is determined mostly on the basis of the distinct association of **landforms** that can be seen in a single view (GLOS 2005, Arold 2005). Although there exist views on landscape that do not integrate humans as an integral part of the landscape (described by Eilart 1976, Jobin *et al.* 2003), the overwhelming majority of standpoints consider the landscape, in one or another way, to be a comprehensive complex of natural (physical, chemical, biological) and anthropogenic factors (Whittow 1984, Isachenko 1991, Bastian 2001, Pärn and Mander 2007). Some researchers even claim that there are almost no landscapes left without anthropogenic influence (Jones 1991). Especially varied and diverse usage can be encountered in connection with cultural geography where **holistic** and multidisciplinary concepts of landscape dominate (Naveh 2001, Bastian 2001, Palang and Fry 2003, Cosgrove 2003, Sooväli 2004, Antrop 2006b) to mention a few.

From the viewpoint of GIS, the variety of concepts brings a challenge to landscape modelling. Conceptual model, data structure and relationships must be carefully considered prior to the creation of the data model of a landscape (Clarke 1990, Chang 2003). Model behaviour and assumptions should be explicit. This is necessary to have confidence that the results of the simulation experiments derive from the behaviour of the conceptual model and the landscape state, and not from implementation artefacts (Fall and Fall 2001). Landscape, however, is not only a simple sum of individual geofactors, but is rather a combination that forms a geographical complex (Bastian 2001, Li *et al.* 2005). This gives to the description of a phenomenon in a model formalism the meaning of great consequence as the selected ideological starting point determines the possibilities for analysis and precision in GIS.

Usually GIS is using universal topographic inventory, the components of which relate to each other like neutral data layers. Many different methods have been used to make the landscape model describe actual relations between landscape components. One common solution is a depiction of different indicators describing attributes of landscape elements (Bastian and Lütz 2006). There are a number of different GIS-based modelling approaches attempting to involve other inherent landscape properties such as landscape structures (Vogt *et al.* 2007), complexity (Papadimitriou 2002), continuous (or fuzzy) mapping

(Burrough *et al.* 2000, Rocchini and Ricotta 2007), landscape functions (Syrbe *et al.* 2007), dimensionality and hierarchy (Purtauf *et al.* 2005) etc.

Two general viewpoints of landscape are adopted in this thesis. First, the holistic theoretical background makes it possible to deal with any kind of human impact on landscapes, as well as with implicit landscape attributes or values. Also, many formal directives are today formulated on the basis of the holistic concept of landscape (Jensen 2005, Antrop 2006b). Second, technically only the basic and simplified concept of landscape as "a mosaic of landforms, vegetation types and land uses" (Urban *et al.* 1987) is needed, since landscape will be perceived here principally by its element's geometry and class or attribute values. This definition of landscape is appropriate for basic GIS measurements dealing with structural landscape pattern in terms of the relative distances of different points (Hudson and Fowler 1966).

As a synthesis of these two viewpoints, **land use/ land cover** is used. Land use is one of the main factors through which man influences the environment (Lausch and Herzog 2002). On the other hand, land use/ land cover data in GIS is ordinarily a solution to represent landscape structure assumedly mirroring the processes which have been going on in a landscape. This perception has even become a central paradigm in modern landscape ecology (Wrbka *et al.* 2004), and in this way copying the idea of many practical land use/ land cover oriented approaches (Miklós 1989, Turner 1990, Lausch and Herzog 2002, Bender *et al.* 2005, Carranza *et al.* 2007 etc).

2.1.1. Landscape changes

A large number of papers can be found dealing with the issues of landscape changes. Landscape changes are also a recurring topic of international scientific conferences and workshops (e.g. Sepp and Bastian 2007).

Change is an essential character of landscapes (Antrop 2003, Bürgi *et al.* 2004, Carranza *et al.* 2007). Thus the extensive interest in investigating landscape changes is natural and serves many practical and planning objectives (Antrop 2005). A wide range of disciplines are involved in landscape change research, bringing with them a diverse range of approaches and terminological variety. This has led some scholars to seek a unifying intellectual framework for landscape change research as a distinct discipline (Musacchio *et al.* 2005).

One of the well-known conceptual frameworks explaining changes in landscape is that of **driving forces** (Palang 1998, Bürgi at al. 2004, Mander *et al.* 2005). Knowledge of driving forces of change and processes on landscapes enables us to reconstruct the past, monitor present landscape processes and predict future developments. However, distinction of driving forces is not a simple task. Every landscape is inherently a geo-complex, in which a change in one component (land cover, vegetation or water regime, etc.) affects the whole complex (Roose *et al.* 2007).

Four **aspects** of change detection are important in monitoring natural resources (Macleod and Congalton 1998):
(1) detecting that changes have occurred,
(2) identifying the nature of the change,
(3) measuring the areal extent of the change, and
(4) assessing the spatial pattern of the change.

All of these aspects can be implemented by GIS if one is able to translate the change of phenomenon either into the change of geometry or attributes in a data model.

Without time, no changes are possible. This means that in addition to spatial factors, **time** or temporal behaviour should also be investigated when analyzing change or movements (Imfeld 2000, Hietel *et al.* 2007).

2.2. Modelling of landscape in GIS

2.2.1. Modelling of landscape changes

Although defined as "simplified representation of a phenomenon or system" (Chang 2003, Batty 2001), there exist different meanings and classification habits for the term "model". In GIS and digital cartography, model may ordinarily denote the following (Clarke 1990, Laurini and Thompson 1994, Burrough and McDonnell 1998, Chang 2003):
(i) a view of reality, phenomenon perception arrangement, its classification and definition procedure (e.g. reality model, conceptual model, spatial data model, presentation model);
(ii) data gathered and specifically arranged to describe the phenomenon (cf. DEM – Digital Elevation Model);
(iii) a graphical model or a map in general as a compilation of map features (a frequent contemporary definition of maps, as can be found in numerous textbooks)
(iv) an organisation of geographically referenced data in GIS, commonly referenced as spatially explicit model;
(v) data structures or geometries (e.g. raster, vector, topological structure, graph)
(vi) arrangement and principles of spatial analyses (e.g. map overlay modelling, network modelling, etc.);
(vii) accepted axioms and rules for handling the data, set of standalone mathematical formulae or script in programming language.

All modelling occasions may be essential depending on problems solved in GIS analysis. It is difficult to classify many models used by GIS users. Only some broad categories are worth mentioning. Chang (2003) distinguishes **spatially explicit models** by their temporal resolution (static or dynamic), spatial resolution (zones or grids) and various modelling approaches (descriptive or prescriptive, deterministic or stochastic, deductive or inductive).

Philosophers have disputed the meaning of space and time since at least the times of Aristotle, who claimed that the change is essentially related to time (Coope 2001). Today change modelers also emphasize that both **space** and **time** should be observed in change analysis (Imfeld 2000, Rogowski and Goyne 2002, Hietel *et al.* 2007).

However, from the standpoint of GIS modelling, it is not as important to conceptualize the time but to perceive the effects of time in terms of changes associated with objects in space (Rogowski and Goyne 2002). Following that, the first ring of problems may arise as to **what information is available** indicating landscape change. At least two datasets from different dates or rules describing the dynamics of investigated change are needed. The first occasion prevails in GIS modelling when one uses remote sensing, aerial photography, land registers or other map-derived layers (Dunn *et al.* 1991). On the other hand, there are temporal data such as palaeobotanical (e.g. fossil pollen) or stratigraphical records and fire-scar histories in landscape change investigation (see Allen *et al.* 1998). In contrast, 3D data collection and processing is also depicted in areas like palaeogeographic shoreline reconstructions and archaeology as well as in modelling nutrient cycles (such as Laas and Kull 2003). Both of the latter-mentioned data sources are usually collected individually and thereby demand special handling before implemented in GIS-analysis.

Apart from the acquisition of data for change detection, one faces the need to **choose relevant indicators** for GIS application. Landscape complexity can be viewed as a result of individual dynamics of different landscape features and functions, having a mutual influence on other system components. It is not always possible to decide what features are relevant: moreover – the value of a feature may depend on which other features are also selected in the investigation (Remm 2004). Then, changes in the environment other than those under investigation may well have occurred between the two time momentums (Campbell 2001). Thus the assessment of indicative features and attributes must precede the real application in order to prevent possible artefacts. It has repeatedly been reported that differences between formal changes between two datasets using map compilation approaches are often the result of differences in classification approaches or mapping technologies rather than actual changes in structure and/or land cover (Bender *et al.* 2005, Thackway *et al.* 2007). Uncertainties and errors are intrinsic to spatial data (Burrough and McDonnell 1998).

Among the other conceptual issues, the **scale of investigation** is one of the most essential. A number of studies have argued that attempting to model landscape change at an inappropriate scale would be futile (e.g. Turner *et al.* 1989, Openshaw 1996, Rogowski and Goyne 2002, Ernoult *et al.* 2003, Mander *et al.* 2005). The scale should be viewed not merely as a dimension of dataset and its resolution (grain), but also in connection with data aggregation. Traditional statistical methods are very sensitive to data aggregation methods, a fact that was recognized by quantitative geographers long ago (Wrigley *et al.* 1996, Uuemaa *et al.* 2005). The scale effect and zoning effect can be implemented as part of cartographic generalization, which in turn can reach the creation of a conceptual reality model and solve conflicts of data coexistence (Slocum *et al.* 2005).

Scaling issues in GIS can even be reduced to the elementary GIS practice to describe spatial data with fixed geometrical primitives and their combination, forming more complicated structures and hierarchies. In Paper I, straightforward cell-by-cell analysis was utilized. This denotes local operation that can be carried out at a specified point or entity without considering the influence of the vicinity. In Paper II, dimensionality was formally raised on the level of linear features, since calculations were made along a narrow corridor (i.e. coastlines). The actual spatial modelling, however, was carried out from point spots, but also involves terrain as a hypsometric field. Thus terrain height interpolation with neighbouring statistics was the key technique of study. Paper III addressed the landscape indices that cannot be perceived merely as areal phenomena and described as a distribution of certain attributes in GIS. We used the Moran I spatial autocorrelation index in order to give complex estimates of spatial homogeneity, not to specific landscape elements but to a whole landscape complex.

To realize what happens to the **landscape as a whole**, employment of a higher aggregation level of landscape change information is suggested (Schneeberger *et al.* 2007). This can mean, for example, that detailed analytical process-oriented models will be replaced by more generalized empirical ones, or more general feature classes will be involved in the reality model. For example, soil erosion on landscape units is explained by geomorphological features, not so much by soil parameters such as soil aggregation (Cotler and Ortega-Larrocea 2006).

It has been claimed that complex dynamics can be projected based on structurally simple, parsimonious approaches (Bolliger *et al.* 2005). Such generic modelling approaches simulate the landscape top-down based on generic parameters that do not require formulation of detailed ecological processes. Paper I demonstrated how arable land feature class alone was separated out as the indicator for changes that had taken place in land use.

Similar principles can be observed in seeking the **indirect indicators** for landscape condition. As discussed in section 2.1., the concept of landscape itself is rather vague, which in turn gives reason to represent landscape on the basis of its formal geometry. Landscape metrics actually quantify landscape structure and thus yield information that complements land use statistics in landscape monitoring (Herzog and Lausch 2001). Several studies have demonstrated that structural landscape indicators have successfully been used to indicate landscape functional values (Riitters *et al.* 1995, Tinker *et al.* 1998, Jones *et al.* 2001, Botequilha Leitão and Ahern 2002, Neel *et al.* 2004, Uuemaa *et al.* 2005). Thus it is natural that one of the most rapidly growing applications in recent years is the derivation of numerous landscape pattern metrics for the assessment of land cover condition, landscape structure and landscape change dynamics (Palang *et al.* 1998, Saura and Castro 2007, Lausch and Herzog 2002, Wrbka *et al.* 2004, Drielsma *et al.* 2007). Widely used means to describe landscape texture metrics can be calculated with the help of FRAGSTATS (McGarigal and Marks 1995). Paper III studied the use of landscape indices in landscape change detection on the base of Moran's I statistics.

One of the general challenges of landscape modelling in GIS is to translate system complexity into **model formalism** (Fall and Fall 2001, Bolliger *et al.* 2005). Although some researchers have been suspicious of the ability of GIS to express high level geographic concepts (Rhind 1988), plenty of strategies, data structures, techniques and modelling tools have been described (Laurini and Thompson 1994, Burrough and McDonnell 1998, Carr 2002, Chang 2003, Bolstad 2006 etc) to work sufficiently well in practice.

Two general ways to represent geographic phenomena in GIS modelling are used: (a) by means of **entities** that are described by their attributes or properties, and (b) by the **field** of an attribute of interest (Burrough and McDonnell 1998). This is commonly implemented as vector and raster graphics respectively, but it is also not rare to manage pixels as entities or vector objects as elements of an attribute field. A raster-based model is preferred if the spatial phenomenon to be modelled varies continuously over space. It is also preferred if satellite images and DEMs constitute a major portion of the input data, or if the modelling involves intense and complex computations (Chang 2003).

The coastline and interpolated horizontals in Paper II and ten land use classes in Paper III were implemented as geometrical entities. Arable land in Paper I was also treated as an entity but formed conceptually by a set of pixels carrying same attribute (class) value. The principles of attribute fields were presented by satellite images as remotely sensed data in Paper I, as well as by the interpolation of terrain hypsometry in Paper II and autocorrelation properties in Paper III.

2.2.2. Techniques of Change Modelling

Traditionally, landscape classification relies upon the intuitive interpretation of different habitat patterns in the field or with the help of cartographic materials.

Two common approaches in environmental modelling can be put forward (Pullar 2004): (i) to use a geographic information system (GIS), or (ii) to use a general purpose dynamic modelling language such as STELLA or MATLAB. GIS is designed to model spatial relationships, but lacks dynamic analysis capability (Burrough 1998). Non-spatial models, on the other hand, maintain the dynamics inherently because of the nature of processing languages. These models are the main tool for creating dynamic simulations, but fail to simulate geographically-distributed systems (Miller *et al.* 2005).

At the same time, this platform does not usually include any spatial modelling capability. As GIS users are not necessarily programmers, and non-spatial models are basically designed to solve specific single input-output subroutines, these two approaches are typically solved separately. GIS users tend to use static and descriptive change models, and when the prescriptive simulation of changes is really the intention, special scripts, macros or standalone programs are put forward. Synthesis with GIS is usually achieved by database connection, while input for dynamics is derived from GIS, and results are converted back to GIS, as described in the glacier dynamics application by Paul *et al.* (2007). Non-spatial models (climate model MAGICC and the Bruun Rule for the calculation of potential erosion) were also used in Paper II to obtain input values for spatial manipulations. What is characteristic – is that non-spatial and spatial operations were performed separately.

In GIS, however, static models dominate. Dynamics, in this case, are modelled mainly indirectly by means of map algebra and/or spatial queries (Laurini and Thompson 1994). The most popular way to analyze the temporal data is to plot the data on a separate 2D map for each observation period (Imfeld 2000), which is also called the technique of **repeated snapshots**.

If two categorical coverages of the same region are available for two different times, an **overlay** can detect the differences (Chrisman 1997). If the coverages used identical categories, the analysis is particularly easy – with the technique of **image differencing**, clear values can be given to the category transition.

Categorical maps are not always the primary source of spatial data in ecological mapping. To achieve solid fact of change, the first step in GIS applications is frequently the **classification** of initial data. Most commonly, remotely sensed images are classified or topographic maps are interpreted (Atkinson *et al.* 1997). A large number of works in environmental modelling, like Alonso-Pérez *et al.* (2003), Bender *et al.* (2005), Qi and Luo (2006) and others use this categorization and post-classification comparison method of change detection. Paper I and Paper III followed the same principle with arable land and land use classification respectively.

The change detection using post-classification comparison method is, however, susceptible to every error in the individual date classification map (Klemas 2001). Some researchers emphasize that validation methods should be involved in change detection (Pontius *et al.* 2004). This is possible with **prediction maps** and change simulation because the three possible two-map comparisons can be used to characterize the dynamics of the landscape, the behaviour of the model and the accuracy of the prediction (Pontius *et al.* 2007). Different map comparison statistics such as most popular Kappa statistic can then be used to evaluate not only the rate of change, but also the similarity between observed and predicted results (Eastman 2003, Visser and Nijs 2006).

Various methods of prediction mapping are described, starting with linear extrapolation and finishing with agent-based modelling (Pontius *et al.* 2007, Remm 2004). Palo *et al.* (2005), for example, used simple overlay masking, Aaviksoo (1993) and López *et al.* (2001) implemented Markov chains, and Thienen *et al.* (2007) fractal distribution to predict landscape changes.

2.2.3. Local and neighbourhood operations

Map overlay combines the geometries and attributes of two feature maps to create the output. If the zonal borders in the involved spatial data sets coincide, the description of change can be performed by just comparing the attribute values of respective zones. The raster operation can take advantage of the fixed cell locations, whereas the vector operations must deal with the intersection of polygon boundaries (Chang 2003). Cell-by-cell operations are called **local operations** and are the main method with remotely sensed data.

With local operations, change detection can be reduced to a map comparison as discussed earlier. However, the lack of change in the category does not necessarily indicate an absence of differences in reality. If the interval or ratio data are used, on the contrary, the rate of variation to be qualified as change is unclear. These common uncertainty problems can be solved with help of fuzzy sets, first introduced by L. Zadeh (Rocchini and Ricotta 2007). On the other hand, differences in cell values may originated not from substantial changes in landscape but, based for example, from image rectification errors, atmospheric and illumination effects, striping, noise, and image processing properties like resampling effects (Lillesand and Kiefer 1994). When changes on lineatures (like the case in Paper II) are investigated, the role of rectification, cast shadow and so-called mixed pixels should be carefully considered. Uncertainty issues have even more importance if local operations with multiple grids will define temporal state of the landscape.

Bringing the holistic landscape concept into focus again, it is clearly inadequate to implement **landscape change** merely in particular points or cells. Many statistical modelling approaches are based on the assumption that the distribution of landscape elements is random and, therefore, each observation is independent. This assumption violates one of the basic tenets of geography – the direct relationship between distance and similarity (Tobler's ‘first law of Geography’), as well as basic ecological theory (Miller *et al.* 2007).

Another theoretical reason to consider local operations to be limited in treatment is the fact that the assumption of spatial and temporal **homogeneity** is not always correct. In reality it is known that landscape processes are frequently pulsatory; coastline reconstructions, for instance, are possible largely because of sea transgression stages witnessed by coastal landforms (Rosentau 2006). Also, McDonald and Urban (2006) argue that many of the rules that govern land cover and land use change vary from place to place, and therefore modelling rules should take into account the actual heterogeneity of landscape. Chrisman (1997) describes the **interaction rules** in neighbourhood analysis, which yield different results in pixel value in the case of certain combinations of categories. The Bruun Rule exploited in Paper II was also made dependant on the coast type and surrounding topography. In environmental modelling it has repeatedly been shown that the value of a focal cell is affected by the neighbouring cells (Oja *et al.* 2005).

All of this encourages one to involve the values of neighbouring cells into the modelling of focal cell dynamics. In geoinformatics this is known as **neighbourhood operations** (Tomlin 1990, Chang 2003). The principle of neighbourhood by itself leads to the continuous field reflecting complexity, which is intrinsic to the holistic landscape conception.

Many ideas and types of neighbourhood operations can be found with raster data. The most common of these, among others, are (Burrough and McDonnell 1998): buffering, spatial filtering, interpolation and the derivation of surface topology.

From this list, interpolation and filtering can be considered to be most widespread. In general, even terrain modelling, especially the calculation of DEM, is based on **interpolation**. At the same time, the determination of height values by interpolation can be problematical if an unpropitious data source is used. The most controversial hypsometric element for interpolation purposes is topographic contour data (Imhof 1982, Dakowicz and Gold 2002). This was a remarkable part of the considerations in the assessment of coastline changes in Paper II.

In Paper III, on the other hand, the neighbourhood approach was implemented through landscape metrics (see section 2.2.1.). From the large number of different indices, a classical estimator of spatial dependence, Moran’s I (1948), was chosen, and this has been proposed as a spatial analogy of autocorrelation used in time series analysis (Taylor 1977). The IDRISI software was applied, which calculates Moran’s I according to the following equation (1)

$$I = n\frac{\sum_{i=1}^{n}\sum_{j=i}^{n} w_{ij}(y_i - \mu)(y_j - \mu)}{\left(\sum_{i=1}^{n}(y_i - \mu)^2\right)\left(\sum_{i\neq j}\sum_{i\neq j} w_{ij}\right)} \qquad (1)$$

where

n – number of values to be taken into account (pixels, in the case of a raster image);

w – spatial weights: 1 in the directions up/down/left/right, 0.70711 (the square root of 2) as the weight of the diagonal neighbouring pixels;

$y_{i/j}$ – value of pixel i resp. j;

μ – mean of values y.

If Moran's I is used on discrete land use data, there arises the problem of how to take into quantitative consideration the qualitative differences in neighbouring land use patches. Read and Lam (2002), for example, used unclassified remote sensing data to calculate Moran's I and landscape metrics for detecting land cover changes in remote sensing data, and found that Moran's I is good for the distinguishing of differing degrees of spatial complexity represented by land cover types.

2.3. Representation of changes

GIS textbooks always highlight the methods of statistical analysis like univariate or multivariate analysis and other „proper" operations of informatics. Graphical operations are frequently presented as supplementary or inevitable just because the data are characterized by spatial properties, even in works (e.g. Carr 2002) where data visualization is fetched up.

At the same time, a variety of problem solving and data exploration tasks are focused on **cartographic representations** supporting both visual thinking and visual communication (DiBiase 1990, Cauvin 2002). Many GIS analyses are initiated from the pure intention to achieve a certain form of visual presentation. The ambition of educational atlases is often to demonstrate the variety of possible cartographic visualizations (ATLAS 2004). Animations and 3D-modelling are principally carried out for representation purposes. Paul *et al.* (2007), for example, explicitly regard the objectives of their study to be the visualization of future glacier change.

Therefore formal links between visual analysis and statistical analysis, and between hypothesis generation and hypothesis checking, need to be established. Such links have the potential to result in visualization methods that would produce added value in scientific research, thus moving visualization away from an operation that merely gives rise to wonder and/or uncritical speculation, towards a role that achieves new insights and supports critical inquiry (Fairbairn et al. 2001).

One of the greatest challenges for cartography with static maps is the representation of any dynamics. The classical solution in this issue is to create a series of maps representing critical snapshots (see section 2.2.2.). Also, the superimposition of multitemporal data and the tracking of temporal events are common representations on a single map. Much more sophisticated methods are based on cartographic generalization and resymbolization, expressing a new, integrated conception of how the components of the research problem interrelate (DiBiase 1990). This all depends on what aspect of change will be chosen to expose. Bertin's (1983) famous **semantic system** offered seven graphic variables and syntactic rules to express static snapshot of reality. Following Bertin's system, one can decide whether to depict a feature's spatial (e.g. location, direction, structure, dimensions) or attribute properties (e.g. value, multivariate values) and describe them in terms of a symbol's shape, size, orientation, value, colour, texture, position etc. From the perspective of cartographic representation, map signs (sign-vehicles) might be evaluated on dual grounds: on the basis of the concepts they prompt (interpretant) and on the basis of the manner in which they correspond to the real or imagined world, i.e. referent (MacEachren 1995). This leads to the liberty to choose between different symbols and object aggregation levels in cartographic representations (Dent 1990, Rouleau 1993, Kraak and Ormeling 2003, Slocum, *et al.* 2005), as much as to use alternative conceptions of visual expression of chorems (Klippel 2003).

Today, a large part of the cartographic community believes that **dynamic maps** are the most suitable method to represent temporal geo-spatial data (Emmer 2001). Many studies have shown that dynamic maps need different principles in visual variables (DiBiase *et al.* 1992, Blok 2000) and the arrangement of graphics (Harrower 2003). Although multimedia animations and simulations in scientific visualization have expanded (Mitas *et al.* 1997, Visser and Nijs 2006), the final rendering is still frequently achieved through manual processing (Paul *et al.* 2007).

Other considerations with cartographic representation result from the **scale** issues described in section 2.2.1. The more information one attempts to pack into a small black-and-white graphic, the more crucial graphic design expertise becomes (DiBiase 1990). The ordinary reaction to this challenge is cartographic generalization in terms of selection, simplification, reclassification and exaggeration of map elements (Slocum *et al.* 2005).

Paper II faced the requirement to show all study areas on a single figure (Figure 3 in the paper). The distinction between the present and new coastline positions derived from the investigation were in most cases imperceptible on the map of Estonia at the given scale. To increase the effectiveness of the graphic, the first decision was to omit the contour of Estonia and compound study areas only into composition. The deficiency of proper geographical location was compensated with links to Figure 2 in the paper. The second measure to strengthen the visual balance of potential coastal change was the conversion of line elements into areal symbology with slight exaggeration. In order to keep focusing on the most crucial inundation zone, different greyscale tones were used.

3. CASE STUDIES IN ESTONIA

This chapter depicts the materials and three GIS-studies in Papers I, II and III in the light of the theoretical framework offered before. Although these studies have different objectives and methods, they use the same fundamental approach. First, all three studies strictly deal with Estonian landscapes. Second, changes in landscape are modelled with a common scheme covering scaling issues, the conceptualization of change indicator, the presence of neighbourhood operators and general purpose modelling approaches in change detection techniques and the aspect of change detection.

3.1. Estonian landscapes

The first scientific system of Estonian landscape regions was compiled by Finnish geographer J. G. Granö in 1922 (Arold 1993, Palang 1998). Today landscape regions in Estonia are mostly determined by relief forms. Thus a region differs significantly from neighbouring areas in terms of its geological structure (Arold 2005).

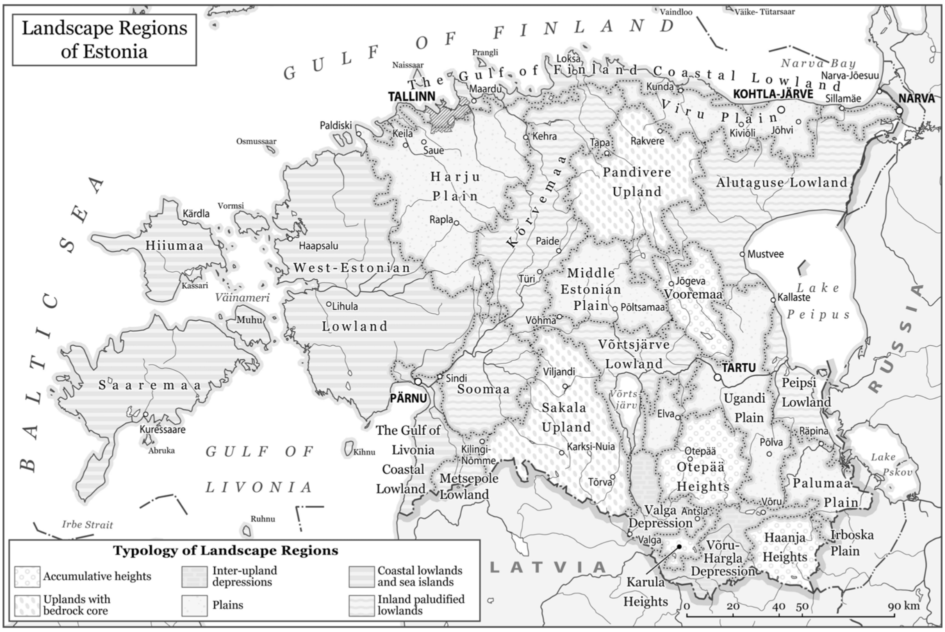

Figure 1. Estonian landscape regions

The county's landscape regions (Figure 1) can be divided into six general groups: 1) accumulative heights (Otepää Heights, Haanja Heights, Karula Heights and Vooremaa); 2) uplands with bedrock core (Pandivere Upland and Sakala Upland); 3) inter-upland depressions (Valga Depression and Võru-Hargla Depression); 4) plains (Harju Plain, Viru Plain, Middle Estonian Plain, Ugandi Plain, Palumaa Plain and Irboska Plain); 5) coastal lowlands and sea islands (the Gulf of Finland Coastal Lowland, West-Estonian Lowland, the Gulf of Livonia Coastal Lowland, Saaremaa and Hiiumaa); 6) inland paludified lowlands (Alutaguse Lowland, Peipsi Lowland, Võrtsjärve Lowland, Kõrvemaa, Soomaa and Metsepole lowlands). By Estonian tradition, uplands (regions 1 and 2) and lowlands (regions 3–6) are differentiated.

3.2. Detection of landscape changes with remote sensing

This section refers to Paper I and adopts remote sensing based on raster images as the method of change detection. Remote sensing is a reliable source for the monitoring and analysis of changes in land cover. Milne (1988) grouped the change detection methods based on satellite imagery into four broad categories: (1) linear procedures (difference images, ratiod images); (2) classification routines (post-classification change, spectral pattern change); (3) the comparison of transformed data sets (vegetation indices, principal components analysis), and (4) other (regression analysis, knowledge-based expert systems, neural networks).

Classification routines predominate in environmental studies. Map and image interpretation (Bolca *et al.* 2005), unsupervised classification (e.g. Zheng *et al.* 1997, Jobin *et al.* 2003), supervised classification (e.g. Shalaby and Tateishi 2007), and image interpretation (e.g. Luo *et al.* 2005, Zha *et al.* 2007) can be named as the most common logics for the detection of land cover categories. In Paper I the **post-classification** map comparison method described in section 2.2.2. was chosen as a key technique to detect areal change.

Objectives

The objectives of the analysis were to assess the rate of land use changes in Estonian agriculture in conditions where the statistical data collection system collapsed in the crucial years between 1990 and 1993, when Estonia gained independence from the USSR and the privatization of collective and state farms took place.

Methodology

Raster applications are treated as the field representation of a geographic phenomenon (see 2.2.1.). If necessary, the concept of entity can be set up in two senses. Ordinarily the entity is regarded as the distinguishable object in the real world and its digital representation. This is the case in change estimation, where the set of cells on a grid, as an areal unit, represents a certain entity of reality model. However, a pixel or grid cell technically acts as a representation of entity in cell-by-cell overlay operations. This is particularly apparent in the case of hybrid data models (Winter 1998).

We evaluated different land use classification methods and available satellite imagery, and deduced that we were unable to detect all varieties of agricultural land use. Although the seasonal reflectance of green plant communities was known (Nilson 1988, Peterson 1992), we failed to differentiate 'grasslands currently in use' from 'successional oldfields', due to the lack of sufficient subsequent satellite scenes for seasonal or annual change. For example, pre-cut and after-cut satellite scenes are necessary in order to detect hay-mowing on grasslands. As a result, we decided to discriminate arable land only as an **indicative** land use class. Two categorical coverages were compared to each other – the area estimates for spring 1993 and the area estimates for spring 1990, when the land reform had not yet begun.

The discrimination of arable land as an **entity** class was established on the basis of Landsat MSS imagery. The static modelling process consisted of a combination of Principal Components Analysis (PCA) classification and decision tree support for masking out water, forests and wetlands. In addition, the manual separation of mining areas and major urban areas was carried out. Beaches on the seashore were confused with arable land. A 150-meter buffer was defined along the coastline to mask this area out. The classification of 'arable land' was performed on unmasked areas by thresholding. Digitized state farm maps at a scale of 1:10 000 in training areas assisted in **verification** of the threshold, and the Estonian Base map was used to control the masking.

The **scale** of the analysis was determined by the Landsat MSS imagery grain, originally of resolution 80 meters but resampled to the 50-meter grid in the subsequent processing. In theory this grain size is capable of perceiving the smallest possible fields of arable land associated with private households. Thus it was judged to be optimal for the discrimination of the postulated entity class.

Results

The changes in arable land use from 1990 to 1993 were estimated as averaged mean values of administrative districts. The abandonment rate of arable land varied from 23% to 63% between districts, and was 32% as a national total compared to the baseline date of 1990. This figures showed some correlation with official statistics, and even more closely to certain expert estimates (Vipper *et al.* 1996).

Remote sensing is the fastest possibility to obtain temporally representative data. The major problems are related to the recognition of entities, which is usually done using certain classification schemes.

3.3. Detection of changes on coastline

Paper II, which provides the framework for this section, addresses change detection differently from the previous work. Four distinctions can be pointed out: (1) formally, it is an entity-based application – coastline is explicitly defined as a research object; (2) external non-spatial models were involved to predict the position of future coastline; (3) the analysis employed the neighbourhood conception (see 2.2.3.); and (4) dimensional representation was close to the cartographic flow maps (cf. Slocum *et al.* 2005) – only the narrow corridor along the seashore was represented and treated according to 'attribute' value on every segment.

One of the simplest solution for observing coastline changes is by manually tracking it from sequent multi-date map or image sources, if these are available. This is done in the Aral Sea (Kravtsova 2001), where coastal changes have been very rapid during the last four decades and are covered by sufficient satellite imagery. When images are not available for a specified time point, topographic maps or digital elevation data (DEM) are used to model changes. The first mentioned solution is fully entity-related, and in most cases yields high-precision results. The second solution is basically a field-related approach exploiting stochastic models.

Objectives

The objective of the paper as a contextual component of the thesis was to determine Estonian coastal areas that are at risk due to presumable global climate warming and sea-level rise by the year 2100. For Estonia, accelerated sea-level rise is a particular concern, as it would cause the flooding of coastal areas, the erosion of sandy beaches, and the destruction of harbour facilities. Two potential change phenomena were focused on – the modelling of sea-level and the transgression of the coastline. Using grid-based modelling, Mäkiaho (2007) demonstrates that coastline as a line feature is determined with difficulty and is related to the scale of the investigations.

Methodology

In the palaeo-geographic reconstruction of coastline, two different techniques are available for water-level surface interpolation. The first technique uses the geostatistic correlation of coastal landforms of the same age (Rosentau *et al.* 2004), and the second technique utilizes interpolated shore displacement curve data (Harff *et al.* 2005). The second technique also allows one to construct a future prediction of the coastline. The elevation model of any time point can be modelled relative to the present elevation model DEM_0 (*ibid.*)

$$DEM_t = DEM_0 - RSL_t, \tag{2}$$

if the difference model, or relative sea level RSL_t is known. RSL_t can be determined through the spatial interpolation of data from shoreline displacement curves. In simplified terms, the relative sea level change consists of two components: $RSL = EC + IC$. Here, *EC* marks the eustatic component controlled mainly by climate and temperature change, which affects the volume of the oceanic water body. *IC* stands for the isostatic component (vertical crustal movements), which in the Baltic area is predominately dependent on glacio-isostatic rebound.

The eustatic component *EC* in our study was modelled outside the GIS with the simple climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change). Earlier experiences (Jaagus 1996) were taken into account in climate change scenarios for Estonia. Three greenhouse-gas emission scenarios were created with a resulting output of sea level rise from 14 to 95 cm by the year 2100. On the map, the maximum global 1.0-meter sea level rise scenario was analysed including the possible biases of the model.

Next, spatial modelling for land retreat was initiated on the map. Seven case study areas characterizing all of the shore types of Estonia have been selected for sea level rise assessment. Data from isostatic land uplift measurements were taken into account in land loss estimates in every study area. Potential erosion was calculated along the coastline at 200 m intervals using the Bruun Rule (Bruun 1962, Hands 1983). As the Bruun Rule is designed for calculating erosion on sandy beaches only, the overfill ratio of 1.0 for sandy shores was modified for the other shore types (for sand to 1.0; for gravel and pebble to 0.7; for till (shingle-rich loam) to 0.4; and for limestone to 0.1).

Results

The study demonstrated that a sea-level rise of 1.0 m would result in considerable changes in coastal ecosystems and would lead to significant economic damage. In particular, different parts of Estonia would suffer for different reasons.

It is impossible to model the coastline without modelling relief. As elevation data is an important source of uncertainty (Imhof 1982, Burrough *et al.* 2001), different additional means are needed to enhance the precision of results. Coastline cannot be handled as a simple contact line on an elevation model: the material forming the coast must be considered. This study demonstrated that the crushing impact of high tide and waves is greatest for sandy beaches and dunes in south-western and north-eastern Estonia.

3.4. Detection of changes on the base of landscape indices

As was discussed above, landscape metrics can adequately reflect some landscape properties (Mander *et al.* 2005). Most of landscape indices belong to the broad category of edge and shape metrics and, for example, quantify the occurrence of ecotones, and are often related to patch area, fractal dimension or the difference between actual and ideal shapes. The number and size of patches (patch area) are also often measured (Lausch and Herzog 2002). Despite the hundreds of different landscape indices, relatively few metrics adequately describe landscape pattern (Riitters *et al.* 1995).

Among landscape structure variables, landscape diversity is of special concern. Spatial heterogeneity has an important influence on a wide range of ecological patterns and processes (Schindler *et al.* 2007). Diversity is also central to holistic and cultural landscape studies (Antrop 2005).

Diversity measures are usually derived from information theory and often involve the use of Shannon's diversity index (Lausch and Herzog 2002). However, **spatial autocorrelation** is an alternative measure of variations (Cressie 1993), and is used intensively in many studies (eg Kosugi *et al.* 2007, Pottier *et al.* 2007, Uuemaa *et al.* 2007). To study landscape heterogeneity in terms of spatial autocorrelation, correlograms are preferred over semivariograms, since – according to Legendre and Fortin (1989) – they are standardized and make it possible to compare different landscapes, and hence are more applicable for temporal analysis. Perhaps the most venerable and widely implemented tool for characterizing the spatial autocorrelation of areal units is the Moran index of spatial contiguity (Moran's I) statistic (Shortridge 2007).

Objectives

The main objectives of Paper III were: (1) to analyse three map series (from approximately 1900, 1940, and 2000) from selected landscape areas in Estonia concerning their differences in spatial autocorrelation and FRAGSTATS indexes; (2) to ascertain whether the Moran's I characteristic and landscape indexes respond to the land cover changes. The aim of this study on the meta-level was to evaluate Moran's I characteristic in the role of synthetic characteristic in order to describe landscape as a whole.

Methodology

We investigated the land use correlograms of the test areas and found these to be quite regular. In order to compare Moran's I correlograms from different test areas and different map series, we introduced a simple characteristic of the half-value distance lag: $h_I=0.5$ – the distance lag where Moran's I drops below 0.5 – as a new landscape metric for the characterization of landscape pattern. We also correlated FRAGSTATS metrics with $h_I=0.5$ in order to detect whether some of the FRAGSTATS metrics indirectly measure spatial autocorrelation.

The utilization of landscape indices usually exploits the principles of the attributes of distinct landscape elements, or an attribute field if raster filtering techniques are used. Here initially existing land use entities were converted into a synthesis **entity** expressing the homogeneity of the landscape. The autocorrelation has been calculated with all appropriate pixels using so-called King's case analysis (Eastman 2003). Using auxiliary images (the CONTRACT module with so-called pixel thinning), we computed the 1st, 2nd, 3rd etc. lags of Moran's I value. These techniques make it possible to diminish the critical influences of scaling and generalization effects, making Moran's I more comparable on different landscape than most of landscape metrics. At the same time, spatial autocorrelation inherently denotes the concept of the neighbourhood approach.

Results

The results of the study demonstrated that the average value of spatial autocorrelation in Estonian landscapes has not significantly changed over time. We were also unable to find a significant difference between spatial autocorrelation in heights and lowlands. We found that the benefit of the h_I=0.5 characteristic is its simple interpretability and the independence of the scale (Uuemaa *et al.* 2005). Thus this characteristic can effectively be used as an indicator in landscape planning and management.

Although the analysis of correlograms did not demonstrate a significant change over time, several landscape metrics indicated that landscapes are more heterogeneous in 2000 than they were in 1900 or 1940.

4. CONCLUSIONS

The results of the study demonstrate that the methods used for the detection of changes depend on several factors, and the theoretical chapter of the thesis addresses these. The paper shows that the primary role in the detection of changes using GIS is played by the aim and concept of change analysis. In relation to these, four major aspects of change detection may be outlined: (1) when did the change occur, (2) what is the character of the change (3) what is the spatial scope of the change and (4) what is the spatial pattern of the change.

At the same time, the detection of changes using GIS is greatly much influenced by the (cartographic) presentation model of the spatial data and the chosen aim of the visualization of results. This affects the determination of the conceptual model of the phenomena carrying the change and the most appropriate representation of the indicator presenting he change in the structure of the spatial data. This principle leads the thesis to a cartographic starting point and visual thinking through semantic change. The cartographic approach used in the thesis helps to combine different parts of the analysis into an integrated solution by understanding the meaning, abstraction, modelling and visualisation of a phenomenon. The spatial abstraction of phenomena is handled here using the cartographic approach, generalisation tools and the selection of the scale of analysis. The GIS-based approach is represented in the thesis by using neighbourhood operators and engaging general non-spatial models in the analysis.

The specific results concerning landscape changes are presented in the three papers that are attached to the thesis. Paper I uses a straightforward overlay operator based on spatial units as applied to raster data from remote sensing. Changes were detected as differences in the area of arable land in spring (used as the indicator here). The results showed a 32% average decrease in arable land detectable on satellite imagery from 1990 to 1993. The results were verified using statistical data and expert estimations.

Paper II uses a formal entity-based application that reduces the change to a linear system (the coastline in this particular case). The actual detection of spatial changes was carried out on cross-sections made every 200 m on this line. The character of the changes and the related detection thereof was previously analysed using the eustatic component of sea-level rise predicted by the non-spatial MAGICC climate model. This was corrected using parameters of isostatic land shift and potential erosion. The results were interpolated into a new location of coastline on a conditional elevation model corresponding to the use of neighbourhood operators in geoinformatic terms.

Paper III made use of indirect indicators. This was necessitated by the desire to express landscape as a complex, synthetic phenomenon. Homogeneity of landscape was used as an appropriate parameter as indicated by spatial autocorrelation. Land use units were mapped as primary entities on three topographic maps from 1886 to 2004. Autocorrelation was calculated using a Moran I indicator acting on the basis of neighbourhood operators. Autocorrelation calculations were transformed into correlograms that could be useful for the comparison of landscapes from different periods. To facilitate comparison, the paper proposed the use of half-value distance lag corresponding to a drop in Moran I by half. The study was carried out on 13 case study areas in Estonia representing almost all landscape regions in Estonia. In general, the study showed a slight change in Estonian landscapes towards heterogeneity, while some areas (such as Alutaguse and Western Estonia) demonstrated a statistically significant change.

5. SUMMARY IN ESTONIAN

RUUMIANDMETE KASUTAVUS MAASTIKUMUUTUSTE TUVASTAMISEKS JA ESITAMISEKS EESTI NÄITEL

Maastikulised uurimised on tänapäeval kujunenud laialt levinud multidistsiplinaarseks uurimisvaldkonnaks, mis on ühendanud väga mitmesuguseid uurimismetoodikaid ja nende rakenduspõhimõtteid. Oluline koht maastikulistes uuringutes on maastikes toimuvate muutuste väljaselgitamisel. Muutuste uurimisel on mindud kahes suunas: ühelt poolt kasutatakse üldotstarbeliste modelleerimiskeelte abil loodud simulatsioonmudeleid ja keskkondi nagu nt STELLA või MATLAB, teiselt poolt üha enam huvitutakse muutuste ruumiliste aspektide uurimisest geoinfosüsteemide (GIS) abil.

Käesolevas uurimistöös on vaatluse alla võetud just geoinfosüsteemide kasutusvõimalused maastikes toimuvate muutuste tuvastamiseks. Maastikumuutuste uurimine GIS-i abil on välja selgitanud palju efektiivseid tehnikaid geoinformaatika enda arengu seisukohalt. Samas on maastiku-uuringud näidanud, et muutuste tuvastamine, nende kaardistamine ja hindamine ei saa toimuda ühe kindla metoodika või tehnilise protseduuri alusel.

Sellest tulenevalt on antud doktoritöö keskseks probleemiks markeerida ruumiandmete kasutatavuse üldised printsiibid maastikumuutuste tuvastamiseks. Ehkki töö läbivaks teemaks on maastikumuutused, on probleemi püstituse seisukohast võetuna olulised just nende muutuste tuvastamisel kasutatud lahendused. Tähelepanu pööratakse sellele, kuidas muutusi maastikes on võimalik GIS-i abil märgata, milliseid mõttelisi ja tehnilisi konstruktsioone selleks vaja läheb. Arutelu on rajatud kolmele ideoloogiliselt erinevale GIS-rakendusele, mis demonstreerivad ruumiandmete valikuvõimalusi seoses maastikumuutuste tuvastamise tehnikatega ja üldise kontseptuaalse lähenemisega. Konkreetsemalt võib töö uurimisteemadena nimetada järgmisi punkte:

a) leida, millised on ruumiandmete ühised kasutusprintsiibid GIS-is maastikumuutuste uurimisel ja analüüsi ülesehitamisel,
b) tuvastada, kuivõrd erinevad ruumiandmete struktuurid on kasutatavad maastikumuutuste GIS-analüüsis ning mil määral mõjutavad otsustusi modelleerimisideoloogia valikul,
c) uurida konkreetselt Eesti maastike näitel muutuste tuvastamise võimalusi selgelt määratletud geoinformaatiliste rakenduste abil,
d) kas kartograafiast tulenevad põhimõtted töö/uurimise läbiviimiseks on kohaldatavad geoinformaatilisele analüüsile.

Töö käigus leiti, et muutuste tuvastamise metoodika sõltub väga mitmetest asjaoludest, millele käesoleva uurimistöö teoreetilises osas on keskendutud. Töös on näidatud, et muutuse uurimisel GIS-keskkonnas on esmaseks määranguks muutuste uurimise eesmärk. Sellega seoses võib välja tuua neli olulisemat muutuste tuvastamise aspekti: (1) kas muutus on aset leidnud, (2) milline on muutuse iseloom, (3) milline on muutuse ruumiline ulatus ja (4) milline on muutuse ruumiline muster.

Samal ajal on muutuste tuvastamine GIS-i abil väga tugevalt mõjutatud ruumiandmete (kartograafilistest) esitusmudelitest ja tulemuste visualiseerimise eesmärgist. Selle all leitakse muutust kandva nähtuste kontseptuaalmudel ja seda kirjeldav kõige sobilikum indikaatori esitusvorm (representatsioon) ruumiandmete struktuuris. Sellest printsiibist tulenevalt on tööle antud kartograafiline lähtepositsioon läbi visuaalse mõtlemise ja semantilise ahela. Töös kasutatud kartograafiline lähenemine aitab analüüsi osad siduda terviklahenduseks läbi nähtuse mõtestamise, abstraheerimise, modelleerimise ja visualiseerimise. Just kartograafilisest vaatenurgast käsitletakse siin nähtuse ruumilist abstraktsiooni, selle generaliseerimisvõtteid ning analüüsi mõõtkava valikut. Geoinfosüsteemipõhise käsitlusena vaadeldakse esitatud rakendustes naabrusoperaatorite kasutamist ning üldotstarbeliste mitteruumiliste mudelite kaasamist analüüsis.

Töö sisulisi muutusi puudutavad põhitulemused on esitatud töö lisana toodud publikatsioonides. Publikatsioonis I kasutati sirgjoonelist eraldispõhist ülekatteoperaatorit kaugseire teel saadud rasterandmestike peal. Muutusi tuvastati kevadise künnimaa, kui indikaatori, pindalalise ulatuse erinevuste alusel. Uurimuse tulemusena tuvastati künnimaa vähenemine 1990–1993 satelliitpiltide alusel keskmiselt 32%. Uurimise usaldusväärsust kontrolliti põlluraamatute-majandikaartide ning eksperthinnangutega.

Publikatsioonis II kasutati formaalselt olemipõhist (*entity-based*) rakendust, milles muutust kandev indikaator taandati lineatuursele süsteemile (so rannajoonele). Ruumiline muutuste tuvastamine sooritati sellel joonel paiknenud 200-meetrise intervalliga punktidest tõmmatud ristprofiilidel. Muutuse iseloom ja selle tuvastamise viis selgitati välja eelnevalt mitteruumiliste MAGICC kliimamudeli poolt määratud eustaatilise meretaseme tõusu näol. Seda korrigeeriti isostaatilise maakerke ja potentsiaalse erosiooni parameetritega. Saadud väärtused interpoleeriti rannajoone uueks asendiks tinglikul reljeefimudelil, mis geoinformaatiliste terminite järgi tähendab naabrusoperaatorite kasutamist.

Publikatsioon III võttis kasutusele kaudsed indikaatorid. Selle põhjenduseks oli soov väljendada maastikku kui kompleksset, sünteetilist nähtust. Sobilikuks mõisteks valiti maastiku homogeensus ja selle indikaatoriks ruumiline autokorrelatsioon. Algsete maastikku kirjeldavate olemitena kaardistati maakasutusüksused kolmel topograafilisel kaardil vahemikus 1886–2004. Autokorrelatsiooni arvutamisel kasutati naabrusoperaatorite põhimõttel toimivat Morani I nimelist indeksit. Autokorrelatsiooni arvutustest koostati korrelogrammid, mida kasutati eri aegadest pärit maastike omavaheliseks võrdluseks. Võrdluse hõlbustamiseks pakuti töös välja Morani I poolestusväärtusele vastav kaugusintervalli (*lag*) pikkuse $h_{I=0.5}$. Uurimus viidi läbi 13-nel testalal, mis esindavad pea kõiki Eesti maastikurajoone. Üldiselt võttes tuvastas uurimus Eesti maastike kerge trendi heterogeensuse suunas, kuid esines ka testalasid (nt Alutaguse ja Lääne Eesti), kus $h_{I=0.5}$ näitas statistiliselt usaldusväärset muutust.

6. REFERENCES

Aaviksoo, K. (1993) Application of Markov Models in Investigation of Vegetation and Land Use Dynamics in Estonian Mire Landscapes. Dissertationes Geographicae Universitatis Tartuensis 4. Tartu: Tartu University Press

Alcamo, J., Leemans, R. and Kreileman, E. (1998) Global Change Scenarios of the 21st Century. Results from the IMAGE 2.1 Model. London: Pergamon and Elsevier Science, 296 p.

Allen, C. D., Betancourt, J. L. and Swetnam, T. W. (1998) Landscape Changes in the Southwestern United States: Techniques, Long-term Data Sets, and Trends. In: Sisk, T. D. (Ed.) Perspectives on the Land Use History of North America: A context for understanding our changing environment. Biological Science Report USGS/BRD/ BSR-1998–0003. U.S.Geological Survey, Biological Resources Division, Reston, VA. pp. 71–84

Alonso-Pérez, F., Ruiz-Luna, A., Turner, J., Berlanga-Robles, C. A. and Mitchelson-Jacob, G. (2003) Land cover changes and impact of shrimp aquaculture on the landscape in the Ceuta coastal lagoon system, Sinaloa, Mexico. *Ocean & Coastal Management*, Vol. 46, Issues 6–7, pp. 583–600

Alumäe, H. (2006) Landscape preferences of local people: considerations for landscape planning in rural areas of Estonia. Dissertationes Geographicae Universitatis Tartuensis 26. Tartu: Tartu University Press

Anderson, J. R., Hardy, E. E., Roach, J. T. and Witmer, R. E. (1976) A Land Use And Land Cover Classification System For Use With Remote Sensor Data. United States Government Printing Office, Washington: 1976, URL: http://landcover.usgs.gov/pdf/anderson.pdf

Antrop, M. (2003) Continuity and change in landscapes. Landscape change and the urbanization process in Europe. In: Mander, Ü., Antrop, M. (Eds.), Multifunctional Landscapes, Vol. 3: Continuity and Change, Southampton. WIT Press, Adv. Ecol. Sci., 16.

Antrop, M. (2004) Landscape change and the urbanization process in Europe. *Landscape and Urban Planning*, Vol. 67, Issues 1–4, pp. 9–26

Antrop, M. (2005) Why landscapes of the past are important for the future. *Landscape and Urban Planning*, 70, pp. 21–34

Antrop, M. (2006a) From holistic landscape synthesis to transdisciplinary landscape management. In: Tress, B., Tress, G., Fry, G., Opdam, P. (Eds.) From Landscape Research to Landscape Planning – Aspects of Integration, Education and Application. Springer, pp. 27–50

Antrop, M. (2006b) Sustainable landscapes: contradiction, fiction or utopia? *Landscape and Urban Planning*, 75, pp. 187–197

Arold, I. (1993) Estonian landscapes, Tartu, 95 p.

Arold, I. (2005) Eesti maastikud, University of Tartu Press, Tartu, 453 p. (in Estonian, summary in English)

Atkinson, P., Cutler, M. and Lewis, H. G. (1997). Mapping sub-pixel proportional land cover with AVHRR imagery. *International Journal of Remote Sensing*, Vol. 18, pp. 917–935.

ATLAS (2004) Eesti atlas. Aunap, R. (Ed.), Tallinn: BIT & TÜGI, 48 p. (in Estonian)

Aunap, R., Uuemaa, E., Roosaare, J. and Mander, Ü. (2006): PAPER III. Spatial correlograms and landscape metrics as indicators of land use changes. – Geo-Environment and Landscape Evolution II. Evolution, Monitoring, Simulation, Management and Remediation of the Geological Environment and Landscape. WIT Transactions on Ecology and the Environment, Vol 89, Editors Martin-Durque, J. F., Brebbia, C. A., Emmanouloudis, D. E., Mander, Ü. Pp 305–315

Bastian, O. (2001) Landscape Ecology – towards a unified discipline? *Landscape Ecology*, 16, pp. 757–766

Bastian, O. and Bernhardt, A. (1993) Anthropogenic landscape changes in Central Europe and the role of bioindication. Landscape Ecology, Vol. 8, No. 2, pp. 139–151

Bastian, O. and Lütz, M. (2006) Landscape functions as indicators for the development of local agri-environmental measures. *Ecological Indicators*, 6. pp. 215–227

Batty, M. (2001) Models in planning: technological imperatives and changing roles. *International Journal of Applied Earth Observation and Geoinformation*, Vol. 3, Issue 3, pp. 252–266

Bender, O., Boehmer, H. J., Jens, D. and Schumacher, K. P. (2005) Using GIS to analyse long-term cultural landscape change in Southern Germany. *Landscape and Urban Planning*, 70, pp. 111–125

BIODIVERSITY (1999) Estonian Biodiversity Strategy and Action Plan. Kull, T. (Ed.), Tallinn-Tartu: Estonian Ministry of the Environment, UNEP, Environmental Protection Institute of the EAU, 165 p, URL: http://enrin.grida.no/biodiv/biodiv/nbsap/estonia.pdf, Consulted on 15 September 2007

Bertin, J. C. (1983) Semiology of Graphics: Diagrams Networks Maps. The University of Wisconsin Press, 432 p.

Blok, C. (2000) Dynamic visualization in a developing framework for the representation of geographic data. *Cybergeo, Symposium "30 years of graphic semiology in honor of Jacques Bertin"*, Article 153, modified on 13 February 2007. URL : http://www.cybergeo.eu/index509.html. Consulted on 13 September 2007

Bolca, M., Altınbaş, Ü., Kurucu, Y. and Esetlili, M. T. (2005) Determination of Change Detection of Landscape of the Kucuk Menderes Delta Using GIS and the Remote Sensing Techniques. *Journal of Applied Sciences*, 5 (4), pp. 659–665

Bolliger, J., Lischke, H. and Green, D. G. (2005) Simulating the spatial and temporal dynamics of landscapes using generic and complex models. *Ecological Complexity*, Vol. 2, Issue 2, pp.107–116

Bolstad, P. (2006) GIS fundamentals: A First Text on Geographic Information Systems. 2nd Edition. White Bear Lake: Eider Press, 539 p.

Botequilha Leitão, A. B. and Ahern, J. (2002) Applying landscape ecological concepts and metrics in sustainable landscape planning. *Landscape Urban Planning*, 59 (2), pp. 65–93

Bruun, P. (1962) Sea level rise as a cause of shore erosion. *Journal of Waterway*, *Port, Coastal and Ocean Engineering*, 88(1–3), 117–130

Bürgi, M., Hersperger, A. M. and Schneeberger, N. (2004) Driving forces of landscape change – current and new directions. *Landscape Ecology*, 19, pp. 857–868

Burrough, P.A. (1998) Dynamic modelling and geocomputation. In: Longley, P. (Ed.), Geocomputation: A Primer. John Wiley & Sons, pp. 165–191

Burrough, P. A., van Gaans, P. F. M. and MacMillan, R. A. (2000) High-resolution landform classification using fuzzy *k*-means. *Fuzzy Sets and Systems*, 113, pp. 37–52

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

Burrough, P. A., Wilson, J. P., van Gaans, P. F. M. and Hansen, A. J. (2001) Fuzzy k-means classification of topo-climatic data as an aid to forest mapping in the Greater Yellowstone Area, USA. *Landscape Ecology*, 16, pp. 523–546

Campbell, J. (2001) Map Use & Analysis. 4th ed. New York: McGraw-Hill, 372 p.

Carr, J. R. (2002) Data visualization in the geosciences. Upper Saddle River, NJ: Prentice Hall, 267 p

Carranza, M. L., Acosta, A., Ricotta, C. (2007) Analyzing landscape diversity in time: The use of Rènyi's generalized entropy function. *Ecological Indicators*, 7, pp. 505–510

Cauvin, C. (2002) Cognitive and cartographic representations: towards a comprehensive approach. *Cybergeo: Cartographie, Imagerie, SIG*, article 206, modifié le 03 mai 2007. URL: http://www.cybergeo.eu/index194.html, Consulted on 12 September 2007

Chang, K.-T. (2003) Introduction to Geographic Information Systems. McGraw-Hill Higher Education, 2nd edition, 400 p.

Chrisman, N. (1997) Exploring Geographic Information Systems. John Wiley & Sons, 298 p.

Clarke, K. C. (1990) Analytical and Computer Cartography. Englewood Cliffs, New Jersey: Prentice Hall

Coope, U. (2001) Why does Aristotle say that there is no time without change. *Proceedings of the Aristotelian Society*, Vol. 101, No. 3, pp. 359–367

Cosgrove, D. (2003) Landscape: ecology and semiosis. In: Palang, H., Fry, G. (Eds.), Landscape Interfaces. Cultural Heritage in Changing Landscapes. Kluwer Academic Publishers, Dordrecht, pp. 15–20.

Cotler, H. and Ortega-Larrocea, M. P. (2006) Effects of land use on soil erosion in a tropical dry forest ecosystem, Chamela watershed, Mexico. *Catena*, 65, pp. 107–117

Cressie, N. A. C. (1993) Statistics for Spatial Data (Revised ed.), Wiley, New York

Dakowicz, M. and Gold, C. M. (2002) Visualizing terrain models from contours – plausible ridge, valley and slope estimation. In: Proceedings of the International Workshop On Visualization and Animation of Landscape, Kunming, China, URL: http://www.acrors.ait.ac.th/kunming/download/maciej.pdf, Consulted on 11 September 2007

Dent, B. D. (1990) Cartography: Thematic Map Design. Dubuque: WCB, 433 p.

DiBiase, D. (1990) Visualization in the Earth Sciences. *Earth and Mineral Sciences, Bulletin of the College of Earth and Mineral Sciences, Pennsylvania State University*, 59(2), pp. 13–18

DiBiase, D., MacEachren, A. M., Krygier, J. B. and Reeves, C. (1992) Animation and the role of map design in scientific visualization. *Cartography and Geographic Information Systems*, 19(4), pp. 201–214

Drielsma, M., Ferrier, S. and Manion, G. (2007) A raster-based technique for analysing habitat configuration: The cost–benefit approach. *Ecological Modelling*, Vol. 202, Issues 3–4, pp. 324–332

Dunn, C. P., Sharpe, D. M., Guntensperger, G. R., Stearns, F. and Yang, Z. (1991) Methods for Analyzing Temporal Changes in Landscape Pattern. In: Turuner, M. G. and Gardner, R. (Eds.) Quantitative Methods in Landscape Ecology. The Analysis and Interpretation of Landscape Heterogeneity. New York: Springer, pp. 173–198

Eastman, R. (2003) IDRISI Kilimanjaro: Guide to GIS and Image Processing. Clark University

Eilart, J. (1976) Man. Culture. Ecosystem. Perioodika, Tallinn.

Emmer, N. N. M. (2001) Determining the effectiveness of animations to represent geospatial temporal data: a first approach. In: 4th Association of Geographic Information Laboratories in Europe Conference on Geographic Information Science (Brno, Czech Republic), pp. 585–589

Ernoult, A., Bureau, F. and Poudevigne, I. (2003) Patterns of organisation in changing landscapes: implications for the management of biodiversity. *Landscape Ecology*, 18, pp. 239–251

Fairbairn, D., Andrienko, N., Andrienko, G., Buziek, G. and Dykes, J. (2001) Representation and its Relationship with Cartographic Visualization. *Cartography and Geographic Information Science*, 28(1), pp. 13–28.

Fall, A. and Fall, J. (2001) A domain-specific language for models of landscape dynamics. *Ecological Modelling*, 141, pp. 1–18

Feng W., Jichang S., Shuqiang Y. and Huowang C. (1999) Spatial data model for feature-based GIS. In: Proceedings of the Workshop on Computer Science and Information Technologies CSIT'99, Moscow, Russia, 1999, pp. 107–111

Forman, R. T. T. and Godron, M. (1986) Landscape Ecology. New York, NY: John Wiley and Sons, Inc., 620 p.

GLOS (2005) Glossary of Geology (5th ed.). Neuendorf, K. K. E., Mehl, J. P., and Jackson, J. A. (Eds.) American Geological Institute, 800 p.

Hands, E. B. (1983) The Great Lakes as a test model for profile responses to sea level changes. In: Komar, P. D. (ed.), Handbook of Coastal Processes and Erosion. Boca Raton, Florida: CRC Press, pp. 167–189

Harff, J., Lampe, R., Lemke, W., Lübke, H., Lüth, F., Meyer, M. and Tauber, F. (2005) The Baltic Sea – a Model Ocean to Study Interrelations of Geosphere, Ecosphere, and Anthroposphere in the Coastal Zone. *Journal of Coastal Research*, 21(3), pp. 441–446

Harrower, M. (2003) Tips for designing effective animated maps. *Cartographic Perspectives* 44, pp. 63–65.

Herzog, F. and Lausch, A. (2001) Supplementing Land-Use Statistics with Landscape Metrics: Some Methodological Considerations. In Environmental Monitoring and Assessment. Springer Netherlands, Volume 72, Number 1 / November, 2001, Pages 37–50

Hietel, E., Waldhardt, R. and Otte, A. (2007) Statistical modeling of land-cover changes based on key socio-economic indicators. *Ecological Economics*, 62, pp. 496–507

Hudson, J. and Fowler, P. (1966). The concept of Pattern in Geography. Dept. of Geography, Univ. of Iowa.

Imfeld, S. (2000) Time, Points and Space - Towards a Better Analysis of Wildlife Data in GIS, Universität Zürich.

Imhof, E. (1982) Cartographic Relief Presentation. Berlin, New York: Walter De Gruyter

Isachenko, A. G. (1991) Landscape studies and physico-geographical land classification. Moscow: Vysshaya Shkola, 366 p. (in Russian)

Jaagus, J. (1996) Climatic trends in Estonia during the period of instrumental observations and climate change scenarios. In: J.-M. Punning, Editor, Estonia in the System of Global Climate Change vol. 4, Tallinn, Institute of Ecology Publication, pp. 35–48

Jensen, L. H. (2005) Changing conceptualization of landscape in English landscape assessment methods. In: Tress, B., Tress, G., Fry, G., Opdam, P. (Eds.) From Landscape Research to Landscape Planning – Aspects of Integration, Education and Application. Springer, pp.

Jobin, B., Beaulieu, J., Grenier, M., Bélanger, L., Maisonneuve, C., Bordage, D. and Filion, B. (2003) Landscape changes and ecological studies in agricultural regions, Québec, Canada. Landscape Ecology 18, pp. 575–590

Jones, M. (1991) The elusive reality of landscape. Concepts and approaches in landscape research. *Norsk Geografisk Tidsskrift*, Vol. 45, pp. 229–244

Jones, K. B., Neale, A. C., Nash, M. S., Van Remortel, R. D., Wickham, J. D., Riitters, K. H. and O'Neill, R. V. (2001) Predicting nutrient and sediment loadings to streams from landscape metrics, a multiple watershed study from the United States mid-Atlantic region. *Landscape Ecology* 16 (4), pp. 301–312.

Klemas, V. V. (2001) Remote Sensing of Landscape-Level Coastal Environmental Indicators. *Environmental Management*, Vol. 27, No. 1, pp. 47–57

Klippel, A. (2003) Wayfinding Choremes – Conceptualizing Wayfinding and Route Direction Elements. Monograph Series of the Transregional Collaborative Research Center, Bremen: Universität Bremen, 195 p.

Kont, A., Jaagus, J. and Aunap, R. (2003): PAPER II. Climate change scenarios and the effect of sea level rise for Estonia. – *Global and Planetary Change*. 36, pp. 1–15

Kosugi, Y., Mitani, T., Itoh, M., Noguchi, S., Tani, M., Matsuo, N., Takanashi, S., Ohkubo, S. and Nik, A. R. (2007) Spatial and temporal variation in soil respiration in a Southeast Asian tropical rainforest. *Agricultural and Forest Meteorology*, Vol. 147, Issues 1–2, pp. 35–47

Kraak, M.-J. and Ormeling, F. (2003) Cartography: Visualization of Geospatial Data (2nd ed.). Pearson Education, 205 p.

Kravtsova, V. I. (2001) Analysis of Changes in the Aral Sea Coastal Zone in 1975–1999. Water Resources, Vol. 28, No. 6, pp. 596–603

Laas, A. and Kull, A. (2003) Application of GIS for soil erosion and nutrient loss modelling in a small river catchment. In: Brebiatos, E., Brebbia, C. A., Coccossis, H. and Kungolos, A. (Eds.) Sustainable Planning and Development. Sothampton, Boston: WITpress, pp. 525–534

Laurini, R. and Thompson, D. (1994) Fundamentals of Spatial Information Systems. Academic Press, 3rd printing, 680 p

Lausch, A. and Herzog, F. (2002) Applicability of landscape metrics for the monitoring of landscape change: issues of scale, resolution and interpretability. *Ecological Indicators*, 2, pp. 3–15

Legendre, P. and Fortin, M.-J. (1989) Spatial pattern and ecological analysis. *Vegetatio*, 80, pp. 107–138

Li, X., He, H. S., Bu, R., Wen, Q., Chang, Y., Hu, Y. and Li, Y. (2005) The adequacy of different landscape metrics for various landscape patterns. *Pattern Recognition* 38, pp. 2626 – 2638

Lillesand, T. M. and Kiefer, R. W. (1994) Remote Sensing and Image Interpretation, 3rd Edition, New York: John Wiley & Sons, 750 p.

Lioubimtseva, E. and Defourny, P. (1999) GIS-based landscape classification and mapping of European Russia. *Landscape and Urban Planning*, Vol. 44, Issues 2–3, pp. 63–75

López, E., Bocco, G., Mendoza, M. and Duhau, E. (2001) Predicting land-cover and land-use change in the urban fringe. *Landscape and Urban Planning*, Vol. 55, Issue 4, pp. 271–285

Luo, F., Qi, S. Z. and Xiao, H. L. (2005) Landscape change and sandy desertification in arid areas: a case study in the Zhangye Region of Gansu Province, China. Environmental Geology, Vol. 49, No. 1, pp. 90–97

MacEachren, A. M. (1995) How Maps Work: Representation, Visualization, and Design. New York: The Guilford Press. 513 p.

Macleod, R. D. and Congalton, R. G. (1998) A quantitative comparison of change-detection algorithms for monitoring eelgrass from remotely sensed data. *Photogrammetric Engineering and Remote Sensing* 64(3), pp. 207–216

Mäkiaho, J.-P. (2007) Estimation of ancient and future shoreline positions in the vicinity of Olkiluoto, an island on the western coast of Finland: The difference between Grid and TIN based GIS-approaches. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 252, pp. 514–529

Mander, Ü., Müller, F. and Wrbka, T. (2005) Functional and structural landscape indicators: Upscaling and downscaling problems. *Ecological Indicators* 5, pp. 267–272

McDonald, R. I. and Urban, D. L. (2006) Spatially varying rules of landscape change: lessons from a case study. *Landscape and Urban Planning* 74, pp. 7–20

McGarigal, K. and Marks, B. J. (1995) FRAGSTATS: spatial pattern analysis program for quantifying landscape structure. USDA Forest Service General Technical Report PNW-GTR-351, Oregon State University, Forest Science Department, Cornvallis, OR

Miklós, L. (1989) The general ecological model of the Slovak Socialist Republic — Methodology and contents. *Landscape Ecology*, Vol. 3, No. 1, pp. 43–51

Miller, J., Franklin, J. and Aspinall, R. (2007) Incorporating spatial dependence in predictive vegetation models. *Ecological Modelling* 202 , pp. 225–242

Miller, I., Knopf, S. and Kossik, R. (2005) Linking General-Purpose Dynamic Simulation Models with GIS. In: Maguire, D. J., Batty, M. and Goodchold, M. F. (Eds.) GIS, Spatial Analysis and Modeling. Redlands: ESRI Press, pp. 113–129

Milne, A. K. (1988) Change detection analysis using Landsat imagery: A review of methodology. In: Proceedings of IGARSS, 88 symposium, Edinburgh, Scotland, 13–16 September, pp. 541–544

Mitas L., Brown W. M. and Mitasova H. (1997) Role of dynamic cartography in simulations of landscape processes based on multi-variate fields. *Computers and Geosciences*, Vol. 23, No. 4, pp. 437–446

Moran, P.A. (1948) The interpretation of statistical maps, *Journal of the Royal Statistical Society. Series B (Methodological),* Vol. 10, No. 2, pp. 243–251

Musacchio, L., Ozdenerol, E., Bryant, M. and Evans, T. (2005) Changing landscapes, changing disciplines: seeking to understand interdisciplinarity in landscape ecological change research. *Landscape and Urban Planning* 73, pp. 326–338

Naveh, Z. (2001) Ten major premises for a holistic conception of multifunctional landscapes. *Landscape and Urban Planning*, Vol. 57, Issues 3–4, pp. 269–284

Neel, M. C., McGarigal, K. and Cushman, S. A. (2004) Behavior of class-level landscape metrics across gradients of class aggregation and area. *Landscape Ecology* 19 (4), pp. 435–455

Nilson, T. (1988) Spectral-Temporal Reflectance Profiles For Some Cereals, Academy of Science, Tartu

Oja, T., Alamets, K. and Pärnamets, H. (2005) Modelling bird habitat suitability based on landscape parameters at different scales. *Ecological Indicators*, Vol. 5, Issue 4, pp. 314–321

Openshaw, S. (1996) Developing GIS-relevant zone-based spatial analysis methods. In: Longley, P. and Batty, M. (Eds.) Spatial Analysis: Modelling in a GIS Environment. Cambridge: GeoInformation International, pp. 55–73

Palang, H. (1998) Landscape changes in Estonia: the past and the future. Dissertationes Geographicae Universitatis Tartuensis 6. Tartu, Tartu University Press

Palang, H. and Fry, G. (2003) Landscape interfaces. In: Palang, H. and Fry, G. (Eds.) Landscape Interfaces. Cultural Heritage in Changing Landscapes. Dordrecht, Boston, London: Kluwer Academic Publishers, pp. 1–15

Palang, H., Mander, Ü. and Luud, A. (1998) Landscape diversity changes in Estonia. *Landscape and Urban Planning* 41 (3–4), pp. 163–169

Palo, A., Aunap, R. and Mander, Ü. (2005) Predictive vegetation mapping based on soil and topographical data: A case study from Saare County, Estonia. *Journal for Nature Conservation* 13, pp. 197–211

Papadimitriou, F. (2002) Modelling indicators and indices of landscape complexity: an approach using G.I.S. *Ecological Indicators* 2, pp. 17–25

Paul, F., Maisch, M., Rothenbühler, C., Hoelzle, M. and Haeberli, W. (2007) Calculation and visualisation of future glacier extent in the Swiss Alps by means of hypsographic modelling. *Global and Planetary Change* 55, pp. 343–357

Peil, T., Sooväli, H., Palang, H., Oja, T. and Mander, Ü. (2004) Estonian landscape study: contextual history. *Belgeo*, 2–3, pp. 227–239

Peterson, U. (1992) Reflectance factor dynamics of boreal forest clear-cut communities during early secondary succession. *International Journal of Remote Sensing* 13, pp. 2247–2262

Peterson, U. and Aunap, R. (1998): PAPER I. Changes in Agricultural Land Use in Estonia in the Nineties Detected with Multitemporal Landsat Imagery. – *Landscape and Urban Planning.* No. 41, pp. 193–201

Pontius, R. G., Boersma, W., Castella, J.-C., Clarke, K., de Nijs, T., Dietzel, C., Duan, Z., Fotsing, E., Goldstein, N., Kok, K., Koomen, E., Lippitt, C. D., McConnell, W., Sood, A. M., Pijanowski, B., Pithadia, S., Sweeney, S., Trung, T. N., Veldkamp, A. T. and Verburg, P. H. (2007) Comparing the input, output, and validation maps for several models of land change. *The Annals of Regional Science. In Press*

Pontius, R. G., Shusas, E. and McEachern, M. (2004) Detecting important categorical land changes while accounting for persistence. *Agriculture, Ecosystems & Environment*, Vol. 101, Issues 2–3, pp. 251–268

Pottier, J., Marrs, R. H. and Bédécarrats, A. (2007) Integrating ecological features of species in spatial pattern analysis of a plant community. *Journal of Vegetation Science*, 18, pp. 223–230

Pullar, D. (2004) SimuMap: a computational system for spatial modelling. *Environmental Modelling & Software* 19, pp. 235–243

Purtauf, T., Thies, C., Ekschmitt, K., Wolters, V. and Dauber, J. (2005) Scaling properties of multivariate landscape structure. *Ecological Indicators* 5, pp. 295–304

Pärn, J. and Mander, Ü. (2007) Landscape factors of nutrient transport in temperate agricultural catchments. In: Brebbia, C. A. (Ed.) River Basin Management IV. WIT Transaction on Ecology and the Environment, Vol. 104, pp. 411–424

Qi, S. and Luo, F. (2006) Land-use change and its environmental impact in the Heihe River Basin, arid northwestern China. *Environmental Geology*, Vol. 50, No. 4, pp. 535–540

Read, J. M. and Lam, N. S.-N. (2002) Spatial methods for characterising land cover and detecting land-cover changes for the tropics. *International Journal of Remote Sensing* 23 (12), pp. 2457–2474

Remm, K. (2004) Case-based predictions for species and habitat mapping. *Ecological Modelling*, Vol. 177, Issues 3–4, pp.259–281

Rhind, D.W. (1988) A GIS research agenda. *International Journal of Geographical Information Systems* 2, pp. 23–28

Richling, A. (1983) Subject of study in complex physical geography (Landscape geography). *GeoJournal* Vol. 7, No. 2, pp. 185–187

Riitters, K. H., O'Neill, R. V., Hunsaker, C. T., Wickham, J. D., Yankee, D. H., Timmins, S. P., Jones, K. B., Jackson, B. L. (1995) A factor analysis of landscape pattern and structure metrics. *Landscape Ecology* 10 (1), pp. 23–39

Rocchini, D. and Ricotta, C. (2007) Are landscapes as crisp as we may think? *Ecological Modelling* 204, pp. 535–539

Rogowski, A. S. and Goyne, J. L. (2002) Modeling Dynamic Systems and Four-Dimensional Geographic Information Systems. In: Clarke, K. C., Parks, B. O. and Crane M. P. (Eds.) Geographic Information Systems and Environmental Modeling. Upper Saddle River, NJ: Prentice-Hall, pp. 122–159

Roosaare, J. (1994) Physical Geography in Estonia: Bridging Western and Eastern Schools of Landscape Synthesis. *GeoJournal*, 33(1), pp. 27–36

Roose, A., Sepp, K., Saluveer, E., Kaasik, A. and Oja, T. (2007) Neighbourhood-defined approaches for integrating and designing landscape monitoring in Estonia. *Landscape and Urban Planning*, Vol. 79, Issue 2, pp. 177–189

Rosentau, A. (2006) Development of Proglacial Lakes in Estonia. Dissertationes Geologicae Universitatis Tartuensis 18. Tartu, Tartu University Press

Rosentau, A., Hang, T. and Miidel, A. (2004) Simulation of the shorelines of glacial Lake Peipsi in Eastern Estonia during the Late Weichselian. *Geological Quarterly*, 4, pp. 13–21

Rouleau, B. (1993) Theory of Cartographic Expression and Design. In: Anson, R.W. and Ormeling, F.J. (Eds.) Basic Cartography: for students and technicians. Vol 1, 2nd Edition, International Cartographic Association, Elsevier Science Publ., pp.

Saura, S. and Castro S. (2007) Scaling functions for landscape pattern metrics derived from remotely sensed data: Are their subpixel estimates really accurate? *ISPRS Journal of Photogrammetry and Remote Sensing* Vol. 62, Issue 3, pp. 201–216

Schindler, S., Poirazidis, K. and Wrbka, T. (2007) Towards a core set of landscape metrics for biodiversity assessments: A case study from Dadia National Park, Greece. *Ecological Indicators, In Press*, doi:10.1016/j.ecolind.2007.06.001

Schneeberger, N., Bürgi, M. and Kienast, P. D. F. (2007) Rates of landscape change at the northern fringe of the Swiss Alps: Historical and recent tendencies. *Landscape and Urban Planning* 80, pp. 127–136

Sepp, K. (1999) The methodology and applications of agricultural lanscape monitoring in Estonia. Dissertationes Geographicae Universitatis Tartuensis 9. Tartu, Tartu University Press

Sepp, K. and Bastian, O. (2007) Studying landscape change: Indicators, assessment and application. *Landscape and Urban Planning*. Vol. 79, Issue 2, pp. 125–126

Shalaby, A. and Tateishi, R. (2007) Remote sensing and GIS for mapping and monitoring land cover and land-use changes in the Northwestern coastal zone of Egypt. *Applied Geography*, Vol. 27, Issue 1, pp. 28–41

Shortridge, A. (2007) Practical limits of Moran's autocorrelation index for raster class maps. *Computers, Environment and Urban Systems*, Vol. 31, Issue 3, pp. 362–371

Slak, M. and Lee, A. (2003) Indicators of landscape dynamics: on-going land cover changes. In: Dramstad, W. and Sogge, C. (Eds.) Agricultural impacts on landscapes: developing indicators for policy analysis: proceedings from the NIJOS/OECD expert meeting on agricultural landscape indicators in Oslo, Norway, October 7–9, 2002. Norsk Institutt for Jord- og Skogkartlegging, Ås, NIJOS Report 7/03, pp. 116–129

Slocum, T. A., McMaster, R. B., Kessler, F. C. and Howard, H. H. (2005) Thematic Cartography and Geographic Visualization. 2nd Ed. Upper Saddle River, NJ: Pearson Prenitce Hall, 518 p.

Sooväli, H. (2004) *Saaremaa waltz*. Landscape imagery of Saaremaa Island in the 20th century. Dissertationes Geographicae Universitatis Tartuensis 21. Tartu, Tartu University Press

Syrbe, R.-U., Bastian, O., Röder, M., and James, P. (2007) A framework for monitoring landscape functions: The Saxon Academy Landscape Monitoring Approach (SALMA), exemplified by soil investigations in the Kleine Spree floodplain (Saxony, Germany). *Landscape and Urban Planning*, Vol. 79, Issue 2, pp. 190–199

Taylor, P. J. (1977) Quantitative Methods in Geography: An Introduction to Spatial Analysis. Boston: Houghton Mifflin, 386 p.

Temme, A. J. A. M., Schoorl, J. M. and Veldkamp, A. (2007) Algorithm for dealing with depressions in dynamic landscape evolution models. *Computers & Geosciences*, Vol. 32, Issue 4, pp. 452–461

Thackway, R., Lee, A., Donohue, R., Keenan, R. J. and Wood, M. (2007) Vegetation information for improved natural resource management in Australia. *Landscape and Urban Planning*, Vol. 79, Issue 2, 15 February 2007, Pages 127–136

Thielen, D. R., San José, J. J., Montes, R. A. and Lairet, R. (2007) Assessment of land use changes on woody cover and landscape fragmentation in the Orinoco savannas using fractal distributions. *Ecological Indicators*, *In Press* *www.elsevier.com/locate/ecolind*

Tinker, D. B., Resor, C. A. C., Beauvais, G. P., Kippfmueller, K. F., Fernades, C. I. and Baker, W. L. (1998) Watershed analysis of forest fragmentation by clearcuts and roads in a Wyoming forest. *Landscape Ecology*, 13 (3), pp. 149–165

Tomlin, C. D. (1990) Geographic information systems and cartographic modelling. Engelwood Cliffs, NJ: Prentice Hall, 249 p.

Turner, M. G. (1990) Spatial and temporal analysis of landscape patterns. *Landscape Ecology*, Vol. 4 No. 1, pp. 21–30

Turner, M. G., O' Neill, R. V., Gardner, R. H., Milne, B. T. (1989) Effects of changing spatial scale on the analysis of landscape pattern. *Landscape Eco*logy 3 (3), pp. 153–162

Urban, D. L., O'Neill, R. V., Shugart Jr., H. (1987) Landscape ecology: a hierarchical perspective can help scientists understand spatial patterns. *BioScience* Vol. 37, No. 2, 119–127.

Uuemaa, E., Roosaare, J. and Mander, Ü. (2005) Scale dependence of landscape metrics and their indicatory value for nutrient and organic matter losses from catchments. *Ecological Indicators*, 5 (4), pp. 350–369

Uuemaa, E., Roosaare, J., Kanal, A. and Mander, Ü. (2007) Spatial correlograms of soil cover as an indicator of landscape heterogeneity. *Ecological Indicators, In Press*, doi:10.1016/j.ecolind.2006.12.002

Vipper, H., Masso, V. and Kuill, T. (1996) Abandonment of land makes harm to Estonia. *Agriculture*, 9, pp. 6–7 (in Estonian)

Visser, H. and de Nijs, T. (2006) The Map Comparison Kit. *Environmental Modelling & Software*, Vol. 21, Issue 3, pp. 346-358

Vogt, P., Riitters, K. H., Iwanowski, M., Estreguil, C., Kozak, J. and Soille, P. (2007) Mapping landscape corridors. *Ecological Indicators* 7, pp. 481–488

Whittow, J. B. (1984) The Penguin dictionary of physical geography. Harmondsworth: Penguin

Winter, S. (1998) Bridging Vector and Raster Representation in GIS. In: Laurini, R., Makki, K., Pissinou, N. (Eds.) Advances in Geographic Information Systems. The Association for Computing Machinery Press, Washington, D.C., pp. 57-62

Wood, D. (1992) The Power of Maps. New York, London: The Guilford Press, 248 p.

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

Wrigley, N., Holt, T., Steel, D. and Tranmer, M. (1996) Analysing, modelling, and resolving the ecological fallacy. In: Longley, P. and Batty, M. (Eds.) Spatial Analysis: Modelling in a GIS Environment. Cambridge: GeoInformation International, pp. 23-407

Zha, Y., Liu, Y. and Deng, X. (2007) A landscape approach to quantifying land cover changes in Yulin, Northwest China. *Environmental Monitoring and Assessment, In Press*

Zheng, D., Wallin, D. O. and Hao, Z. (1997) Rates and patterns of landscape change between 1972 and 1988 in the Changbai Mountain area of China and North Korea. *Landscape Ecology*, 12, pp. 241–254

Zonneveld, I. S. (1995) Land Ecology: An Introduction to Landscape Ecology as a Base for Land Evaluation, Land Management and Conservation. Amsterdam: SPB Academic Publishing, 199 p.

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PUBLICATIONS

Peterson, U., **Aunap, R.** (1998)
Changes in agricultural land use in Estonia
in the 1990s detected with multitemporal Landsat MSS imagery.
Landscape and Urban Planning, No. 41, pp. 193–201

II

Kont, A., Jaagus, J., **Aunap, R.** (2003)
Climate change scenarios and the effect of sea-level rise for Estonia.
Global and Planetary Change, 36, pp. 1–15

III

Aunap, R., Uuemaa, E., Roosaare, J., Mander, Ü. (2006)
Spatial correlograms and landscape metrics as indicators of land use changes.
In: Martin-Durque, J. F., Brebbia, C. A., Emmanouloudis, D. E., Mander, Ü. (Eds.)
Geo-Environment and Landscape Evolution II. Evolution, Monitoring, Simulation,
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Ahas, R., Aasa, A., Silm, S., **Aunap, R.**, Kalle, H., Mark, Ü. (2007) Mobile Positioning in Space–Time Behaviour Studies: Social Positioning Method Experiments in Estonia. *Cartography and Geographic Information Science*, Vol. 34, No.4, 2007, pp. 259–273. *In Print*

Aunap, R., Uuemaa, E., Roosaare, J., Mander, Ü. (2006) Spatial correlograms and landscape metrics as indicators of land use changes. In: Martin-Durque, J. F., Brebbia, C. A., Emmanouloudis, D. E., Mander, Ü. (Eds.) Geo-Environment and Landscape Evolution II. Evolution, Monitoring, Simulation, Management and Remediation of the Geological Environment and Landscape. WIT Transactions on Ecology and the Environment, Vol. 89, pp. 305–315

Eesti atlas (*Atlas of Estonia*). **Aunap, R.** (Ed.), Tallinn: BIT & TÜGI, 48 p. (*in Estonian*)

Kont, A., Jaagus, J., **Aunap, R.** (2003) Climate Change Scenarios and the Effect of Sea Level Rise for Estonia. *Global and Planetary Change*, 36, pp. 1–15

Kont, A., Jaagus, J., **Aunap, R.**, Ratas, U., Rivis, R. (2008) Implications of Sea-Level Rise for Estonia. *Journal of Coastal Research*, 24, pp. xx–xx. *To be Publish*

Kurs, O., Cabouret, M., **Aunap, R.** (2002) Les frontières terrestres de l'Estonie. *Mosella*, Tome XXVII N° 1–2, p. 27–37.

Kurs, O., **Aunap, R.** (2003) Estlands fastlandsgrenser. *Norsk Geografisk Tidsskrift*, Vol. 57. No. 1, pp. 53–57

Machado Santiago, R., Kurs, O. **Aunap, R.**, Iglesias Campos, A. (2004) Las fronteras de Estonia como Estado miembro de la Unión Europea. *Cuadernos Geográficos*. Publicación semestral. Universidad de Granada. Núm. 35 (2004–2), pp. 117–141

Oja, T., Roosaare, J., **Aunap, R.**, Jagomägi, J. (2000) Spatial data models in Estonia. In: Winter, S. (Ed.) Geographical Domain and Geographical Information Systems – Geoinfo Series No.19, pp. 81–83

Palo, A., **Aunap, R.** and Mander, Ü. (2005) Predictive vegetation mapping based on soil and topographical data: A case study from Saare County, Estonia. *Journal for Nature Conservation*, Vol. 13, Issues 2–3, pp 197–211

Peterson, U., **Aunap, R.** (1998) Changes in Agricultural Land Use in Estonia in the Nineties Detected with Multitemporal Landsat Imagery. *Landscape and Urban Planning*, No. 41, pp. 193–201

Peterson, U., **Aunap, R.**, Eilart, J. (1998) Eestimaa nähtuna kosmosest (*Estonia Seen from Space*). Tallinn: Koolibri, 32 p. (*in Estonian*)

Roose, A., **Aunap, R.**, Tamm, T. (2005) A framework and techniques for environmental mapping of the Estonian monitoring data. In: Goodchild, M. (Ed.) GIS Planet 2005 Proceedings. May 30-June 2, 2005, Estoril, Portugal, Lisboa: Instituto Geografico Portugues

Timár, G., **Aunap, R.**, Molnár, G. (2004) Datum transformation parameters between the historical and modern Estonian geodetic networks. In: Punning, J.-M. (Ed.) Estonia. Geographical studies 9. Estonian Geographical Society, Estonian Academy Publishers, Tallinn, pp. 99–106

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