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A methodology of the satellite mapping and monitoring of protected landscapes in Estonia

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Abstract. The paper presents a methodology and reports on the results of land cover monitoring of seven protected areas covering 3600 km^2 using Landsat images from the years 1986–1998. An extensive Land Cover Nomenclature containing 87 categories was elaborated by applying a hybrid classification process combined with classification masks. Land cover changes were monitored and modelled using the Markov Model approach, which characterized the magnitude, direction, and rate of dominant processes, and was used for the prediction of future developments. Landscape diversity parameters and indices were calculated and their changes monitored. The use of Landsat 5 TM satellite imagery combined with ancillary data, GIS, and fieldwork serves as an efficient means for medium-scale landscape monitoring, which is needed in managing protected landscapes. Monitoring maps reveal the main environmental trends over ten years (from the 1980s to the 1990s). This makes it possible to predict threats to conservation objectives, and serves as a reliable input for local and international environment management efforts.

Key words: Landsat TM, GIS, land cover nomenclature, Markov Model, landscape diversity.

INTRODUCTION

Ecosystems as highly complex patterns of physiogenetic, biotic, and anthropogenic factors directly or indirectly correlated with one another form a paramount functional correlation represented by ‘landscape’ (Leser & Rodd, 1991). The use of medium-scale (M 1 : 50 000) satellite remote sensing has proven promising for the operative observation of current and historical states and for the assessment of the diversity of land cover (LC) of these landscapes.

Landsat 5 TM (Thematic Mapper) sensor has many advantages in ecological applications (Cohen & Goward, 2004) because of its suitable spatial resolution (grain size associated with the grain of land management), spectral resolution (all major portions of the solar electromagnetic spectrum are represented), and temporal resolution (systematically collected remote sensing data over more than 30 years). The broad spectral range of the Landsat data offers good opportunities for the interpretation of the essential characteristics of vegetation (abundance, state of biomass, etc.), subsoil character, and, importantly, the water content of both. This is especially important in territories covered with peatlands, where the percentage of moisture is high in the vegetation and moss surface.

Moreover, information from Landsat satellites has by far the best cost–benefit ratio. In land use/land cover satellite monitoring studies high-resolution satellite images (IKONOS, QuickBird, SPOT5) offer a much greater potential for accurate vegetation mapping (Ozdemir et al., 2005), especially in mires (Langanke et al., 2007). However, they are more expensive than Landsat and not available from earlier years.

Identification of meaningful biogeophysical features in satellite images requires the existence of a consistent and universal land cover nomenclature (LCN) for the observed patterns. The world-wide land use and land cover classification scheme (Anderson et al., 1976) needs to be adapted to local environmental conditions and should encompass all natural, semi-natural, and man-made patterns that can be recognized from satellite images. Their dynamics, followed on multi-date images, will reflect the environmental development.

In 1996 a national project entitled 'Remote Sensing of Estonian Landscapes' (RSEL), focusing on the monitoring of landscapes in selected nature protection areas from medium-scale (M 1 : 50 000) satellite images, was launched. Monitoring paid special attention to protected areas, but the surroundings were included to provide for 'neighbourhood ecology' (Forman, 1995; Kintz et al., 2006). The monitoring sites in Estonia consist therefore of protected (core) and reconciled 3 km wide buffer zones around them to better satisfy the needs of nature management.

The objectives of the present work were:

1. Development of a methodology for highly selective LC recognition from satellite images by using GIS technologies and field work
2. Computer-aided classification of LC patterns in satellite images using classification masks
3. Highlighting qualitative and quantitative changes in the monitoring sites
4. Predicting LC development trends in monitoring sites
5. Selecting diversity metrics for the studying of landscape diversity.

This work is an extension of similar studies by using aerial photos (Aaviksoo, 1988, 1993a) and monitoring and modelling LC dynamics by using Markov Models (MM) (Aaviksoo, 1995a).

Recently, several similar studies have mapped LC and observed changes in protected areas, nature reserves, or natural parks (Poulin et al., 2002; Groom et al., 2005; Hilbert, 2006; Von Wehrden et al., 2006) and predicted their future trends using the Markovian approach (Flamenco-Sandoval et al., 2007) to name but a few.

The present paper puts emphasis on a comprehensive approach, meaning the use of all available national and local GIS-based data, allowing us to archive a highly selective satellite mapping of the protected areas.

MATERIAL

Study areas

Estonia has in all 948 protected areas on 6826 km^2 (as of 6.07.2007) (Sirel, 2008) covering 15% of the Estonian territory of 45 227 km^2.

The 10 study areas, nature protection or core areas in dark grey and buffer zones around them in light grey, are depicted in Fig. 1 together with all other protected areas in Estonia. The first seven were studied using Landsat 5 TM multi-date satellite images and medium-scale GIS (1 : 50 000), the rest using single-date Landsat 7 ETM+ images and large-scale (1 : 10 000) GIS data.

Initially, the methodology reported here was developed for the RSEL project and applied on seven study areas – Alam-Pedja Nature Reserve (NR), Soomaa National Park (NP), Saarejärve Protected Park (PP), Lahemaa NP, Karula NP, Vilsandi NP, and Endla NR, which together cover 1773 km^2 of protected and 1784 km^2 of buffer areas (Table 1).

Saarejärve, Lahemaa, and Vilsandi are also National Integrated Monitoring Areas (IMA) and Alam-Pedja, Soomaa, Vilsandi, and Endla are Ramsar sites. The selection of the four NPs, two of which belong with Saarejärve PP to the IMA category, as satellite monitoring sites was caused by their status as permanent national environmental monitoring sites in Estonia (Riigi Teataja I, 1999). Available satellite mapping work in two other mire areas – Endla and Alam-Pedja

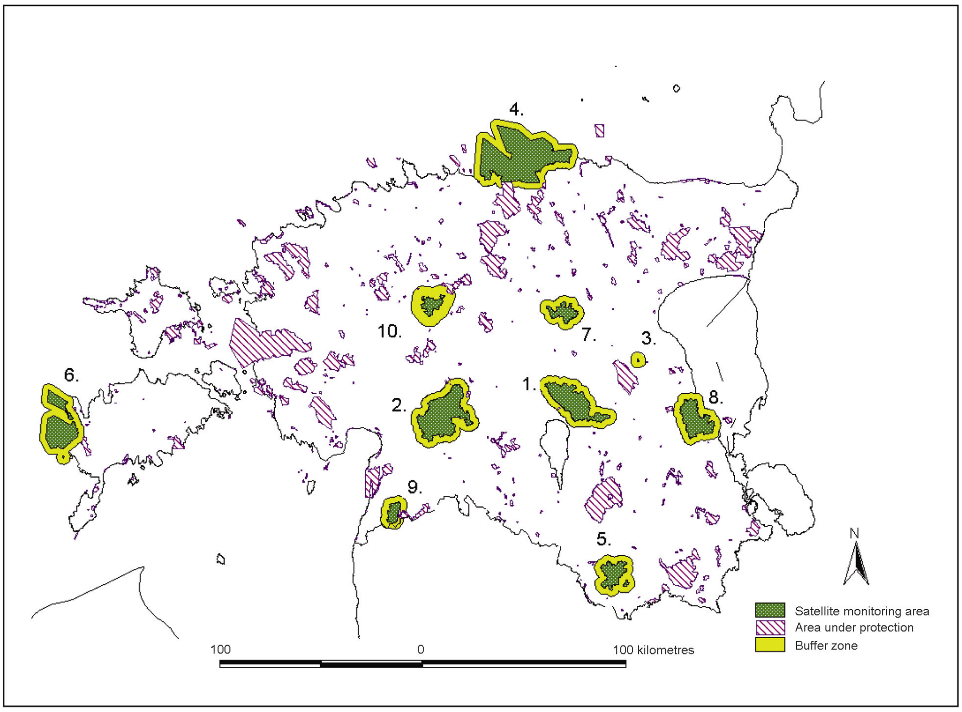


Fig. 1. Satellite image based mapping and monitoring in protected areas in Estonia. RSEL monitoring sites: 1 – Alam-Pedja NR, 2 – Soomaa NP, 3 – Saarejärve PP (and IMA), 4 – Lahemaa NP (and IMA), 5 – Karula NP, 6 – Vilsandi NP (and IMA), 7 – Endla NR. Other satellite mapping areas: 8 – Emajõe Suursoo LR, 9 – Nigula NR, and 10 – Kõnnumaa LR.

Table 1. Core and buffer areas in satellite image based monitoring sites in Estonia (in km^2)

Site	Satellite mapping dates	Core	Buffer	Whole
Alam-Pedja NR	1988, 1995	259.79	312.34	572.13
Soomaa NP	1988, 1995	368.33	348.97	717.30
Saarejärve PP*	1988, 1995	01.11	42.05	43.16
Lahemaa NP*	1988, 1995	727.63	451.33	1178.96
Karula NP	1992, 1997	109.29	215.58	324.87
Vilsandi NP*	1986, 1998	230.61	235.87	466.48
Endla NR	1988, 1995	76.29	178.32	254.61
Total		1773.05	1784.46	3557.51

* Integrated monitoring areas.

(Aaviksoo, 1995b; Aaviksoo et al., 2000) – offered a useful extension of the study, explaining the inclusion of these two areas into the list of RSEL monitoring sites.

The high representation of mire landscapes in Estonia is explained by their importance – they cover approximately 1/5 of the country's territory (Arold, 2005). Vilsandi is altogether the oldest (since 1910) protected area in Estonia. Single-date satellite data of three areas (Emajõe Suursoo Landscape Reserve (LR), Nigula NR, and Kõnnumaa LR) were used for an advancement of the Estonian LCN (ELCN) on habitat level in the RSEL project (Sepp & Kiis, 2007).

Data

Satellite data

As far as possible, cloud-free satellite images taken on nearly anniversary dates were used (Table 2), following the requirement of the phenological coincidence of the multi-date images. For the full and quarter scene (187/19, 189/19) images this requirement was fulfilled, but in the case of Karula NP, successive cloud-free images from the same phenological stage were not available.

Table 2. Landsat 5 Thematic Mapper imagery data

Path/row	Date	Scene	Monitoring site(s)
187/19	08.06.1988	Full	Soomaa NP, Alam-Pedja NR, Saarejärve PP, Lahemaa NP, Endla NR
187/19	12.06.1995	Full	
189/19	03.07.1986	Quarter	Vilsandi NP
189/19	04.07.1998	Quarter	
186/20	12.06.1992	Mini	Karula NP
186/20	29.08.1997	Mini	

Ancillary data

The availability of ancillary data and GIS is country specific. In the present study these included large-scale aerial photos (available from the 1950s to the present), forest management maps (scale 1 : 20 000) and concurrent inventory (taxation) data of forest stands (available in every 10 years), digital soil maps (scale 1 : 100 000; 1 : 50 000, and, since 2003, scale 1 : 10 000), the Estonian Base Map (1993, scale 1 : 50 000) in Transverse Mercator projection (EBM_TM) and since 2001 in Lambert Conformal Conical projection (EBM_L), which is simultaneously the official reference database in Estonia, cadastral maps (scale 1 : 10 000, compiled since 1992), geobotanical maps (compiled in protected areas since the 1950s; Kalda, 1991), agricultural survey data (field books composed for vast arable territories from the Soviet period, maps at scales of 1 : 10 000, descriptions of land use by crops grown, etc.), and daily recorded meteorological data of the nearest station of the monitoring site. The last were important in ordering satellite data, and to understand the appearance of the LC status, especially the effects of moisture content on the whole territory scanned by the satellite.

Field data

All mapping and monitoring sites were visited and ground truth data were gathered at the time of satellite data acquisitions: in June, July, or August. The typological authenticity of all classified LC units was verified in the nature using pre-classified satellite images. When it became apparent in situ that LC attribution was misleading, a better place for LC characterization was chosen in the field. Only verified LC unit areas were used as training sites in the final supervised classification of satellite images. In the case of cultivated areas, the land use information of the year of the satellite imaging was requested from farmers.

All fieldwork was documented, using a standardized form. The Global Positioning System (GPS) was used for the determination of the geographical coordinates of the field description study plot (25 × 25 m) centre. The documentation contains a description of vegetation layers (tree, shrub, dwarf shrub, grass, and moss/lichen), dominant and co-dominant species, and canopy coverage. Ground photos were taken.

The metadata of the whole set of information (satellite, aerial photo, ancillary, and field recoinnance data) for every monitoring site were consolidated in order to serve as a basis for the ongoing monitoring of the study areas.

METHODOLOGY

The methodology of mapping LC and monitoring the dynamics of Estonian mire landscapes, using aerial photos, was developed earlier (Aaviksoo, 1993a, b; 1995a). The initial methodology for the RSEL project was based on this experience (Aaviksoo & Meiner, 2001), combining it with the results of satellite mapping of landscapes (O’Neill et al., 1994; Ehlers & Rhein, 1995; Howard et al., 1995; Welch et al., 1995; Zheng et al., 1997; RESE, 1999).

The main effort in the further development of the methodology was directed towards compiling a more detailed and hierarchical LCN suitable for reliable mapping of mainly natural LC categories, characteristic of protected areas in Estonia. The development was carried out gradually: (1) the initial methodology with implementation in test areas in 1996 to 1997, (2) verification of the methodology, its improvement, and extension to other protected areas in 1998 to 2000, (3) integration of the methodology and compilation of the ELCN (Table 3).

This integrated mapping methodology contains eight steps: (1) pre-processing of the raw satellite images, (2) masking of the pre-processed satellite images, (3) unsupervised classification of the masked images, (4) identification of the training sites for supervised classification, (5) field checking and verification of the training sites using ancillary data, (6) supervised classification of the images, (7) elimination of the ‘salt-and-pepper noise’, and (8) analysis of the resulting maps. In several cases the analysis of the maps forced us to repeat steps 4 to 7 to improve the result, especially when a conflicting classification occurred along masking borders.

For satellite image processing and classification as well as map production PCI Geomatica 8.2 (earlier PCI EASI/PACE) software was used throughout this work. The georeferenced vector files of the thematic GIS coverages were provided by ARC/INFO 7.2.1 and ArcView 3.1 software. Landscape diversity indices were computed using the FRAGSTATS (McGarigal & Marks, 1995) program.

Land cover mapping

Pre-processing

The individual study areas were each covered by one satellite image and interpretation of the images was carried out separately. Therefore atmospheric corrections were not needed. Geometric rectification was essential to make reliable use of the GIS data. Ordered system-corrected images were rectified with polynomial functions by using around 10 well-defined ground control points (GCP) per each image identified on the Estonian Base Map. Smaller than half a pixel residual distortion was achieved by using the nearest-neighbour resampling procedure, which does not introduce any new pixel spectral vectors into the data (Schowengerdt, 1997). The same set of GCP was used for both image dates.

Masking

In the early stages of the project, satellite images were classified either automatically (clustering) or using spectral signatures of predefined LC types, applying a straightforward spectral-based image processing technology. The result proved to be unsatisfactory – the number of resolved LC types as well as the accuracy of the resulting maps were low (Aaviksoo et al., 2000). The main reason for this is the spectral similarity of geobotanically different LC types. This is best demonstrated in Fig. 2, where three herbal vegetation dominated LC categories from ecologically very different settings show similar spectral signatures.

Table 3. Hierarchical GIS-based Estonian Land Cover Nomenclature (ELCN) for medium-scale satellite imagery mapping and monitoring in the RSEL project (**bold – CORINE LCN code, incl.** ***in italic Estonian additional 4th level categories***)

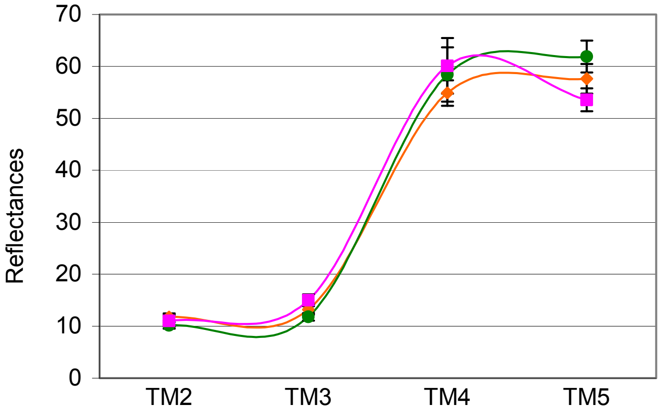
Landscape type	Land cover class	Land cover type	Land cover subtype
1. WATER	1.1. WATER BODIES	1.1.1. Sea (**523**)	1.1.1.1. Deep sea
			1.1.1.2. Shallow seacoast
			1.1.1.3. Shallow sea with reeds
		1.1.2. Inland water bodies (**512**)	1.1.2.1. Lake
			1.1.2.2. Bog pool
		1.1.3. Inundation	1.1.3.1. Flooded coast
			1.1.3.2. Flooded river shore
2. LAKE SHORES AND SEA COASTS	2.1. BARREN SURFACE	2.1.1. Fine-grained surface (**331**)	2.1.1.1. Sand
			2.1.1.2. Pebble and gravel
		2.1.2. Coarse-grained surface	2.1.2.1. Moraine
	2.2. SCARCE VEGETATION	2.2.1. Sparsely vegetated areas (**333**)	2.2.1.1. White dune
			2.2.1.2. Vegetation b/w stones
3. WETLANDS	3.1. REEDS	3.1.1. Coastal marshes	3.1.1.1. Coastal reed (***4111***)
		3.1.2. Inland marshes (**411**)	3.1.2.1. Shore reed and cattail (***4111***)
	3.2. SUBMERGED GRASSLANDS	3.2.1. Salt marshes (**421**)	3.2.1.1. Coastal meadow with halophilic plants (***4211***)
		3.2.2. Fresh marshes	3.2.2.1. Floodplain grassland
			3.2.2.2. Paludified grassland
4. MIRES	4.1. OPEN FENS AND SWAMPS	4.1.1. Sedge fens	4.1.1.1. Quaking fen
			4.1.1.2. Sedge fen
		4.1.2. Moss and sedge swamps	4.1.2.1. Quaking swamp
			4.1.2.2. Sedge swamp
	4.2. WOODED FENS AND SWAMPS	4.2.1. Shrub and wooded fens	4.2.1.1. Shrub fen of *Salix* spp. (***3242***)
			4.2.1.2. Wooded fen (***3242***)
		4.2.2. Shrub and wooded swamps	4.2.2.1. Shrub swamp of *Salix* spp. (***3242***)
			4.2.2.2. Wooded swamp (***3242***)
	4.3. OPEN BOGS	4.3.1. Open bogs (**412**)	4.3.1.1. Bog lagg (***4121***)
			4.3.1.2. Hollow (*Rhynchospora* spp.) bog (***4121***)
			4.3.1.3. Moss-tussock (*Sphagnum* spp.) bog (***4121***)

Table 3. *Continued*

Landscape type	Land cover class	Land cover type	Land cover subtype
			4.3.1.4. Cotton grass (*Eriophorum*/*Trichophorum*) (***4121***)
			4.3.1.5. Cotton grass–dwarf shrub (*Eriophorum*/*Trichophorum* spp.–*Ericaceous*) bog (***4121***)
	4.4. WOODED BOGS	4.4.1. Shrub and wooded bogs	4.4.1.1. Dwarf shrub (*Ericaceous*) bog (***4121***)
			4.4.1.2. Wooded cotton grass–tussock bog (***3242***)
			4.4.1.3. Wooded dwarf shrub bog (***3242***)
		4.4.2. Complex bogs	4.4.2.1. Open ridge–lawn bog (***4121***)
			4.4.2.2. Treed-ridge–lawn bog (***3242***)
			4.4.2.3. Treed-ridge–lawn–pool bog (***3242***)
5. FOREST LANDS	5.1. MIRE FORESTS	5.1.1. Deciduous forests (**311**)	5.1.1.1. Birch (*Betula pubescens*) forest
			5.1.1.2. Alder (*Alnus glutinosa*) forest
		5.1.2. Coniferous forests (**312**)	5.1.2.1. Spruce forest
			5.1.2.2. Pine forest
		5.1.3. Mixed forests (**313**)	5.1.3.1. Mixed forest
	5.2. DRY AND FRESH FORESTS	5.2.1. Deciduous forests (**311**)	5.2.1.1. Birch (*Betula pendula*) forest
			5.2.1.2. Grey alder (*Alnus incana*) forest
			5.2.1.3. Aspen forest
		5.2.2. Coniferous forests (**312**)	5.2.2.1. Pine forest
			5.2.2.2. Spruce forest
		5.2.3. Mixed forests (**313**)	5.2.3.1. Mixed deciduous (ash, oak, maple) forest
			5.2.3.2. Mixed coniferous (pine, spruce) forest
			5.2.3.3. Mixed (deciduous/coniferous) forest
	5.3. RENEWABLE FORESTS	5.3.1. Clearings (**324**)	5.3.1.1. Fresh clear-cut (***3241***)
			5.3.1.2. Grassy clear-cut (***3241***)
			5.3.1.3. Shrubby clear-cut (with single trees) (***3241***)
		5.3.2. Plantations (**324**)	5.3.2.1. Young pine plantation (***3241***)
			5.3.2.2. Young spruce plantation (***3241***)
		5.3.3. Afforested grasslands (**324**)	5.3.3.1. Deciduous stand (***3241***)
			5.3.3.2. Coniferous stand (***3241***)

Table 3. *Continued*

Landscape type	Land cover class	Land cover type	Land cover subtype
	5.4. SHRUBLANDS	5.4.1. Deciduous shrublands (**324**)	5.4.1.1. Floodplain shrublands (***3241***)
			5.4.1.2. Meadow, overgrowing with shrubs (***3241***)
		5.4.2. Coniferous shrublands (**322**)	5.4.2.1. Juniper
	5.5. BURNT AREAS	5.5.1. Burnt forests and mires (**334**)	5.5.1.1. Forest
			5.5.1.2. Mire
6. GRASSLANDS	6.1. NATURAL AND SEMI-NATURAL GRASSLANDS	6.1.1. Natural grasslands (**321**)	6.1.1.1. Alvar grassland
			6.1.1.2. Boreal heath grassland
			6.1.1.3. Boreo-nemoral grassland
		6.1.2. Semi-natural grasslands	6.1.2.1. Alvar grasslands with juniper
			6.1.2.2. Wooded grassland
7. AGRICULTURAL LANDS	7.1. CULTIVATED GRASSLANDS	7.1.1. Pastures (**231**)	7.1.1.1. Cultivated haylands (for hay mowing)
			7.1.1.2. Cultivated pasture (for cattle)
	7.2. PLOUGHED FIELDS	7.2.1. Arable lands (**211**)	7.2.1.1. Bare soil (unvegetated in image)
			7.2.1.2. Cornfield
			7.2.1.3. Fodder crop field
			7.2.1.4. Industrial crop field
			7.2.1.5. Fallow
		7.2.2. Plantations (**222**)	7.2.2.1. Orchards (fruit trees)
			7.2.2.2. Berry plantation (bushes)
			7.2.2.3. Berry plantation (strawberry)
		7.2.3. Afforested pastures (after 10 years of disuse)	7.2.3.1. Deciduous young stand
			7.2.3.2. Coniferous young stand
8. ARTIFICIAL LANDS	8.1. OPENCAST MINES	8.1.1. Mineral extraction areas (**131**)	8.1.1.1. Sandpit
			8.1.1.2. Gravel pit
			8.1.1.3. Oil shale quarry
		8.1.2. Peat extraction areas (**412**)	8.1.2.1. Milled peat area (***4122***)
			8.1.2.2. Abandoned peat milling area
9. URBAN	9.1. URBAN AREAS	9.1.1. Dense built-up areas (**111**)	9.1.1.1. Town
		9.1.2. Tenuous built-up areas (**112**)	9.1.2.1. Village
			9.1.2.2. Cemetery



	TM2	TM3	TM4	TM5
Crop	11.76	13.19	54.89	57.62
Coastal meadow	10.16	11.80	58.44	61.92
Open bog	11.00	14.99	60.11	53.57

Fig. 2. The similarity of the spectral signatures of herbal vegetation in ecologically different ecotopes (TM2 to TM5 are the spectral channels of the Landsat TM sensor).

To distinguish between these types, classification masks (stratification) separating the areas were used (Aaviksoo & Meiner, 2001). EBM_TM provides for that purpose seven thematic layers: (1) forests and natural grasslands (FG), (2) mires (M), (3) water (W), (4) agricultural lands (A), (5) peat excavation areas (P), (6) mines (M), and (7) urban areas (U).

The study areas are mostly covered by different forests and other natural LC types, whose status is strongly dependant on soils. Digital soil maps offered for masking purposes four thematic layers: mineral soils (MI), minerotrophic (fen) soils (F), mixotrophic (swamp) soils (S), and ombotrophic (bog) soils (B).

By combining the 7 + 4 available thematic layers, 12 classification masks were created (Table 4). For the first eight masks the full hybrid (unsupervised/supervised) classification was carried out, in the case of agricultural and peat excavation areas we limited ourselves to unsupervised classification only, for mines and urban areas no further classification was carried out.

Pre-classification

This step was carried out for the most recent (1990s) satellite images. Natural groupings of the spectral properties of masked pixels of the satellite image were examined using the ISOCLUST method. The parameters for this unsupervised classification (most importantly the number of resolvable spectral clusters) were determined in an iterative process to result in the best experiential correspondence between the identified spectral clusters and the representation of the evolving

Table 4. Classification masks as combinations of thematic GIS layers

Mask No.	Mask description	Thematic layers
1	Forests and grasslands on mineral soils	FG + MI
2	Forests and grasslands on minerotrophic (fen) soil	FG + F
3	Forests and grasslands on mixotrophic (swamp) soils	FG + S
4	Forests and grasslands on ombotrophic (bog) soils	FG + B
5	Mires on minerotrophic soils	M + F
6	Mires on mixotrophic soils	M + S
7	Mires on ombotrophic soils	M + B
8	Water (sea, lakes and great pools in mires)	W
9	Agricultural lands (cultivated fields and grasslands)	A
10	Peat excavation areas (incl. abandoned)	P
11	Mines (open mineral extraction areas)	M
12	Urban areas (incl. other artificial land)	U

classification units. The whole set of the available ancillary material was needed at this stage for qualitative assessments of the (intermediate) classification results. The pre-classification stage resulted in a number of spectral clusters in correspondence to fixed classification units of the evolving ELCN.

Identification of training sites

Further, 'spectral training sites' have to be determined on the images, establishing reliable spatial correspondence between a clearly identified LC category and any spectral class of the satellite image.

All training areas (at least three for each LC category, as is the custom) covered at least 21 homogeneous pixels (more than 1.2 ha) and fulfilled the following spectral requirements: (1) separability for normally distributed spectral classes, which is expressed by the *Bhattacharyya* distances (Mather, 1993), must be more than 1.8; (2) spectral signatures of LC must be representative (standard deviation must be less than 2) and documented for further investigation in the future; (3) the scatter plot of all spectral classes in the feature space must cover the entire spectral space.

In multi-date images (T_1 and T_2) training sites were preferably located to the same places (unless they were changed during the investigation period).

Field checking of training sites

The previous stage resulted in a fieldwork map and a route for ground truthing. All the identified training sites were checked in situ or, if this was not possible, by an extensive evaluation based on all available ancillary data. Any failure to confirm a correspondence in field recoinnance work resulted in the identification of a more suitable new training site.

Final classification

The checked training sites were introduced into the georeferenced image, and classification was carried out under all different masks, using the Maximum Likelihood Algorithm in Supervised Classification (Lillesand & Kiefer, 2000).

Where possible, 4th level categories of the ELCN (Table 4) – LC subtypes (LCST) – were taken into consideration in delineating the training site polygons. When this level was not achievable, 3rd level categories – LC types (LCT) – were used.

Elimination of salt-and-pepper noise

The final maps contained ‘salt-and-pepper’ noise (individual pixels with a differing LC category than in neighbouring pixels). To filter out those pixels, a 3 × 3 median filter for replacing ‘noisy pixels’ was used (PCI User’s Guide, 1995).

Analysis and finalization of the resultant maps

After classification under all masks, the final LC maps were compiled by concatenating the masked sub-maps into one whole. The line of the concatenation of the masked maps was checked in detail to identify any possible classification conflicts along the concatenation lines. In the case of conflicting differences between LC types along the concatenation line, the classification procedure was repeated with modified training sites.

The documentation of all 2 × 7 LC maps included the following data:

(1) training site polygons – locations in maps, centre point coordinates, identificators
(2) reference data – coordinates of georeference points, field recoinnance data, forest management, cadastral map data
(3) spectral signatures of all LC categories
(4) photos of representative LC training sites in nature
(5) statistical data of LC.

Assessment of mapping accuracy

The accuracy of the classification can be assessed by comparing the resultant LC maps with the ‘reality’ at a number of checking GCPs randomly selected on the study area. The results are best expressed in the form of an error matrix, the rows of which correspond to the map LC category and columns of the ‘real’ LC category. The diagonal elements reflect the number of accurate mappings for all LC types. A number of different accuracy indicators (overall accuracy, errors of omission and commission, Kappa coefficients, etc.) can be calculated using this matrix. The one most important integral characteristic of the accuracy of the maps is the overall accuracy, which is calculated as the ratio of the sum of the diagonal elements of the error matrix to the total number of GCPs.

A large number of checking points must be used to ensure reliability of the error matrix. Congalton (1991) suggested that a minimum of 50 samples for each LC category in the error matrix be collected, which we took as a reference. This resulted in about 600 checking points in most cases. In one study area – Endla – 4000 samples were used for a more detailed analysis.

For better representation, stratified random sampling was used and three-by-three window buffered around point (Menard et al., 2002) was used as control units. The reference data were mainly provided by large-scale aerial photos, and to a smaller extent by CORINE Land Cover, cadastral, and forest management maps.

Detection and modelling of land cover change

The results of classifications (so-called classification maps) at T_1 and T_2 were used as inputs for the detection and monitoring of LC change, using the post-classification comparison method (Singh, 1989).

Change maps and the transition matrix

Quantitative and qualitative changes in LC have been followed by compiling change maps on the 2nd (LCC) level of the ELCN (Table 3). Use of 16 LC types from the 19 available on this level enabled us to obtain an overview of the main changes in the LCC, i.e. altogether $16 \times 16 = 256$ possible transitions. Change maps for each monitoring site were generated by superimposing LCC maps of two dates, T_1 and T_2, for every location on the map. The result allows following changes in LC categories for every pixel of the image over time ($T_1 \rightarrow T_2$). By calculating the areas of all possible transition types between LC categories, we may represent the result in the form of a matrix, where diagonal elements represent no-change and off-diagonal elements change from one (row) LCC to another (column) LCC category. This matrix is called the transition matrix T_{ij}, where i indicates the initial and j the final category.

Observation and modelling of changes by transition matrices (Debussche et al., 1977; Aaviksoo, 1995a; Dale et al., 2002) are especially useful for landscape management purposes.

The Markov Model (MM) and the prognosis of future change

The transition matrix allows modelling the evolution of LC change. If we normalize each row of the transition matrix T_{ij} by the total area of the patches of the corresponding LCC, the elements of the row will represent the probability of change from the initial class i to the final class j determined by the column index j for the whole study area, resulting in a normalized matrix M_{ij}.

Let us describe the initial state of the monitoring site by V_i, where the elements of V_i represent the total area of all patches of LC type i in the initial map. Then the final state V_f, where the elements reflect the total area of all patches of type j in the final map can be calculated as

$$V_f = M_{fi} * V_i.$$

The matrix M can be used for the prognosis of the evolution of the monitoring site. The future state V_F can be found by multiplying the current state vector (V_f) by matrix M:

$$V_F = M * V_f.$$

This step can be repeated to yield next generations of LC change. This non-linear MM of predicting future states was successfully used (Aaviksoo, 1995a), and its reliability for describing natural and man-induced changes was checked using three-date aerial photo studies (Aaviksoo & Kadarik, 1989).

Assessment of landscape diversity

Studies of landscape diversity have been carried out since the 1980s, when the first quantitative investigation methods of landscape structure were devised (e.g. Krummel & Gardner, 1987). Initially, three indices of landscape diversity were proposed (O'Neill et al., 1988), but today there are more than 100 different indices, which reflect various aspects of the 'diversity phenomenon'. Land cover maps may well be used to calculate diversity indices and, in the case of repetitive maps, also to monitor changes in diversity (Stoms & Estes, 1995), which is important in nature conservation areas. In the present work, a number of diversity indices were calculated using LCC maps but the results are reported for only five: (1) mean patch size (MPS), (2) edge index (EI), (3) mean nearest neighbour distance (MNN), (4) Shannon's diversity index (SHDI), and (5) contagion index (CONTAG), which we consider most representative in protected areas diversity and their change studies.

Before calculations, all patches with an area of less than 1 ha were merged to neighbouring areas because their inclusion in the case of medium-scale Landsat TM data has proved misleading (Zheng et al., 1997).

RESULTS AND DISCUSSION

The central result of the present paper is the ELCN that emerged from the proposed methodology and is suitable for the LC mapping and monitoring of protected areas and their immediate neighbourhoods from medium-scale satellite images, analysis of the observed change of LC, modelling of the change, and assessment of landscape diversity (change) using the compiled maps.

Estonian Land Cover Nomenclature

In Estonia, only visual interpretation of false-colour satellite data has been used previously: (1) in the compilation of the Estonian Base Map (EBM_TM, M 1 : 50 000, source SPOT (1993) and (2) in the CORINE Land Cover (CLC) project (M 1 : 100 000, Landsat 5 TM in 1996; Landsat 7 ETM+ in 1998, and SPOT-4 and IRS-1C,-1D in 2006). Both of these used predetermined methods and a limited LCN.

The present, RSEL, work was started in parallel with the pan-European CLC project in 1996. The aim, scale, underlying mapping and monitoring methodology, and LCNs were, however, different. The present work focused primarily on nature protection areas in Estonia, using the minimum mapping unit of 1.3 ha and computer-aided classification, whereas CLC had adopted a more general approach with the minimum mapping area of 25 ha (Heymann et al., 1994; Bossard et al., 2000; Büttner et al., 2004). Nevertheless, a reasonable correspondence could be established between the CLC LCN and the present, ELCN, which can be seen as an extension of the former.

In addition to the extensive CLC project, other classification systems of vegetation have been proposed before. The UNESCO system (1973) classifies vegetation according to physiognomy and floristic composition and has been used for mapping vegetation throughout the world. Several later systems have spun off from the UNESCO system, most notably the USNVC system (Grossman et al., 1998) and the Land Cover Classification System, LCCS of FAO/UNEP (Di Gregorio & Jansen, 2000).

The European CLC project uses 44 LC classes (32 in Estonia), which constitute the 3rd level units in a hierarchical classification scheme. We propose to expand the CLC scheme for Estonia, adding 4th level categories by dividing the three existing 3rd level categories – transitional woodlands (3.2.4), inland marshes (4.1.1), and peatlands (4.1.2) – into six sub-categories.This proved both necessary and possible in the case of Estonian (and the other northern) landscapes, which are rich in ecologically different forests and wetlands (Meiner, 1999). This was further grounded as spectral attention was paid to protected areas, dominated by natural and semi-natural landscapes.

The resultant ELCN, as presented in Table 3, is organized into four levels as follows:

The 1st level is the landscape type level (LT, 9 items), which closely corresponds to its regional analogues, including CLC and EBM. Actually, the six landscape types of the EBM were used in compiling the classification masks in this project.

The 2nd level is the LC class level (LCC, 19 items). It is further used to follow and model LC change and diversity.

The 3rd level is the LC type level (LCT, 39 items). CLC uses the term *land cover class* to denote the classification units at this level.

The 4th level is the LC subtype level (LCST, 87 items) and broadly corresponds to ecotopes (E) in geosciences or habitats (H) in biosciences. This level was in most cases the level of initial supervised classification in this work.

This classification is open-ended. Categories may be added to any of the hierarchical levels. For excample, more 4th level mire categories were added when using Landsat ETM+ data in investigating mire landscapes (Aaviksoo & Leivits, 2001) and in a detailed habitat mapping in two protected areas in Estonia with the integration of large-scale GIS (Sepp & Kiis, 2007). Therefore, Landsat TM imagery is not the only source of information for LC and determination of classification categories, but these depend also on ancillary data (aerial photos, expert knowledge, soil data, fieldwork, etc.).

The present approach has proved especially efficient in classifying natural landscape categories, mainly mires and forests, in medium scale. Estonia is very rich in mires – 20% of its territory or 9000 km^2 has a more than 30 cm thick peat cover (Arold, 2005). Mires are divided into fens (60%), bogs (28%), and transitional mires (12%) (Valk, 1988). Therefore, extensive inclusion of mire landscape categories into ELCN is fully appropriate.

The first attempt to interprete mire landscapes in nature reserves was done by Aaviksoo (1988, 1993b), using large-scale aerial photos and displaying 19 classification categories. Its extension to satellite images of mire reserves contained 35 units (Aaviksoo, 1995b) and was expanded to 58 categories in the satellite monitoring of Lahemaa NP (Aaviksoo & Muru, 2001). The first use of Landsat 7 ETM+ data and large-scale GIS as classification masks made it possible to achieve about ninety 4th level categories (Aaviksoo, 2004), of which 60 were natural.

It must be emphasized that an extensive ELCN is possible only if reliable ancillary materials, most importantly soil maps, are available at interpretation. These maps reflect previous local research on vegetation classification for mires (Masing, 1984), forests (Lõhmus, 1984), grasslands (Krall et al., 1980), and especially ecological–phytocoenological classifications (Laasimer, 1965; Marvet, 1970; Paal, 1997), and were indispensable for specification of the 4th level LC categories.

Land cover maps

As a result, 14 geo-referenced maps (2 for each study area) were generated using the 4th (LCST) level classification categories (4th level maps). The number of actually represented categories on each map ranged between 20 and 45 (on average 32), depending on the study area. The hierarchical ELCN allows aggregation of higher level categories to lower level categories and thus generation of maps at the LCT (3rd), LCC (2nd), and LT (1st) levels. In the following, these different maps were used in different applications. Aside from academic interests, these maps were used in the practical elaboration of the management plans for the protected areas.

Accuracy of land cover maps

The accuracy of the maps was checked at the LCC level. Checkpoints were selected randomly, using the stratified random sample model and excluding the urban and

Table 5. Ground control points (GCP), land cover classes (LCC), and accuracy coefficients (A – overall accuracy, K – Kappa coefficients) of the maps of two dates, T_1 and T_2

Study area (T_1, T_2)	No. of GCP	No. of LCC	T_1		T_2	
			A	K	A	K
Alam-Pedja (1988, 1995)	650	13	76%	72%	76%	71%
Soomaa (1988, 1995)*	650	13	66%	61%	71%	66%
Saarejärve (1988, 1995)	550	11	74%	69%	72%	67%
Lahemaa (1988, 1995)	600	12	86%	82%	87%	83%
Karula (1992, 1997)	600	12	78%	74%	77%	73%
Vilsandi (1986, 1998)	600	12	76%	71%	78%	74%
Endla (1988, 1995)	4000	16	90%	89%	92%	90%

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* Only the unsupervised classification procedure was carried out for this study area, considerably reducing the resultant accuracy.

agricultural LC categories, since these categories were determined solely on the basis of the classification masks. Taking into account the high number of checking points, no ground truthing was carried out and reference was provided mainly by aerial photos, to a lesser extent by other ancillary materials. Error matrixes were compiled for all maps. Error characteristics – overall accuracy (A) and Kappa coefficients (K) – were calculated (Table 5).

The overall accuracy of the maps ranged between 70% and 90%. This is an acceptable level of accuracy when taking into account the number of classification categories (11 to 13). It was argued (Jensen, 1996) that landscape mapping from satellite images can be considered reliable in applications if the accuracy is higher than 85%. Of our seven study areas, this accuracy level was reached in the case of Endla and Lahemaa. The largest classification errors occurred in the case of open bogs, mixed forests, and shrublands, which points to the difficulties in delineating naturally continuous transitions (as, for example, in the case of mixed forests, which constitute a separate class between coniferous and deciduous forests).

Land cover change maps and transition matrixes

Changes in landscapes were monitored on seven study areas over time periods of 7 to 12 years depending on the dates of repetitive satellite images. The initial LC maps were first aggregated to the 2nd or LCC level, which is the suitable level to study LC change on areas measuring more than 100 km^2. On that level, some 16 (depending on the study area) different LC categories are represented, allowing us to get a comprehensive picture of changes (for smaller areas with fewer LC categories present, change can, naturally, also be studied at higher levels of detail).

Transition probability matrixes, compiled for all study areas, enable to quantitatively follow change trends and predict future development. As an example, the probability matrix for the Vilsandi study area covering 466 km^2 of coastal landscapes on the western coast of the island of Saaremaa in the Baltic Sea is given in Table 6. The diagonal elements of the matrix give the probability that no

Table 6. Transition probability matrix between final (V1998) and initial (V1986) states in the Vilsandi NP monitoring site

No.	Land Cover Class	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	V_{1986} **(ha)**
1	Water	**99**	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**28 212**
2	Coastal reeds	14	**86**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**342**
3	Barren coasts	0	0	**24**	39	20	0	0	6	1	10	0	1	0	0	0	0	**492**
4	Sparse coastal vegetation	0	0	9	**30**	20	0	0	16	12	10	0	3	0	0	0	0	**1 046**
5	Natural grasslands	0	0	3	8	**62**	0	0	6	4	7	7	5	0	0	0	0	**4 397**
6	Open bogs	0	0	0	0	0	**94**	5	0	0	0	0	1	0	0	0	0	**33**
7	Wooded bogs	0	0	0	0	0	31	**67**	0	1	0	0	0	0	0	0	0	**62**
8	Alvar grasslands (juniper)	0	0	1	13	5	0	0	**58**	20	3	0	0	0	0	0	0	**793**
9	Juniper shrublands	0	0	1	6	6	0	0	12	**53**	18	1	2	0	0	0	0	**667**
10	Coniferous forests	0	0	1	3	3	0	0	1	2	**81**	1	7	0	0	0	0	**3 764**
11	Deciduous forests	0	0	0	0	11	0	0	0	0	2	**56**	30	0	0	0	0	**1 698**
12	Mixed forests	0	0	1	2	5	0	0	0	0	32	2	**58**	0	0	0	0	**2 540**
13	Arable lands	0	0	0	0	0	0	0	0	0	0	0	0	**40**	51	9	0	**1 611**
14	Cultivated grasslands	0	0	0	0	0	0	0	0	0	0	0	0	30	**61**	9	0	**715**
15	Fallow lands	0	0	0	0	0	0	0	0	0	0	0	0	20	40	**40**	0	**30**
16	Urban and artificial lands	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**100**	**246**
	V_{1998} **(ha)**	**27 850**	**704**	**373**	**1 164**	**3 539**	**51**	**44**	**1 001**	**949**	**4 524**	**1 352**	**2 494**	**865**	**1 275**	**217**	**246**	**46 647**
	1986–1998, %	**99**	**206**	**76**	**111**	**80**	**154**	**71**	**126**	**142**	**120**	**80**	**98**	**54**	**178**	**723**	**100**	

change will occur over the observation period. The last column, V1986, gives the total area (in hectares) of all LCC in the initial year 1986 and the row V1998, in the final year 1998. The last row shows the percentage increase (decrease) in the total area of LCC over the study period.

The Vilsandi study area represents mostly coastal landscapes. Analysis of the transition matrix allows us to follow the main trends of LC change. The most pronounced changes are the doubling of coastal reeds (from 342 to 704 ha) and cultivated grassland (from 715 to 1275 ha), as well as the appearance of fallow lands (from 30 to 217 ha) at the expense of arable lands and cultivated grasslands. Coniferous forests expanded at the expense of mixed forests, and the latter were augmented by deciduos forest areas. It must be noted that the accuracy of the maps was no more than 70% to 80%, and thus changes of 20% or less should be interpreted with caution. A more detailed and focused study of the change in areas with the help of ancillary material is needed to look beyond major trends of change due to mapping accuracy limitations.

Transition matrixes were compiled for the core (protected) area, the buffer area around it, and the whole study area, thus providing a possibility of following differences of LC development.

Main trends of land cover change

The transition probability matrix can be used to predict the future state of the study area and a graphic representation of LC at three – past, present, and future – dates allows a good visual picture of the observed change. For the Vilsandi study area this is done in Fig. 3, where the resultant graph of changes is given. From the figure we can see that the prediction of future development based on the Markov Model is essentially non-linear. The increase of one LCC over the study period may cease in the future (as in the case of cultivated grasslands) or, vice versa, a decrease may end (as in the case of arable lands). This is a result of the hidden successional dynamics revealed only in the transition matrix, making this modelling superior to a simple linear extrapolation of the observed changes into the future. A more comprehensive analysis of this non-linear modelling is given in (Aaviksoo, 1995a).

Coastal landscapes were also represented in the Lahemaa study area where, however, forest types were more prominent. We observed a considerable increase of coniferous forests at the expense of mixed forests in this case, as well as arable lands turning fallow.

In mire landscapes, as represented by the Alam-Pedja, Soomaa, and Endla monitoring sites, about half of the total territory is covered by mires. The main development trends were an increase in forest types (minerotrophic and mixotrophic mire forests as well as deciduous forests) and the turning of cultivated lands into fallow lands. The proportion of open bogs decreased and grasslands increasingly became covered with shrubs.

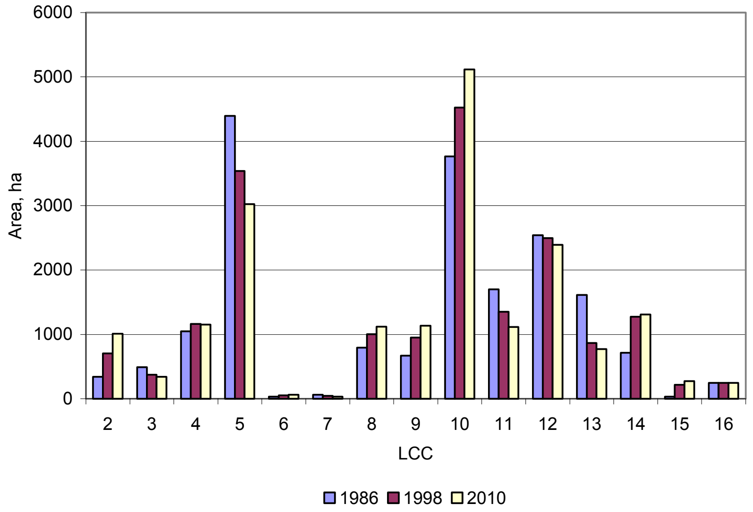

Fig. 3. Land cover changes at the Vilsandi monitoring site. 1 – water (not indicated), 2 – coastal reeds, 3 – barren coasts, 4 – sparse coastal vegetation, 5 – natural grasslands, 6 – open bogs, 7 – wooded bogs, 8 – alvar grasslands with junipers, 9 – juniper shrublands, 10 – coniferous forests, 11 – deciduous forests, 12 – mixed forests, 13 – arable lands, 14 – cultivated grasslands, 15 – fallow lands, 16 – urban and artificial lands.

Forested and agricultural landscapes prevailed in the Karula and Saarejärve study areas. The main trends were widening of mixed forests at the expense of coniferous forests and the overgrowing of natural grasslands with shrubs. Arable and agricultural lands had turned fallow or had become grasslands.

Summarizing the observed changes over all study areas (covering in total some 8% of the Estonian land territory) allowed us to reveal the following five major trends of LC change in Estonia from the 1980s through the 1990s:

1. **Afforestation:** the most noteworthy trend is the increase of different forest LCCs at the expense of clearcuts, shrublands, grasslands, and agricultural LCCs. A visible natural trend towards increasing forest areas in fens, transitional bogs, and bogs was evident. The compaction of young pine stands resulted in the transition of wooded mire categories into forest mires in the Alam-Pedja NR and Soomaa NP. However, to prevent interpretation of natural succession of errors in the mires, a longer investigation period is suggested. Afforestation at the expense of renewable forests had the greatest share in the case of deciduous forests in the Alam-Pedja NR (26%), Karula NP (17%), and Lahemaa NP (37%). The rate of afforestation of natural grasslands was higher in Soomaa NP, where they (1095 ha in total) were occupied by shrublands at a rate of 38 ha/yr.
2. **Changes in the composition of forest stands:** the observed expansion of coniferous stands in forests was firstly taken as a hypothesis. The measurements of and fieldwork on mixed forest (deciduous and coniferous, as well as mixed coniferous (pine and spruce) stands in Lahemaa NP) areas confirmed the significant trend of the broadening of the share of pine and spruce in these

stands between 1986 and 1998. The increase in coniferous stands was approximately 10%. Spruce forest stands are a climax community in Estonia. The increasing amount of coniferous stands (more precisely, the reaching of spruce trees to the upper canopy layer) in mixed (even in coniferous mixed) forests was clearly visible in Lahemaa and Vilsandi NPs, in Saarejärve IMA, and in Alam-Pedja NR.

3. **Deforestation and increase of fallow areas in buffer zones:** protected areas have no clear-cuts. In buffer zones, forest clearing activities have intensified, and hence the areas under clear-cuts have increased by 80% in the Karula NP and by 60% in the Endla NR buffer zones. Arable land has considerably decreased in the study areas and fallow, shrubland, and even young forest areas have come instead. The evolution of the abandoned fields depends most significantly on their immediate vicinity. Usually, previous arable fields turn fallow after 3 years. They are covered with shrubs after 5 years and trees (birch, less often pine and spruce) invade 10 years after abandonment. In the case of cultural grasslands, this process can be even quicker. The rates of shrinking of arable land were greatest in the Karula NP and Saarejärve IMA buffer zones, where 40–50% of the arable land was abandoned during the investigation period. Meantime, fallow land increased 13 and 7 times respectively in the Karula NP and Saarejärve IMA buffer zones.
4. **The overgrowing of natural and semi-natural grasslands:** there was a clear trend of the overgrowing of natural grasslands with shrubs and later with deciduous, and less with coniferous trees. Floodplain shrubby grasslands are in the process of turning into forests in Lahemaa (14%), in Karula (36%), and in Alam-Pedja (22% of these areas had changed into young deciduous forest during the investigation period). Semi-natural alvars are changing due to the ceasing of sheep herding in coastal pastures. Especially remarkable was the overgrowing of semi-natural (alvar) grassland with juniper in Lahemaa NP, where alvar grasslands diminished by 770 ha. Alvar grasslands in Vilsandi with <30% juniper cover turned into dense juniper shrublands on an area of 280 ha.
5. **Overgrowing of seashores with reeds and cattail:** this process occurred in all monitoring sites in conditions of shallow sea water. In Vilsandi NP the area occupied by reeds doubled in 12 years due to environmental (nutrient) problems in the coastal zone. The area with sparse vegetation cover expanded 11% during the investigation period at the expense of barren coast.

All the observed trends (except for the last) are clear manifestations of the socio-economic changes that took place in Estonia from 1988 to 1992. The abandoning of the Soviet economic model affected directly agricultural and forestry practices – collective and state farms were dismantled, land reform was carried out, subsidies for agrobusiness were substantially reduced, large forest areas were returned to former private owners, and extensive melioration works were stopped. This all resulted in changed land use practices, which was in turn reflected in LC dynamics. This change will continue in the coming years unless major structural changes occur in the agricultural sector.

Landscape diversity

One of the aims of landscape monitoring is to follow changes in landscape diversity. We calculated five different diversity indexes from the 2nd level maps for all seven study areas and separately for the core and buffer areas on both dates. The average patch areas ranged between 10 and 30 ha, the edge indexes between 60 and 140 m/ha, nearest neighbour distances between 200 and 320 m, Shannon diversity indexes between 1.2 and 2.2, and contagion indexes between 50% and 70%. As a result, $7 \times 2 \times 5 = 70$ time-separated pairs of diversity index change were calculated. Although the indexes varied considerably between different study areas and core and buffer zones, all indexes of the same area changed less than 5%, or occasionally 10%, over time. Despite the overall erratic pattern of index change, some conclusions can still be drawn.

Of the 70 time-pairs, in 42 cases diversity increased against 28 when it decreased or remained the same. More remarkably, in 28 cases the diversity indexes evolved in the same direction in both core and buffer areas against 7 in which the development moved in the opposite direction. And last but not least, landscape diversity increased in all cases for the Karula and Vilsandi study areas, and decreased in the cases of the Alam-Pedja and Lahemaa study areas. This essentially allows us to conclude that the diversity of landscapes increased from the 1980s to the 1990s, and that increases, or occasionally decreases, were much more dependent on the overall settings of a given study area than on the protection regime.

CONCLUSIONS

A comprehensive integrated methodology for medium-scale (M 1 : 50 000) LC mapping and monitoring using satellite images and national GIS data was developed. The methodology focuses on the differentiation of mostly natural LC categories and was applied to seven nature protection areas and their immediate surroundings covering a total of 3558 km^2 or 8% of the Estonian territory.

In the course of the work, a hierarchical ELCN was developed including 9 categories at the 1st or landscape type (LT) level, 19 categories at the 2nd or land cover class (LCC) level, 39 categories at the 3rd or land cover type (LCT) level, and 87 categories at the 4th or land cover subtype (LCST) or ecotope (habitat) level.

This ELCN and the corresponding mappings can be used in regional comparisons (CORINE LC and others) at the 1st level, to follow LC change and development on the regional and national levels at the 2nd level, and for planning and compiling management plans at the local level (3rd and 4th levels). They also can be used at different space and time scales as landscape dignostics (Bastian et al., 2006).

Land cover maps of two dates were used in monitoring LC change in the protected areas and their buffer zones. The main observed trends of development over ten years (from the 1980s to the 1990s) were the expansion of reeds and afforestation as a result of natural succession, the development of shrublands, and the extension of fallow land and clear-cuts as a result of economic (in)activity.

The Markov Model (MM) was used to model the changes and predict future trends. Landscape diversity and its development were assessed using different characteristics. An increase in the landscape fragmentation in both protected areas and their neighbourhoods was observed.

The developed methodology has proven to be a cost- and time-efficient way of monitoring landscape dynamics, useful in the practical process of the management of nature protection areas. Future work based on the developed methodology will move from medium to large scale mapping using IKONOS and QuickBird data. This is highly promising in the mapping and monitoring of the Natura 2000 habitat sites.

A more prolonged observation period is needed in order to reliably reveal the natural succession trends of the protected areas, which to date can only tentatively be recognized from the LC change maps.

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REFERENCES

Aaviksoo, K. 1988. Natural and anthropogenous changes in a mire and its neighborhood. In *Dynamics and Ecology of Wetlands and Lakes in Estonia* (Zobel, M., ed.), pp. 90–105. Acad. Sci. Est. SSR, MAB, Tallinn.

Aaviksoo, K. 1993a. Application of Markov Models in Investigation of Vegetation and Land Use Dynamics in Estonian Mire Landscapes. PhD thesis, University of Tartu.

Aaviksoo, K. 1993b. Changes of plant cover and land use types (1950’s to 1980’s) in three mire reserves and their neighbourhood in Estonia. *Landscape Ecol.*, **8**(4), 287–301.

Aaviksoo, K. 1995a. Simulating vegetation dynamics and land use in a mire landscape using a Markov model. *Landscape Urban Plan.*, **31**, 129–142.

Aaviksoo, K. 1995b. Vegetation of Endla Nature Reserve classified on the basis of Landsat TM data. In *Consortium Masingii* (Aaviksoo, K., Kull, K., Paal, J. & Trass, H., eds), pp. 27–36. Tartu.

Aaviksoo, K. 2004. Eesti maastike kaugseire – olemus, tulemus ja tulevikunägemus. In *Kaugseire alased uuringud Eestis* (Oja, T. & Nilson, T., eds). *Publ. Inst. Geogr. Univ. Tartu.*, 95, 185–200.

Aaviksoo, K. & Kadarik, H. 1989. Dynamics of wetland landscapes and reliability of prediction of their development. *Sov. J. Ecol.*, **20**(4), 221–226.

Aaviksoo, K. & Leivits, A. 2001. Combining multi-date remote sensing and longterm bird census data in two mire landscapes in Estonia. http://nigula.ee/pub/landcover1.pdf

Aaviksoo, K. & Meiner, A. 2001. Satellite monitoring of Estonian landscapes. *Publ. Inst. Geogr. Univ. Tartu.*, 92, 233–238.

Aaviksoo, K. & Muru, K. 2001. Lahemaa maastike satelliitseire. *ELUS AR*, **80**, 18–52.

Aaviksoo, K., Paal, J. & Dislis, T. 2000. Mapping of wetland habitat diversity using satellite data and GIS: An example from the Alam-Pedja Nature Reserve, Estonia. *Proc. Est. Acad. Sci. Biol. Ecol.*, **49**, 177–193.

Anderson, J. R., Hardy, E. E., Roach, J. T. & Witmer, R. E. 1976. A land use and land cover classification system for use with remote sensor data. *U.S. Geological Survey. Professional Paper*, 964, 1–28.

Arold, I. 2005. *Eesti maastikud*. Tartu Ülikooli Kirjastus.

Bastian, O., Krönert, R. & Lipsky, Z. 2006. Landscape diagnosis on different space and time scales – a challenge for landscape planning. *Landscape Ecol.*, **21**, 359–374.

Bossard, M., Feranec, J. & Otahel, J. 2000. *CORINE Land Cover Technical Guide – Addendum Technical Report*, 40. EPA.

Büttner, G., Feranec, J., Jaffrain, G., Mari, L., Maucha, G. & Soukup, T. 2004. The CORINE Land Cover 2000 Project. *EARSeL eProc.*, **3**(3), 331–346. http://las.physik.uni-oldenburg.de/eProceedings/

Cohen, W. B. & Goward, N. 2004. Landsat's role in ecological applications of remote sensing. *Bioscience*, **54**(6), 535–545.

Congalton, R. G. 1991. A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sens. Environ.*, **37**, 35–46.

Dale, V., Fortes, D. T. & Ashwood, T. L. 2002. A landscape-transition matrix approach for land management. In *Integrating Landscape Ecology into Natural Resource Management* (Liu, J. & Taylor, W. W., eds), pp. 265–293. Cambridge University Press.

Debussche, M., Gordon, M., Lepart, L. & Romane, F. 1977. An account of the use of a transition matrix. *Agro-ecosysystems*, **3**, 81–92.

Di Gregorio, A. & Jansen, L. J. M. 2000. *Land Cover Classification System (LCCS): Classification Concepts and User Manual*. FAO, Rome.

Ehlers, M. & Rhein, U. 1995. Environmental monitoring – statewide comparative landuse classification in Lower Saxony focusing on moor and pasture areas. In *Proc. 9th Int. Symp. on Computer Science for Environ. Protection CSEP'95*, 1, 209–218. Berlin.

Flamenco-Sandoval, A., Ramos, M. M. & Masera, O. R. 2007. Assessing implications of land-use and land-cover change dynamics for conservation of a highly diverse tropical rain forest. *Biol. Cons.*, **138**(1–2), 131–145.

Forman, R. T. T. 1995. Some general principles of landscape and regional ecology. *Landscape Ecol.*, **10**(3), 133–142.

Groom, G., Mücher, C. A., Ihse, M. & Wrbka, T. 2005. Remote sensing in landscape ecology: Experiences and perspectives in a European context. *Landscape Ecol.*, **20**(6), 627–644.

Grossman, D. H., Faber-Langendoen, D., Weakley, A. S., Anderson, M., Bourgeron, P., Crawford, R., Goodin, K., Landaal, S., Metzler, K., Patterson, K. D., Pyne, M., Reid, M. & Sneddon, L. 1998. *International Classification of Ecological Communities: Terrestrial Vegetation of the United States. Vol. I. The Nature Conservancy*. Arlington, VA.

Heymann, Y., Steenmans, Ch., Croisille, G. & Bossard, M. 1994. *CORINE Land Cover. Technical Guide*. Office for Official Publications of the European Communities, Luxembourg.

Hilbert, K. W. 2006. Land cover change within the Grand Bay National Estuarine Research Reserve: 1974–2001. *J. Coast. Res.*, **22**(6), 1552–1557.

Howard, D., Bunce, R., Jones, M. & Haines-Young, R. 1995. *Development of the Countryside Information System. Countryside Survey 1990 Series*, Vol. 2. London.

Jensen, J. R. 1996. *Introductory Digital Processing: A Remote Sensing Perspective*. Prentice Hall Inc., New Jersey.

Kalda, A. 1991. Large-scale vegetation mapping in the planning of nature conservation area. In *Scripta Botanica 6* (Leht, M., ed.), pp. 98–111. Tallinn.

Kintz, D. B., Young, K. R. & Crews-Meyer, K. A. 2006. Implications of land use/land cover change in the buffer zone of a national park in the tropical Andes. *Environ. Manage.*, **38**(2), 238–252.

Krall, H., Pork, K., Aug, H., Püss, E., Rooma, I. & Teras, T. 1980. *Eesti NSV looduslike rohumaade tüübid ja tähtsamad taimekooslused*. Eesti NSV Põllumajandusministeeriumi Informatsiooni ja Juurutamise Valitsus, Tallinn.

Krummel, J. R. & Gardner, R. H. 1987. Landscape pattern in a disturbed environment. *Oikos*, **48**, 321–324.

Laasimer, L. 1965. *Eesti NSV taimkate*. Valgus, Tallinn.

Langanke, T., Burnett, C. & Lang, S. 2007. Assessing the mire conservation status of a raised bog site in Salzburg using object-based monitoring and structural analysis. *Landscape Urban Plan.*, **79**, 160–169.

Leser, H. & Rodd, H. 1991. Landscape ecology – fundamentals, aims and perspectives. In *Modern Ecology: Basic and Applied Aspects* (Esser, G. & Overdieck, D., eds), pp. 831–844. Elsevier, Amsterdam.

Lillesand, T. M. & Kiefer, R. W. 2000. Remote Sensing and Image Interpretation. Wiley, New York.

Lõhmus, E. 1984. *Eesti metsakasvukohatüübid*. Eesti NSV Agrotööstuskoondise Info- ja Juurutus-valitsus, Tallinn.

Marvet, A. 1970. Eesti taimekoosluste määraja. *Abiks loodusvaatlejale*, 61. Teaduste Akadeemia, Tartu.

Masing, V. 1984. Estonian bogs: Plant cover, succession and classification. In *European Mires* (Moore, P. D., ed.), pp. 120–148. Academic Press, London.

Mather, P. M. 1993. *Computer Processing of Remotely-sensed Images*. Wiley, Great Britain.

McGarigal, K. & Marks, M. 1995. Spatial Pattern Analysis Program for Quantifying Landscape Structure. Gen. Tech. Rep. PNW-GTR-351. U. S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Meiner, A. (ed.). 1999. *Land Cover of Estonia. Implementation of CORINE Land Cover Project in Estonia*. Ministry of the Environment, Estonian Information Centre, Tallinn.

Menard, S., Kindscher, K. & Peterson, D. 2002. Using Ecological Systems as Land Cover Map Units for the GAP Analysis Program in Kansas: Summary Report to USGS-BRD Gap Analysis Program. NatureServe, Minneapolis, MN and Kansas Biological Survey, Lawrence, KS. Unpublished report.

O'Neill, R. V., Krummel, J. R., Gardner, R. H., Sugihara, G., Jackson, B., DeAngelis, D. L., Milne, B. T., Turner, M. G., Zygmunt, B., Christensen, S. W., Dale, V. H. & Graham, R. L. 1988. Indices of landscape pattern. *Landscape Ecol.*, **1**(3), 153–162.

O'Neill, R. V., Jones, K. B., Riitters, K. H., Wickham, J. D. & Goodman, I. A. 1994. *Landscape Monitoring and Assessment Research Plan*. EPA, Washington.

Ozdemir, I., Asan, U., Koch, B., Yesil, A., Ozkan, U. Y. & Hemphill, S. 2005. Comparison of Quickbird-2 and Landsat-7 ETM+ data for mapping of vegetation cover in Fethiye-Kumluova coastal dune in the Mediterranean region of Turkey. *Fresenius Environ. Bull.*, **14**(9), 823–831.

Paal, J. 1997. *Eesti taimkatte kasvukohatüüpide klassifikatsioon*. Keskkonnaministeeriumi Info- ja tehnokeskus, Tallinn.

PCI User's Guide Ver. 6.0. 1995. Ontario.

Poulin, M., Careau, D., Rochefort, L. & Desrochers, A. 2002. From satellite imagery to peatland vegetation diversity: How reliable are habitat maps? *Cons. Ecol.*, **6**(2).

RESE (Remote Sensing for the Environment). 1999. Programme Plan Phase II 2000–2002.

Riigi Teataja I. 1999. 81, 741.

Schowengerdt, R. A. 1997. *Remote Sensing, Model and Methods for Image Processing*. Academic Press, San Diego.

Sepp, E. & Kiis, K. 2007. Matsalu rahvuspargi ja Nigula looduskaitseala satelliitseire 1986–2001. Riiklik keskkonnaseire programm, alamprogramm “Eluslooduse mitmekesisuse ja maastike seire”, allprogramm “Maastike kaugseire”. http://eelis.ic.envir.ee:88/seireveeb/

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

Sirel, K. 2008. Kaitsealad, hoiualad ja kohalikud objektid seisuga 31.12.2007. http://eelis.ic.envir.ee

Stoms, D. M. & Estes, J. E. 1995. A remote sensing research agenda for mapping and monitoring biodiversity. *Int. J. Remote Sens.*, **14**(10), 1839–1860.

UNESCO. 1973. *UNESCO International Classification and Mapping of Vegetation*. Paris.

Valk, U. (ed.). 1988. *Eesti sood*. Valgus, Tallinn.

Von Wehrden, H., Wesche, K., Miehe, G. & Reudenbach, C. 2006. Vegetation mapping in Central Asian dry eco-systems using Landsat ETM+ – a case study on the Gobi Gurvan Sayhan National Park. *Erdkunde*, **60**(3), 261–272.

Welch, R., Remillard, M. & Dore, R. F. 1995. GIS database development for South Florida’s national parks and preserves. *Photogramm. Eng. Remote Sens.*, **61**(11), 1371–1381.

Zheng, D., Wallin, D. O. & Hao, Z. 1997. Rates and patterns of landscape change between 1972 and 1988 in the Changbai Mountain area of China and North Korea. *Landscape Ecol.*, **12**(5), 241–254.

Looduskaitsealade satelliitseire metoodika Eestis

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Ökolooglise kaugseire rakendusena on välja arendatud looduskaitsealade maastike satelliitseire metoodika. Seire teostamiseks keskmises mõõtkavas on sobilikud Landsat TM-i digitaalandmed, mis kombineerituna kõikvõimalike lisamaterjalidega (aerofotod, puistuplaanid, katastrikaardid jm) võimaldavad kaardistada maakatet 87 ökotoobi (elupaigatüüp, kasvukohatüüp) piires. Selleks on loodud Eesti maakatte 4-tasemeline klassifitseerimisskeem, mis tugineb maakattemustrite välisilmele ja struktuurile ning võtab võimalusel arvesse Eesti ala varasemaid taimkatte, eriti ökoloogilis-fütotsönoloogilisi klassifikatsioone.

Metoodikat on rakendatud ja selle sobivust uuritud 7 satelliitseire alal, kus lisaks maakatte kaardistamisele on 10-aastase perioodi vältel vaadeldud ajaloolisi muutusi maakattes, selle mitmekesisuses, samuti on heidetud pilk muutuste tulevikusuundadele.

CORINE Land Coveri maakatte andmebaasile täiendavalt võimaldab loodud metoodika koostada detailsemat (miinimumkaardistusüksus on 10 korda suurem) maakattekaarti ja teha järeldusi toimunud muutustest nii kaitsealal kui selle naabruses, olles seeläbi abiks kaitsekorralduse efektiivsuse kontrollil ning vajadusel selle edasiste alternatiivide valikul.